TECHNICAL MEMORANDUM

Recommendations for Design Storms for Use in Hydrologic Modeling in Tacoma Washington

MG Schaefer Ph.D. P.E.

1.0 OVERVIEW

Design storms are commonly used by hydrologists and Civil Engineers in hydrologic modeling for estimating peak flow rates, runoff volumes and hydrograph shapes for use in design of stormwater infrastructure or for assessing the performance of existing infrastructure. Design storms can be synthetically developed based on statistical characteristics of observed storms or may be scaled directly from historical storm events. Both synthetic design storms and historical design storms will be provided and discussed in this Technical Memorandum (TM).

Success in rainfall-runoff modeling using an event-based hydrologic modeling approach is dependent in-part upon utilizing a design storm that contains storm characteristics that are representative of the site of interest. In the Pacific Northwest, west of the Cascade Mountains, there are three distinctive categories of storm characteristics. These storm characteristics may be generally categorized as short-duration, intermediate-duration, and long-duration storms (Schaefer[13]) based on the storm duration at which precipitation within the storm was most rare. The short-duration and long-duration storms are of particular interest in urban settings. Short duration, high-intensity, storms are commonly the controlling storm type for sizing of conveyance structures where passage of peak flow rates is the primary concern. Long-duration, low to moderate intensity, storms are typically used where runoff volume or a combination of peak flow rate and runoff volume are the concerns. These storms are applicable for sizing of stormwater detention facilities or for sizing of conveyance structures for stormwater systems serving large service areas.

2.0 MODELING APPLICATIONS FOR SYNTHETIC AND HISTORICAL DESIGN STORMS

In general, synthetic design storms are commonly used as the regulatory requirement for the more routine hydrologic modeling applications for sizing and design of stormwater infrastructure.

Historical design storms are generally used in two situations. Historical storms are often used to assess performance of existing stormwater infrastructure in response to flooding produced by a storm which has occurred within a City's jurisdiction and the storm/flooding characteristics are familiar to the public and City officials. A second application is where a suite of historical design storms, with differing temporal characteristics, are used to provide a more robust evaluation of the sizing and design of large scale stormwater infrastructure where high capital costs warrant a more detailed hydrologic assessment.

3.0 SHORT-DURATION HIGH-INTENSITY STORMS

Short-duration high-intensity storms are primarily warm season convective events and may also occur in the fall and early-winter periods produced by squall lines associated with the passage of cold fronts (Figure 1). Periods of intense precipitation often occur over 10-30 minutes with precipitation commonly extending over a 1-hour to 3-hour period. These storms are limited in areal coverage but can produce very high intensities over isolated areas. These storms are often termed thunderstorms as they are sometimes accompanied by thunder, lightning, and hail. They can produce very flashy runoff hydrographs with a large flood peak, particularly in urban watersheds where much of the land surface is covered by imperious surfaces. The short-duration storm is often the controlling storm type for sizing conveyance structures in urbanized areas. Figures 2a, 2b and 2c depict examples of short-duration high-intensity storms observed in the Tacoma and Seattle areas of the Puget Sound Lowlands of western Washington.

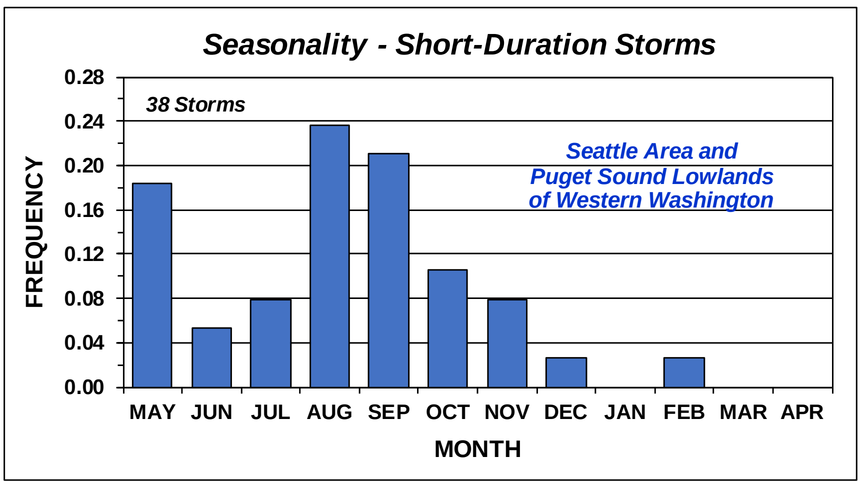

Figure 1 – Seasonality of Short-Duration High-Intensity Storms in the Seattle Area and Puget Sound Lowlands

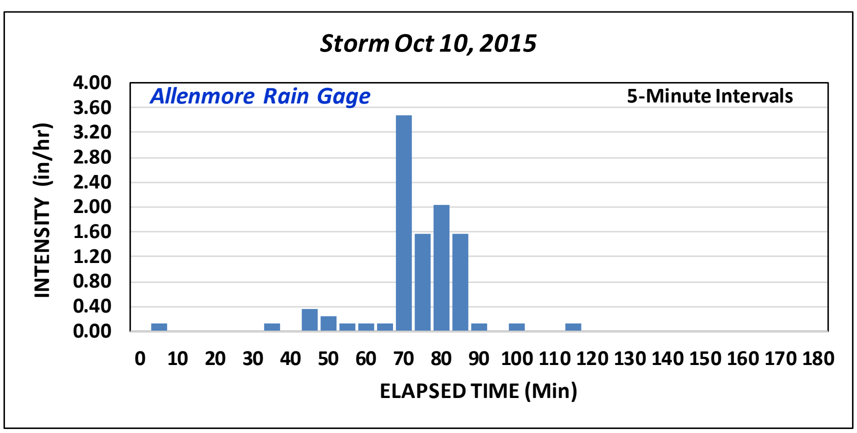

Figure 2a – Hyetograph for Storm of October 10, 2015 Recorded at Allenmore Rain Gage, Tacoma WA

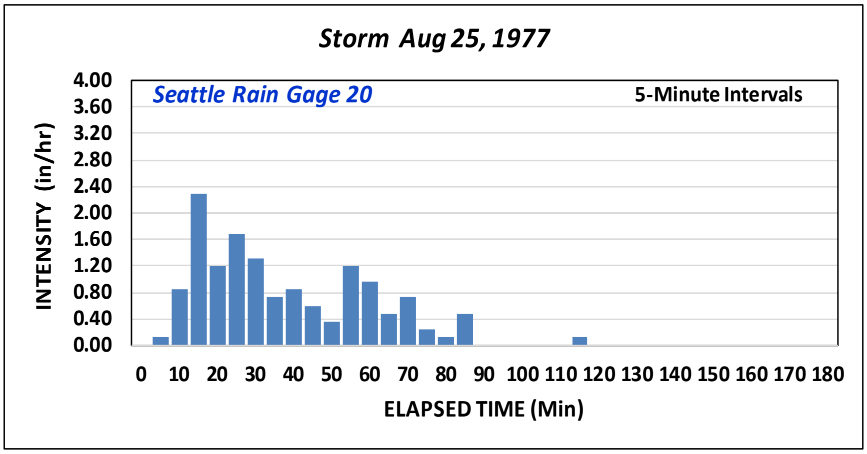

Figure 2b – Hyetograph for Storm of August 25, 1977 Recorded at Seattle Public Utilities Rain Gage 20

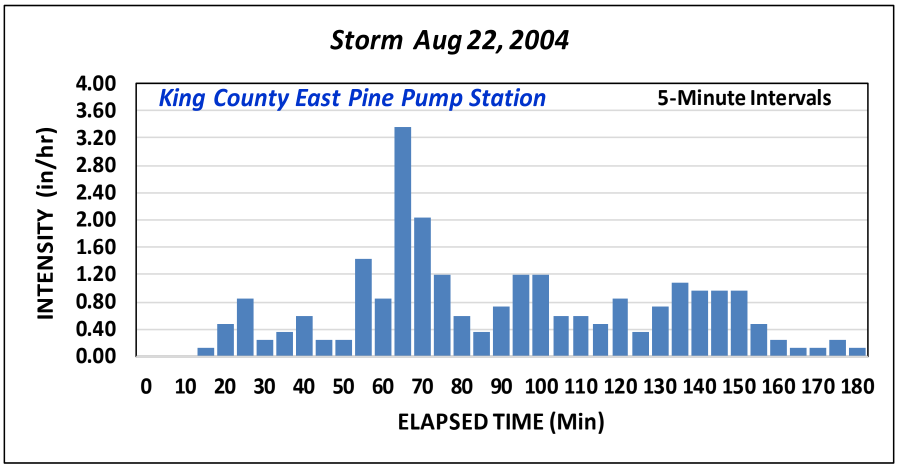

Figure 2c – Hyetograph for Storm of August 22, 2004 Recorded at King County East Pine Pump Station

4.0 LONG-DURATION LOW TO MODERATE-INTENSITY STORMS

Long-duration storms with low to moderate intensities occur primarily in the fall and winter months in the Pacific Northwest (Figure 3). These storms are produced by synoptic scale (continental scale) mid-latitude cyclones and associated fronts where atmospheric rivers originating in the warmer waters of the Pacific Ocean may provide a sustained source of atmospheric moisture. These storms are characterized by long periods of both intermittent and continuous precipitation with durations ranging from near 24-hours to over 72-hours. They can produce large total volumes of precipitation that occur over very large areas (Miller[9]). This type of storm typically produces floods with a sustained flood peak that is well supported by a large runoff volume. The long duration storm is usually the controlling storm type for design/analysis of stormwater detention facilities where runoff volume, in addition to flood peak discharge, is a primary consideration. Figures 4a, 4b and 4c depict examples of long-duration storms recorded in the City of Tacoma.

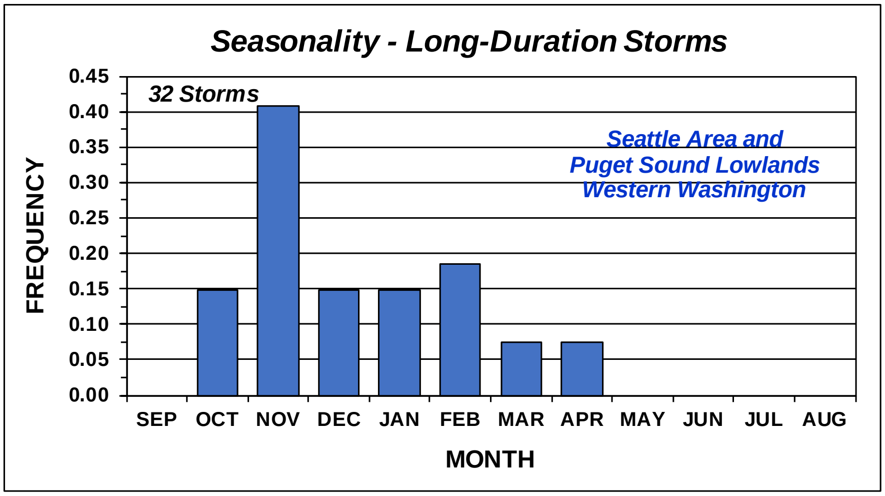

Figure 3 – Seasonality of Short-Duration High-Intensity Storms in the Seattle Area and Puget Sound Lowlands

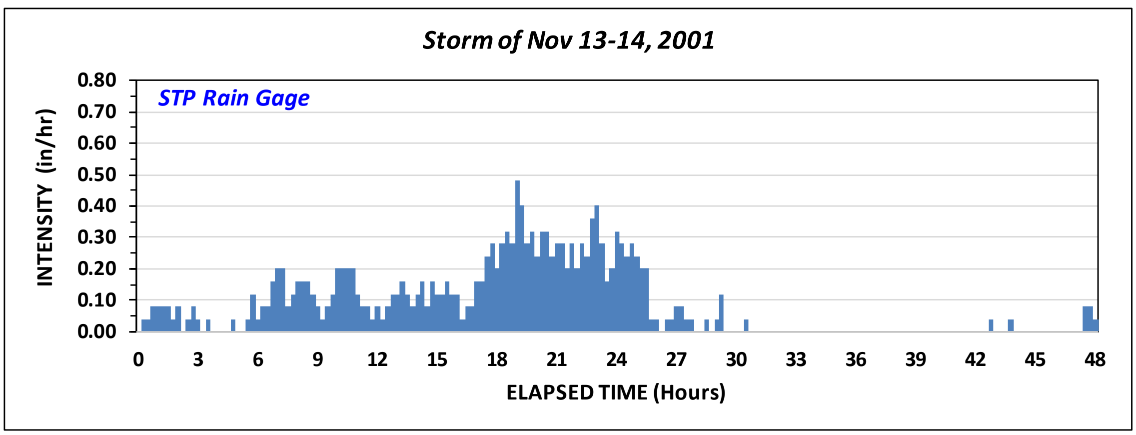

Figure 4a – Hyetograph for Storm of November 13-14, 2001 Recorded at the STP Station, Tacoma WA

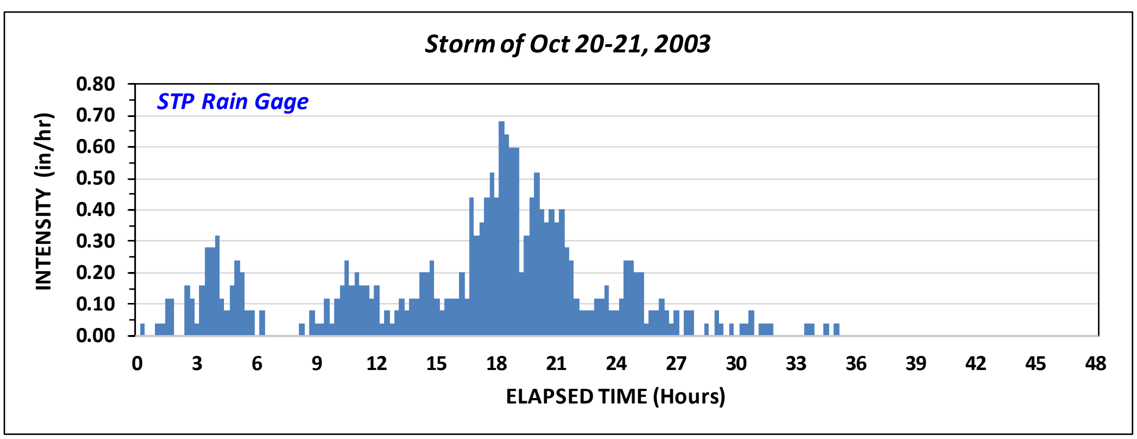

Figure 4b – Hyetograph for Storm of October 20-21, 2003 Recorded at the STP Station, Tacoma WA

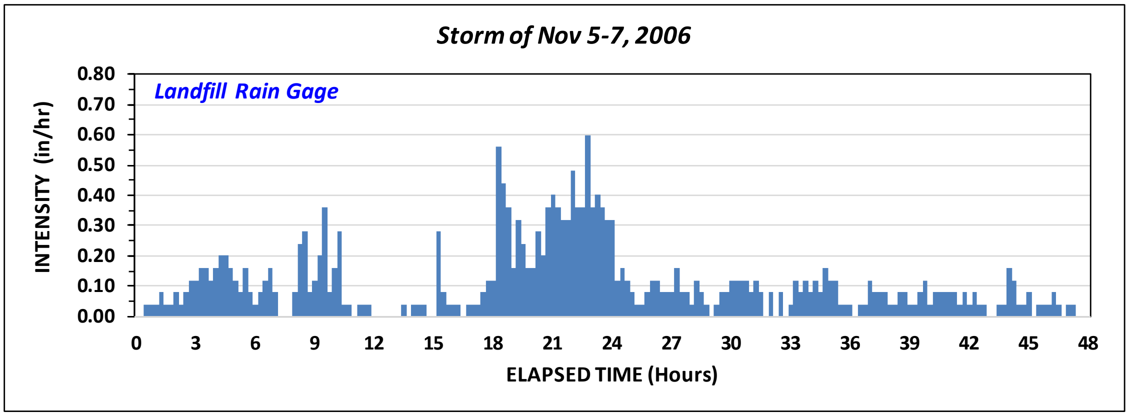

Figure 4c – Hyetograph for Storm of November 5-7, 2006 Recorded at the Landfill Station, Tacoma WA

5.0 SYNTHETIC DESIGN STORMS AVAILABLE FROM PRIOR STUDIES

Synthetic design storms are assembled in a manner to contain characteristics observed in historical storms. Several studies of temporal storm characteristics have been conducted for locations in the Puget Sound Lowlands that are applicable to the Tacoma area. This includes studies conducted by NOAA (Frederick et al[5]), and studies conducted for the Washington Department of Ecology Dam Safety program in 1989, Washington Department of Transportation in 2002, City of Seattle in 2003, and Washington Department of Ecology Dam Safety program in 2008 (Schaefer[13,15,16,17,19]). This collection of studies provides a thorough examination of storms in the Puget Sound Lowlands that are applicable to the Tacoma area.

Short-duration and long-duration synthetic design storms that were developed from storms observed in the Seattle area are recommended for use in the Tacoma area. The Seattle study included analyses of 30 historical short-duration storms and 29 long-duration storms that occurred in the Puget Sound Lowlands, primarily in King County, during the period from 1941-2002. Details about the development of the Seattle synthetic design storms may be found in Schaefer[17].

The synthetic design storms are expressed in dimensionless form which allows the storms to be scaled by precipitation for a user-specified recurrence interval for a duration which is characteristic of the storm type of interest. Figures 5 and 6 depict the temporal patterns of the short-duration and long-duration synthetic design storms, respectively. Tables 1 and 2 list the ordinates of the synthetic design storms. The term *Intensity Index* is the dimensionless form of precipitation intensity (in/hr) and replaces precipitation intensity on the ordinate axis for hyetographs.

Specifically, precipitation for the 2-hour duration is used to scale the short-duration synthetic design storm which has a time-step of 5-minutes and the design storm has a total duration of 180-minutes. The resultant incremental precipitation ordinates have units of inches and the corresponding intensities (in/hr) are obtained by multiplying the precipitation increments by 12.

Precipitation for the 24-hour duration is used to scale the long-duration synthetic design storm which has a time-step of 15-minutes and a total duration of 64 hours. The resultant incremental precipitation ordinates have units of inches and the corresponding intensities (in/hr) are obtained by multiplying the precipitation increments by 4.

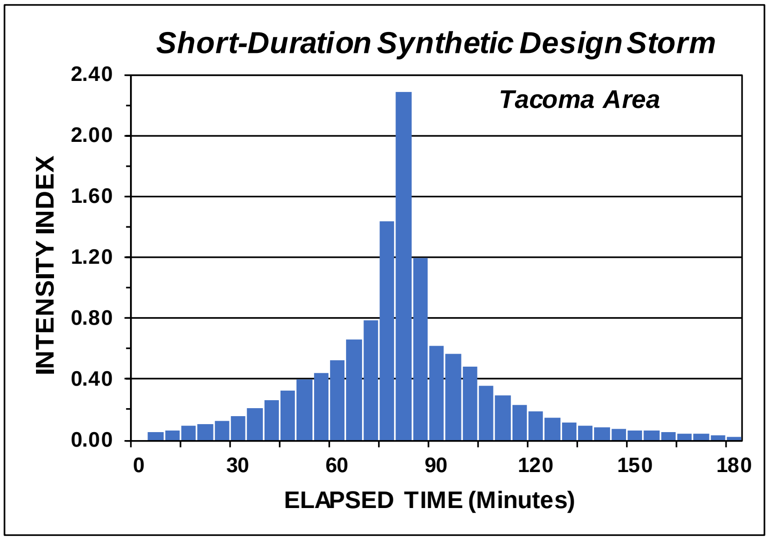

Figure 5 – Short-Duration Dimensionless Synthetic Design Storm for the City of Tacoma

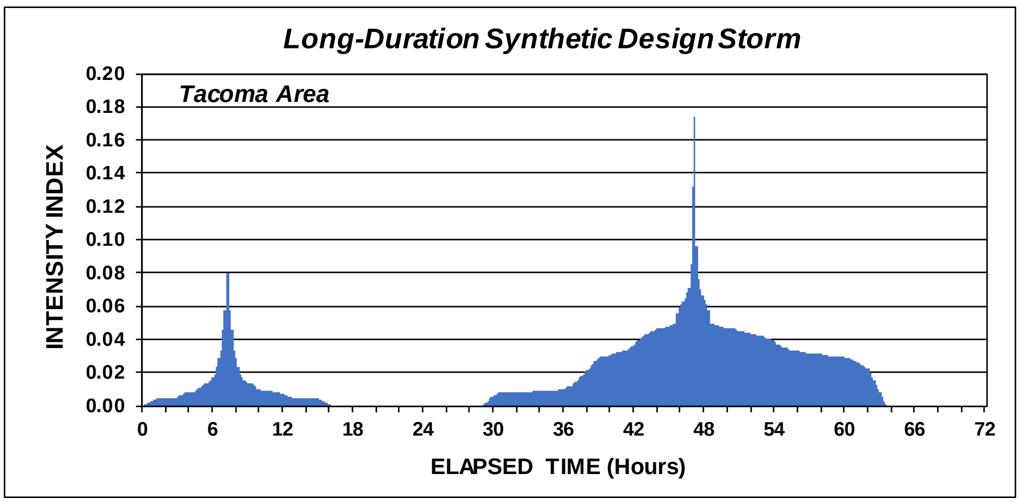

Figure 6 – Long-Duration Dimensionless Synthetic Design Storm for the City of Tacoma

Table 1 – Dimensionless Ordinates of the Short-Duration Synthetic Design Storm

DIMENSIONLESS ORDINATES OF SHORT-DURATION SYNTHETIC DESIGN STORM		
ELAPSED TIME (Min)	INCREMENTAL ORDINATES	CUMULATIVE ORDINATES
0	0.0000	0.0000
5	0.0045	0.0045
10	0.0055	0.0100
15	0.0075	0.0175
20	0.0086	0.0261
25	0.0102	0.0363
30	0.0134	0.0497
35	0.0173	0.0670
40	0.0219	0.0889
45	0.0272	0.1161
50	0.0331	0.1492
55	0.0364	0.1856
60	0.0434	0.2290
65	0.0553	0.2843
70	0.0659	0.3502
75	0.1200	0.4702
80	0.1900	0.6602
85	0.1000	0.7602
90	0.0512	0.8114
95	0.0472	0.8586
100	0.0398	0.8984
105	0.0301	0.9285
110	0.0244	0.9529
115	0.0195	0.9724
120	0.0153	0.9877
125	0.0125	1.0002
130	0.0096	1.0098
135	0.0077	1.0175
140	0.0068	1.0243
145	0.0062	1.0305
150	0.0056	1.0361
155	0.0050	1.0411
160	0.0044	1.0455
165	0.0038	1.0493
170	0.0032	1.0525
175	0.0026	1.0551
180	0.0020	1.0571

Table 2 – Dimensionless Ordinates of Long-Duration Synthetic Design Storm

DIMENSIONLESS ORDINATES OF LONG-DURATION SYNTHETIC DESIGN STORM								
ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE
0.00	0.0000	0.0000	8.17	0.0039	0.1352	16.17	0.0000	0.1931
0.17	0.0001	0.0001	8.33	0.0032	0.1384	16.33	0.0000	0.1931
0.33	0.0002	0.0003	8.50	0.0028	0.1412	16.50	0.0000	0.1931
0.50	0.0003	0.0006	8.67	0.0026	0.1438	16.67	0.0000	0.1931
0.67	0.0004	0.0010	8.83	0.0024	0.1462	16.83	0.0000	0.1931
0.83	0.0005	0.0015	9.00	0.0023	0.1485	17.00	0.0000	0.1931
1.00	0.0006	0.0021	9.17	0.0023	0.1508	17.17	0.0000	0.1931
1.17	0.0007	0.0028	9.33	0.0022	0.1530	17.33	0.0000	0.1931
1.33	0.0007	0.0035	9.50	0.0021	0.1551	17.50	0.0000	0.1931
1.50	0.0007	0.0042	9.67	0.0019	0.1570	17.67	0.0000	0.1931
1.67	0.0007	0.0049	9.83	0.0017	0.1587	17.83	0.0000	0.1931
1.83	0.0007	0.0056	10.00	0.0016	0.1603	18.00	0.0000	0.1931
2.00	0.0007	0.0063	10.17	0.0015	0.1618	18.17	0.0000	0.1931
2.17	0.0007	0.0070	10.33	0.0015	0.1633	18.33	0.0000	0.1931
2.33	0.0007	0.0077	10.50	0.0015	0.1648	18.50	0.0000	0.1931
2.50	0.0007	0.0084	10.67	0.0015	0.1663	18.67	0.0000	0.1931
2.67	0.0007	0.0091	10.83	0.0015	0.1678	18.83	0.0000	0.1931
2.83	0.0008	0.0099	11.00	0.0015	0.1693	19.00	0.0000	0.1931
3.00	0.0009	0.0108	11.17	0.0014	0.1707	19.17	0.0000	0.1931
3.17	0.0010	0.0118	11.33	0.0014	0.1721	19.33	0.0000	0.1931
3.33	0.0011	0.0129	11.50	0.0013	0.1734	19.50	0.0000	0.1931
3.50	0.0012	0.0141	11.67	0.0013	0.1747	19.67	0.0000	0.1931
3.67	0.0013	0.0154	11.83	0.0012	0.1759	19.83	0.0000	0.1931
3.83	0.0014	0.0168	12.00	0.0012	0.1771	20.00	0.0000	0.1931
4.00	0.0014	0.0182	12.17	0.0011	0.1782	20.17	0.0000	0.1931
4.17	0.0014	0.0196	12.33	0.0010	0.1792	20.33	0.0000	0.1931
4.33	0.0014	0.0210	12.50	0.0009	0.1801	20.50	0.0000	0.1931
4.50	0.0015	0.0225	12.67	0.0009	0.1810	20.67	0.0000	0.1931
4.67	0.0016	0.0241	12.83	0.0008	0.1818	20.83	0.0000	0.1931
4.83	0.0018	0.0259	13.00	0.0008	0.1826	21.00	0.0000	0.1931
5.00	0.0020	0.0279	13.17	0.0007	0.1833	21.17	0.0000	0.1931
5.17	0.0021	0.0300	13.33	0.0007	0.1840	21.33	0.0000	0.1931
5.33	0.0023	0.0323	13.50	0.0007	0.1847	21.50	0.0000	0.1931
5.50	0.0023	0.0346	13.67	0.0007	0.1854	21.67	0.0000	0.1931
5.67	0.0024	0.0370	13.83	0.0007	0.1861	21.83	0.0000	0.1931
5.83	0.0026	0.0396	14.00	0.0007	0.1868	22.00	0.0000	0.1931
6.00	0.0028	0.0424	14.17	0.0007	0.1875	22.17	0.0000	0.1931
6.17	0.0032	0.0456	14.33	0.0007	0.1882	22.33	0.0000	0.1931
6.33	0.0039	0.0495	14.50	0.0007	0.1889	22.50	0.0000	0.1931
6.50	0.0048	0.0543	14.67	0.0007	0.1896	22.67	0.0000	0.1931
6.67	0.0056	0.0599	14.83	0.0007	0.1903	22.83	0.0000	0.1931
6.83	0.0076	0.0675	15.00	0.0007	0.1910	23.00	0.0000	0.1931
7.00	0.0096	0.0771	15.17	0.0006	0.1916	23.17	0.0000	0.1931
7.17	0.0133	0.0904	15.33	0.0005	0.1921	23.33	0.0000	0.1931
7.33	0.0133	0.1037	15.50	0.0004	0.1925	23.50	0.0000	0.1931
7.50	0.0096	0.1133	15.67	0.0003	0.1928	23.67	0.0000	0.1931
7.67	0.0076	0.1209	15.83	0.0002	0.1930	23.83	0.0000	0.1931
7.83	0.0056	0.1265	16.00	0.0001	0.1931	24.00	0.0000	0.1931
8.00	0.0048	0.1313						

Table 2 – Dimensionless Ordinates of Long-Duration Synthetic Design Storm (Continued)

DIMENSIONLESS ORDINATES OF LONG-DURATION SYNTHETIC DESIGN STORM								
ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE
24.17	0.0000	0.1931	32.17	0.0014	0.2137	40.17	0.0053	0.3402
24.33	0.0000	0.1931	32.33	0.0014	0.2151	40.33	0.0053	0.3455
24.50	0.0000	0.1931	32.50	0.0014	0.2165	40.50	0.0054	0.3509
24.67	0.0000	0.1931	32.67	0.0014	0.2179	40.67	0.0054	0.3563
24.83	0.0000	0.1931	32.83	0.0014	0.2193	40.83	0.0054	0.3617
25.00	0.0000	0.1931	33.00	0.0014	0.2207	41.00	0.0055	0.3672
25.17	0.0000	0.1931	33.17	0.0014	0.2221	41.17	0.0055	0.3727
25.33	0.0000	0.1931	33.33	0.0015	0.2236	41.33	0.0056	0.3783
25.50	0.0000	0.1931	33.50	0.0015	0.2251	41.50	0.0057	0.3840
25.67	0.0000	0.1931	33.67	0.0015	0.2266	41.67	0.0058	0.3898
25.83	0.0000	0.1931	33.83	0.0015	0.2281	41.83	0.0060	0.3958
26.00	0.0000	0.1931	34.00	0.0015	0.2296	42.00	0.0062	0.4020
26.17	0.0000	0.1931	34.17	0.0015	0.2311	42.17	0.0064	0.4084
26.33	0.0000	0.1931	34.33	0.0015	0.2326	42.33	0.0066	0.4150
26.50	0.0000	0.1931	34.50	0.0015	0.2341	42.50	0.0068	0.4218
26.67	0.0000	0.1931	34.67	0.0015	0.2356	42.67	0.0069	0.4287
26.83	0.0000	0.1931	34.83	0.0015	0.2371	42.83	0.0070	0.4357
27.00	0.0000	0.1931	35.00	0.0015	0.2386	43.00	0.0072	0.4429
27.17	0.0000	0.1931	35.17	0.0015	0.2401	43.17	0.0072	0.4501
27.33	0.0000	0.1931	35.33	0.0015	0.2416	43.33	0.0073	0.4574
27.50	0.0000	0.1931	35.50	0.0016	0.2432	43.50	0.0074	0.4648
27.67	0.0000	0.1931	35.67	0.0016	0.2448	43.67	0.0075	0.4723
27.83	0.0000	0.1931	35.83	0.0017	0.2465	43.83	0.0076	0.4799
28.00	0.0000	0.1931	36.00	0.0017	0.2482	44.00	0.0077	0.4876
28.17	0.0000	0.1931	36.17	0.0018	0.2500	44.17	0.0078	0.4954
28.33	0.0000	0.1931	36.33	0.0019	0.2519	44.33	0.0078	0.5032
28.50	0.0000	0.1931	36.50	0.0019	0.2538	44.50	0.0078	0.5110
28.67	0.0000	0.1931	36.67	0.0020	0.2558	44.67	0.0079	0.5189
28.83	0.0000	0.1931	36.83	0.0022	0.2580	44.83	0.0079	0.5268
29.00	0.0000	0.1931	37.00	0.0024	0.2604	45.00	0.0079	0.5347
29.17	0.0001	0.1932	37.17	0.0026	0.2630	45.17	0.0081	0.5428
29.33	0.0003	0.1935	37.33	0.0028	0.2658	45.33	0.0082	0.5510
29.50	0.0005	0.1940	37.50	0.0030	0.2688	45.50	0.0082	0.5592
29.67	0.0007	0.1947	37.67	0.0032	0.2720	45.67	0.0093	0.5685
29.83	0.0009	0.1956	37.83	0.0034	0.2754	45.83	0.0099	0.5784
30.00	0.0010	0.1966	38.00	0.0036	0.2790	46.00	0.0102	0.5886
30.17	0.0011	0.1977	38.17	0.0038	0.2828	46.17	0.0104	0.5990
30.33	0.0012	0.1989	38.33	0.0040	0.2868	46.33	0.0107	0.6097
30.50	0.0013	0.2002	38.50	0.0042	0.2910	46.50	0.0114	0.6211
30.67	0.0013	0.2015	38.67	0.0045	0.2955	46.67	0.0118	0.6329
30.83	0.0013	0.2028	38.83	0.0047	0.3002	46.83	0.0142	0.6471
31.00	0.0013	0.2041	39.00	0.0048	0.3050	47.00	0.0220	0.6691
31.17	0.0013	0.2054	39.17	0.0049	0.3099	47.17	0.0290	0.6981
31.33	0.0013	0.2067	39.33	0.0049	0.3148	47.33	0.0160	0.7141
31.50	0.0014	0.2081	39.50	0.0049	0.3197	47.50	0.0127	0.7268
31.67	0.0014	0.2095	39.67	0.0050	0.3247	47.67	0.0116	0.7384
31.83	0.0014	0.2109	39.83	0.0051	0.3298	47.83	0.0110	0.7494
32.00	0.0014	0.2123	40.00	0.0051	0.3349	48.00	0.0106	0.7600

Table 2 – Dimensionless Ordinates of Long-Duration Synthetic Design Storm (Continued)

DIMENSIONLESS ORDINATES OF LONG-DURATION SYNTHETIC DESIGN STORM								
ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE
48.17	0.0102	0.7702	56.17	0.0054	1.1067			
48.33	0.0096	0.7798	56.33	0.0054	1.1121			
48.50	0.0082	0.7880	56.50	0.0054	1.1175			
48.67	0.0082	0.7962	56.67	0.0053	1.1228			
48.83	0.0082	0.8044	56.83	0.0053	1.1281			
49.00	0.0081	0.8125	57.00	0.0053	1.1334			
49.17	0.0080	0.8205	57.17	0.0053	1.1387			
49.33	0.0079	0.8284	57.33	0.0052	1.1439			
49.50	0.0079	0.8363	57.50	0.0052	1.1491			
49.67	0.0078	0.8441	57.67	0.0052	1.1543			
49.83	0.0078	0.8519	57.83	0.0052	1.1595			
50.00	0.0077	0.8596	58.00	0.0052	1.1647			
50.17	0.0077	0.8673	58.17	0.0051	1.1698			
50.33	0.0077	0.8750	58.33	0.0051	1.1749			
50.50	0.0077	0.8827	58.50	0.0051	1.1800			
50.67	0.0076	0.8903	58.67	0.0050	1.1850			
50.83	0.0075	0.8978	58.83	0.0050	1.1900			
51.00	0.0075	0.9053	59.00	0.0050	1.1950			
51.17	0.0074	0.9127	59.17	0.0050	1.2000			
51.33	0.0074	0.9201	59.33	0.0049	1.2049			
51.50	0.0073	0.9274	59.50	0.0049	1.2098			
51.67	0.0073	0.9347	59.67	0.0049	1.2147			
51.83	0.0073	0.9420	59.83	0.0049	1.2196			
52.00	0.0072	0.9492	60.00	0.0048	1.2244			
52.17	0.0072	0.9564	60.17	0.0048	1.2292			
52.33	0.0072	0.9636	60.33	0.0048	1.2340			
52.50	0.0071	0.9707	60.50	0.0047	1.2387			
52.67	0.0071	0.9778	60.67	0.0046	1.2433			
52.83	0.0070	0.9848	60.83	0.0045	1.2478			
53.00	0.0070	0.9918	61.00	0.0044	1.2522			
53.17	0.0069	0.9987	61.17	0.0043	1.2565			
53.33	0.0068	1.0055	61.33	0.0042	1.2607			
53.50	0.0067	1.0122	61.50	0.0041	1.2648			
53.67	0.0067	1.0189	61.67	0.0039	1.2687			
53.83	0.0066	1.0255	61.83	0.0038	1.2725			
54.00	0.0065	1.0320	62.00	0.0037	1.2762			
54.17	0.0062	1.0382	62.17	0.0033	1.2795			
54.33	0.0062	1.0444	62.33	0.0029	1.2824			
54.50	0.0060	1.0504	62.50	0.0025	1.2849			
54.67	0.0059	1.0563	62.67	0.0021	1.2870			
54.83	0.0059	1.0622	62.83	0.0017	1.2887			
55.00	0.0058	1.0680	63.00	0.0013	1.2900			
55.17	0.0057	1.0737	63.17	0.0009	1.2909			
55.33	0.0056	1.0793	63.33	0.0005	1.2914			
55.50	0.0055	1.0848	63.50	0.0001	1.2915			
55.67	0.0055	1.0903	63.67	0.0000	1.2915			
55.83	0.0055	1.0958	63.83	0.0000	1.2915			
56.00	0.0055	1.1013	64.00	0.0000	1.2915			

6.0 HISTORICAL DESIGN STORMS

As discussed earlier, historical storms can be rescaled into a dimensionless format that allows the historical storm to be rescaled to a user-specified recurrence interval for the key duration. This is accomplished by dividing each ordinate in the time-series for the historical storm (temporal pattern) by the precipitation amount for the key duration, where the key duration is representative of the duration during the storm when the majority of precipitation occurs. The key durations for the selected historical storms are either 30-minutes or 2-hours for the short-duration historical storms and 24-hours for the long-duration historical storms.

A group of noteworthy historical short-duration and long-duration storms were identified and rescaled into a dimensionless format for use in hydrological modeling. These storms were selected because they were large magnitude events that produced flooding in urban areas and because they represent a diversity of storm characteristics with regard to precipitation intensities, shapes of the hyetographs and total storm duration.

Figures 2a, 2b, 2c and Figures 7a and 7b depict the temporal patterns of the short-duration high-intensity storms that were selected as representative of the diversity of storm characteristics for the short-duration storm type. Figures 4a, 4b, 4c and Figures 8a and 8b depict the temporal patterns of long-duration low to moderate intensity storms that were selected as representative of the diversity of storm characteristics for the long-duration storm type. Excel workbooks are provided as a separate deliverable that contain dimensionless forms of the historical storms for scaling of the historical storms to user-specified magnitudes.

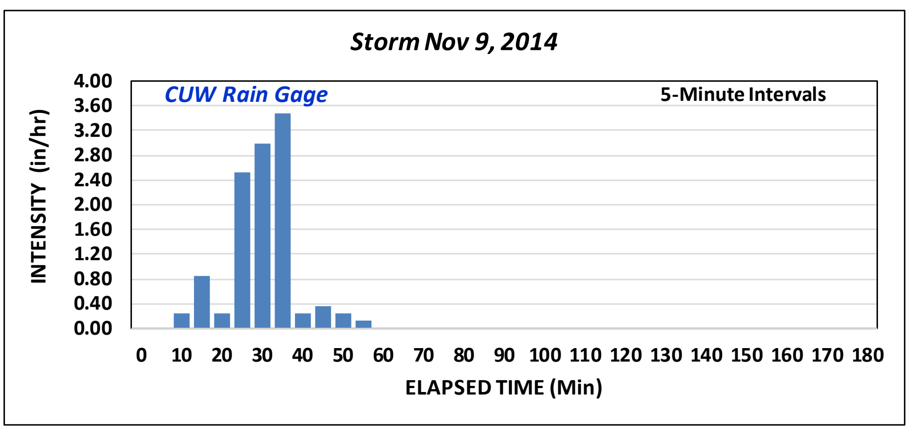

Figure 7a – Hyetograph for Storm of November 9, 2014 Recorded at the CUW Station, Tacoma WA

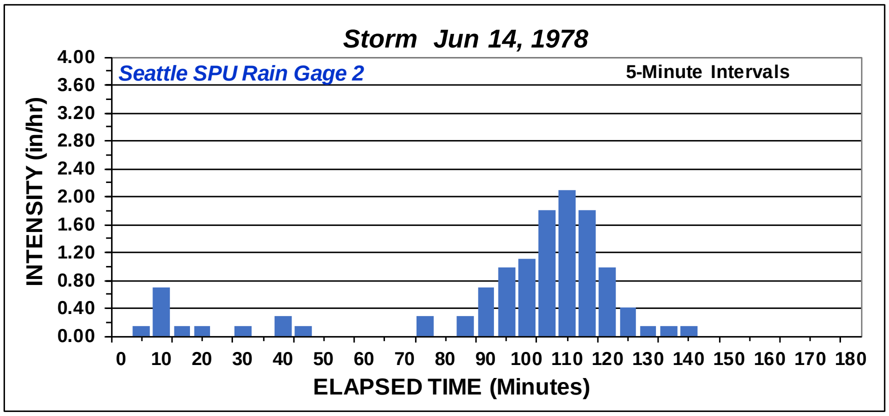

Figure 7b – Hyetograph for Storm of June 14, 1978 Recorded at Seattle SPU Rain Gage 2

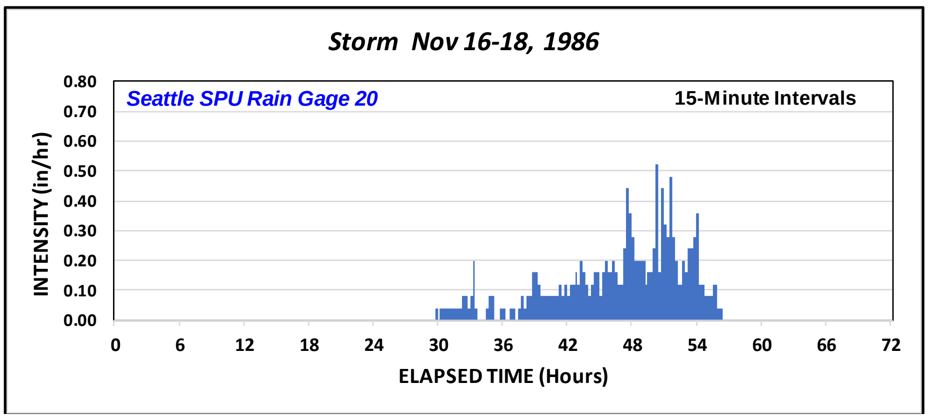

Figure 8a – Hyetograph for Storm of November 16-18, 1986 Recorded at Seattle SPU Rain Gage 20

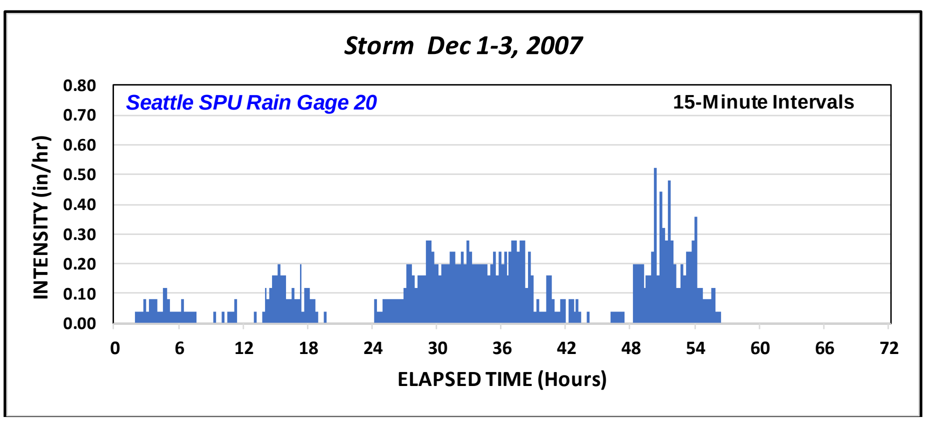

Figure 8b – Hyetograph for Storm of December 1-3, 2007 Recorded at Seattle SPU Rain Gage 20

6.1 Precipitation Magnitudes for Selected Recurrence Intervals

Precipitation for either the 30-minute or 2-hour duration is used for scaling of the short-duration design storms and precipitation for the 24-hour duration is used to scale the long-duration design storms. Precipitation-frequency (PF) relationships for the 30-minute and 2-hour durations are shown in Figure 9a, and Figure 9b depicts the PF relationship for the 24-hour duration which are applicable to the Tacoma area. Tables 4 and 5 list precipitation magnitudes for selected recurrence intervals for the 30-minute, 2-hour and 24-hour durations.

6.2 Precipitation-Frequency Relationship for Short-Duration Design Storms

Regional L-moment precipitation-frequency analyses (Hosking and Wallis[6] and L-RAP[8]) have been conducted for Washington State (Schaefer et al[14,16]) and for Seattle Washington (Schaefer[17,18]) which are applicable to the City of Tacoma. In particular, precipitation-frequency characteristics for short-duration high-intensity storms (Thunderstorms) are very similar for short inter-durations throughout the Puget Sound Lowlands. The findings of regional precipitation-frequency studies for short-duration precipitation were based on 17 precipitation stations located within the City of Seattle and operated by Seattle Public Utilities for the period from 1965-2007. Another 10 NOAA stations were analyzed that were located within surrounding areas and had records dating from the mid-1940's.

6.3 Precipitation-Frequency Relationship for Long-Duration Design Storms

Two regional precipitation-frequency studies have been conducted in Washington that included Tacoma and areas within the Puget Sound Lowlands. One statewide study was conducted for the 2-hour and 24-hour durations for the Washington Department of Transportation (Schaefer et al[16]) and another study was conducted for the 6, 12, 24, 48 and 72-hour durations for the City of Seattle (Schaefer[17]). The statewide study included precipitation maxima from 430 precipitation stations at the 24-hour duration and precipitation maxima from 146 stations at the 2-hour duration. The precipitation-frequency study for Seattle included 17 precipitation stations located within the City of Seattle with a period of record from 1965-2007 and another 13 NOAA stations that were located within the Puget Sound Lowlands with periods of record dating from the 1930's.

The findings from these studies were reviewed and Table 3a lists the regional L-moment statistics applicable to the Tacoma area for the 24-hour duration which is the key duration for scaling of long-duration design storms. There is minor variation of the at-site mean across the City of Tacoma for the 24-hour duration with the general pattern of slightly higher at-site mean values to the west and slowly grading to somewhat lower at-site mean values to the east. The value of the 24-hour at-site mean shown in Table 3a is representative of the location of the NOAA Tacoma 1 daily precipitation station (45-8278) and is deemed adequate for design storm applications.

6.4 Generalized Extreme Value Distribution

The Generalized Extreme Value (GEV) probability distribution was identified as the best-fit probability distribution based on the method of L-moments (Hosking and Wallis[6]) for the 2-hour and 24-hour key durations in all of the studies cited previously. The cumulative distribution function (*CDF*) for the GEV distribution is:

$$F(x) = exp(-exp\{-LN(1-\kappa(x-\xi)/\alpha\}/\kappa) \quad (1a)$$

where: $F(x)$ is the cumulative distribution function; x is the precipitation magnitude; and ξ, α, and κ are location, scale and shape parameters, respectively for precipitation annual maxima series data where $\kappa \neq 0$.

The inverse cumulative distribution function ($x(F)$) for the GEV is:

$$x(F) = \xi + \alpha(1 - (-LN(P))^{\kappa})/\kappa \qquad (1b)$$

where: $x(F)$ is the quantile function for precipitation; and P is the non-exceedance probability where $\kappa \neq 0$.

The Annual Exceedance Probability (AEP) is related to the non-exceedance probability by:

$$AEP = 1 - F(x) \qquad (2a)$$

and the commonly used Recurrence Interval (RI) as a measure of storm rarity is computed as:

$$RI_{AMS} = 1/AEP \qquad (2b)$$

where: RI_{AMS} is the recurrence interval (years) for annual maxima series data.

These findings are based on analyses of precipitation Annual Maxima Series (AMS) data. Estimation of the recurrence intervals for frequent events, more common than 1:10 AEP (10-year recurrence interval) are typically conducted using what is termed Partial Duration Series (PDS) data where all precipitation maxima exceeding a user-specified threshold are included in the analysis. In assembling the PDS data, the threshold is set such that storms that occur several times per year are included in the analysis. Estimates for precipitation magnitudes that occur frequently can be computed using the Langbein[7] adjustment to the findings from the analyses of AMS data as:

$$RI_{PDS} = 1/(-LN(1 - 1/RI_{AMS}) \qquad (2c)$$

where: RI_{PDS} is the estimated recurrence interval (years) for a partial duration series data analysis.

Table 3a lists the regional L-moment statistics applicable to the Tacoma area for the key durations for the short-duration and long-duration design storms. Table 3b lists the GEV distribution parameters for the key durations.

Table 3a – Regional L-Moment Statistics for Key Durations for Short-Duration and Long-Duration Design Storms Applicable to the City of Tacoma

DESIGN STORM KEY DURATION (Hours)	REGIONAL L-MOMENT STATISTICS		
	At-Site Mean (in)	L-Cv	L-Skewness
30-minutes	0.298	0.1840	0.2500
2	0.564	0.1575	0.2200
24	2.100	0.1630	0.1865

Table 3b – Distribution Parameters for the Generalized Extreme Value Distribution for Short-Duration and Long-Duration Design Storms Applicable to the City of Tacoma

DESIGN STORM KEY DURATION (Hours)	GEV DISTRIBUTION PARAMETERS		
	Location ξ	Scale α	Shape κ
30-minutes	0.2483	0.0698	-0.1211
2	0.4858	0.1187	-0.0767
24	1.8096	0.4817	-0.0259

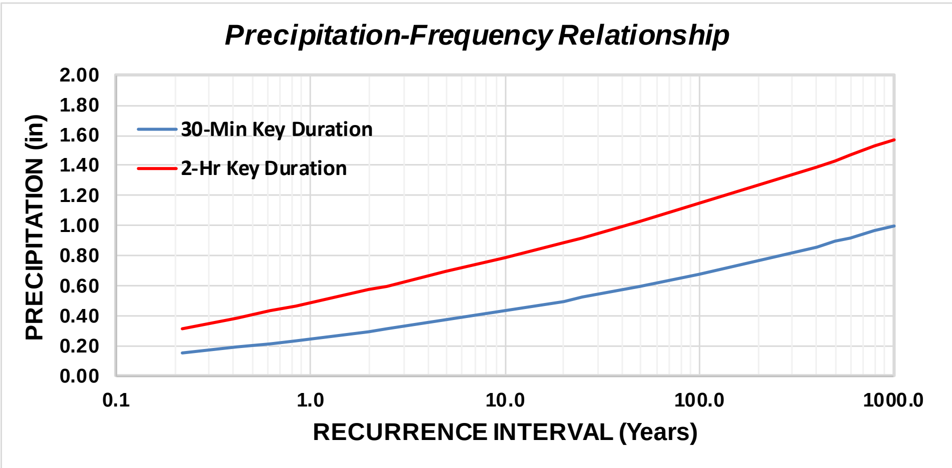

Figure 9a– Precipitation-Frequency Relationship for Precipitation Annual Maxima for the 2-Hour Key Duration for Scaling of Short-Duration Design Storms

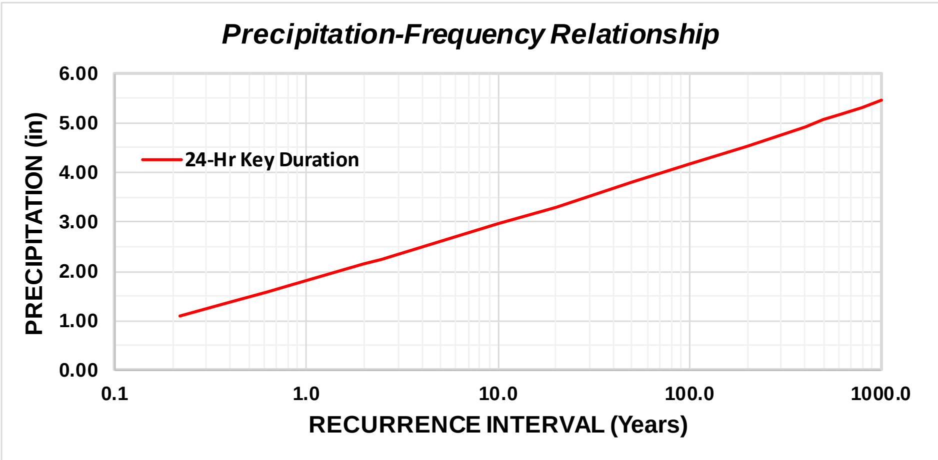

Figure 9b– Precipitation-Frequency Relationship for Precipitation Annual Maxima for the 24-Hour Key Duration for Scaling of Long-Duration Design Storms

Table 4 – Precipitation-Frequency Estimates for Selected Recurrence Intervals for 2-Hour and 24-Hour Key Durations for Scaling of Design Storms

PRECIPITATION (Inches)									
KEY DURATION	RECURRENCE INTERVAL (Years)								
	2	5	10	25	50	100	200	500	1000
30-Minutes	0.30	0.37	0.43	0.52	0.60	0.68	0.77	0.90	1.00
2-Hour	0.57	0.69	0.79	0.92	1.03	1.14	1.26	1.43	1.57
24-Hour	2.15	2.60	2.95	3.45	3.80	4.15	4.55	5.05	5.45

7.0 CLIMATE CHANGE CONSIDERATIONS

There is consensus in the scientific community that Climate Change is occurring and has been occurring to some extent dating to the start of the Industrial Revolution (1870). The Position Paper from the American Geophysical Union[1] is an example of the perspective of experts from a diverse group of scientific disciplines regarding the causes and effects of Climate Change. In general, Climate Change is anticipated to increase the variability in the seasonal weather at any given location and cause changes in the long-term patterns of air temperature, precipitation, cloud cover and evapotranspiration. In particular, higher air temperatures and resultant sea-surface temperatures provides the potential for increases in the levels of atmospheric moisture. An increase in atmospheric moisture increases the potential for increased precipitation magnitudes to be produced by atmospheric dynamics associated with Mid-Latitude Cyclones and convective storm activity in the Pacific Northwest. This situation creates the potential for changes in both the magnitude and frequency of large precipitation events.

There remain large uncertainties in the outputs from Global Circulation Models in the estimation of the magnitude, frequency and areal extent of changes due to Climate Change for any given large geographical area. Recognizing these uncertainties, it is prudent to stay in contact with nationally recognized research institutions such as the University of Washington Climate Impacts Group to stay current on recent findings and projections. In the interim, it is recommended that a policy be adopted to increase the conveyance/storage capacity for sizing and design of stormwater infrastructure relative to current standards.

These new policies could take several forms with a simple approach being applying a Factor of Safety (FS) of perhaps 10% to 15% for increasing precipitation magnitudes which would result in upsizing of stormwater infrastructure. As background, a 1°F increase in sea-surface temperature results in about a 5% increase in atmospheric moisture and the potential for a 5% increase in precipitation magnitude given the same atmospheric dynamics for a storm. The UW Climate Impacts Group should be consulted to provide information and guidance in setting an interim policy to address the impacts from Climate Change.

SELECTED REFERENCES

1. American Geophysical Union (AGU), Position Paper on Climate Change, http://sites.agu.org/sciencepolicy/files/2013/07/AGU-Climate-Change-Position-Statement_August-2013.pdf
2. Benjamin JR and Cornell CA, Probability and Statistics for Civil Engineers, McGraw-Hill, 1970.
3. Cunnane C, Unbiased Plotting Positions - A Review, Journal of Hydrology, 37, 205-222, 1978.
4. Daly C, Neilson RP, and Phillips DL, A Statistical-Topographic Model for Mapping of Climatological Precipitation over Mountainous Terrain (PRISM Parameter-Elevation Regression on Independent Slopes Model), Journal of Applied Meteorology, Volume 33, pp140-158, 1994.
5. Frederick RH, Richards FP and Schwerdt RW, Interduration Precipitation Relations for Storms-Western United States, NOAA Technical Report NWS 27, US Department of Commerce, NOAA, September 1981.
6. Hosking JRM and Wallis JR, Regional Frequency Analysis – An Approach Based on L-Moments, Cambridge Press, 1997.
7. Langbein WB, Annual Floods and the Partial Duration Flood Series, Transaction American Geophysical Union, Vol 30, pp879-881, 1949.
8. L-RAP, L-Moments Regional Analysis Program, developed by MG Schaefer and BL Barker, MGS Software LLC, Olympia WA.
9. Miller JF, Frederick RH and Tracey RS, NOAA ATLAS 2, Precipitation - Frequency Atlas of the Western United States, U.S. Dept. of Commerce, NOAA, National Weather Service, Wash DC, 1973.
10. National Climatic Data Center (NCDC), Surface Land Daily Cooperative Summary of the Day Data, TD-3200, Asheville NC.
11. National Climatic Data Center (NCDC), Hourly Precipitation Data, TD-3240, Asheville NC.
12. National Oceanic and Atmospheric Administration (NOAA), National Network of Weather Observing Sites, National Weather Service, Washington DC.
13. Schaefer MG, Characteristics of Extreme Precipitation Events in Washington State, Washington State Dept. of Ecology, Report 89-51, October 1989
14. Schaefer MG, Regional Analyses of Precipitation Annual Maxima in Washington State, Water Resources Research, Vol.26, No.1, pp119-132, January 1990.
15. Schaefer MG, Design Storm Construction, Technical Note 3, Washington State Dept. of Ecology, Dam Safety Guidelines, Publication 92-55G, April 1993.
16. Schaefer MG, Barker BL, Taylor GH and Wallis JR, Regional Precipitation-Frequency Analysis and Spatial Mapping of Precipitation for 24-Hour and 2-Hour Durations in Western Washington, prepared for Washington State Department of Transportation, Report WA-RD 544.1, MGS Engineering Consultants, March 2002.
17. Schaefer MG, Analyses of Precipitation-Frequency and Storm Characteristics for the City of Seattle, prepared for Seattle Public Utilities, March 2003.

18. Schaefer MG, Assessment of City of Seattle Intensity-Duration-Frequency Curves With Addition of Storm Data from 2003-2007, prepared for Seattle Public Utilities, October 2007

19. Schaefer MG, Update Design Storm Construction, Technical Note 3, Washington State Dept. of Ecology, Dam Safety Guidelines, 2007.

20. Stedinger JR, Vogel RM and Foufoula-Georgiou E, Frequency Analysis of Extreme Events, Chapter 18, Handbook of Hydrology, D Maidment (editor), McGraw-Hill Inc, NY 1993.

21. Weiss LL, Ratio of True to Fixed Interval Maximum Rainfall, Journal Hydraulics, ASCE, 90(HY1), pp77-82, 1964.