Naval Information Warfare Center PACIFIC

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January 2020

Long-term Rainfall Analysis at Select DoD-relevant Sites for the Determination of Appropriate Toxicity Exposure Durations

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ADMINISTRATIVE INFORMATION

The work described in this report was performed by the Energy and Environmental Sustainability branch of the Advanced Systems and Applied Sciences division, Naval Information Warfare Center Pacific (NIWC Pacific), San Diego, CA. The Navy Environmental Sustainability Development to Integration (NESDI) Program, Project #547, and the Environmental Security Technology Certification Program (ESTCP), Project ER-201727, provided funding for this Basic Applied Research project. Further assistance was provided by San Diego State University Research Foundation.

Released by
Robert George, Branch Head
Energy and Environmental Sustainability

Under authority of
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Advanced Systems and Applied Sciences

RJP

EXECUTIVE SUMMARY

This analysis effort was conducted in support of projects #547 “Demonstration of Improved Toxicity Methodology to Link Stormwater Discharges to Receiving Water Impacts at Navy Sites” as supported by the Navy Environmental Sustainability Development to Integration (NESDI) Program and #ER-201727 “Derivation and Demonstration of an Environmentally Relevant Approach for Stormwater Toxicity Testing Compliance Monitoring” as supported by the Environmental Security Technology Certification Program (ESTCP).

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1. INTRODUCTION

Industrial and municipal discharges are required to comply with increasingly stringent water quality requirements for stormwater runoff and other intermittent discharges. These requirements general include end-of-pipe monitoring for whole effluent toxicity (WET), enforced by National Pollutant Discharge Elimination System (NPDES) permits, prior to mixing in the receiving water. Current WET protocols developed by the US Environmental Protection Agency were designed for the assessment of continuous point source discharges (USEPA 1995, 2002a, b, c). These same methods are now being applied to episodic discharges, such as stormwater, as well. These procedures have been criticized for failing to use exposures more representative to intermittent, or episodic, events, instead using continuous static exposures. Standard WET testing protocols expose test organisms for substantially longer periods of time (48 hours to 7 days) than the discharges themselves are present at the end-of-pipe (almost always less than 24 hours). The hypothesis is that this approach significantly overestimates the potential toxic impact.

An environmentally relevant and scientifically defensible exposure design for laboratory toxicity testing is needed to better to assess impacts to receiving waters related to episodic discharges such as stormwater runoff. In order to implement an appropriate exposure duration for toxicity testing, the duration of discharge due to storm events must be investigated. Discharge data from the numerous outfalls across the country is not widely accessible, however, rainfall data is widely available. At sites where surfaces are largely impervious, such as Department of Defense (DoD)/Navy installations, rainfall duration can be used as a proxy for discharge duration. Note that dose of exposure and mixing (e.g. dynamics in the receiving water) is also a critical factor that will affect toxicological responses.

This document details analyses conducted on historical rainfall data at numerous locations across the United States in order to develop site-specific recommendations for exposure durations for laboratory toxicity testing specifically for assessment of stormwater discharges. If applied properly, a modification to generate more realistic exposure conditions for toxicity testing will still provide an appropriate level of protection, particularly given that the exposure at the end-of-pipe will be further reduced once it mixes in the receiving environment.

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2. RAINFALL DURATION AS A PROXY FOR DISCHARGE DURATION

Current data on discharge duration from outfalls across the U.S. is limited, though there are some examples available as shown below for Naval Base San Diego (NBSD). It was determined that rainfall duration could be used as a proxy for discharge duration in areas where most of the drainage basin feeding the discharge consists of impervious surfaces, a common characteristic at most industrial sites. Figure 2-1 shows accumulated discharge from three outfalls were measured from NBSD during a given storm event over a 14-hr period. The three discharges all show different accumulation profiles. Figure 2-2 through Figure 2-4 show each discharge plotted along with the accumulated rainfall monitored during the same period. All three discharges exhibit high correlations (standard linear regression) between the accumulated rainfall and the accumulated discharge (OF72: $R^2 = 0.9917$; OF73: $R^2 = 0.9943$; OF124: $R^2 = 0.9939$). This assessment produces an example indicating the appropriateness of using rainfall duration as a proxy for discharge duration. Figure 2-1 shows how runoff patterns for 3 different outfalls at NBSD are consistent despite varying volumes due to catch basin. Figure 2-2 through Figure 2-4 show how accumulated rainfall closely matches runoff volume for these same industrial locations.

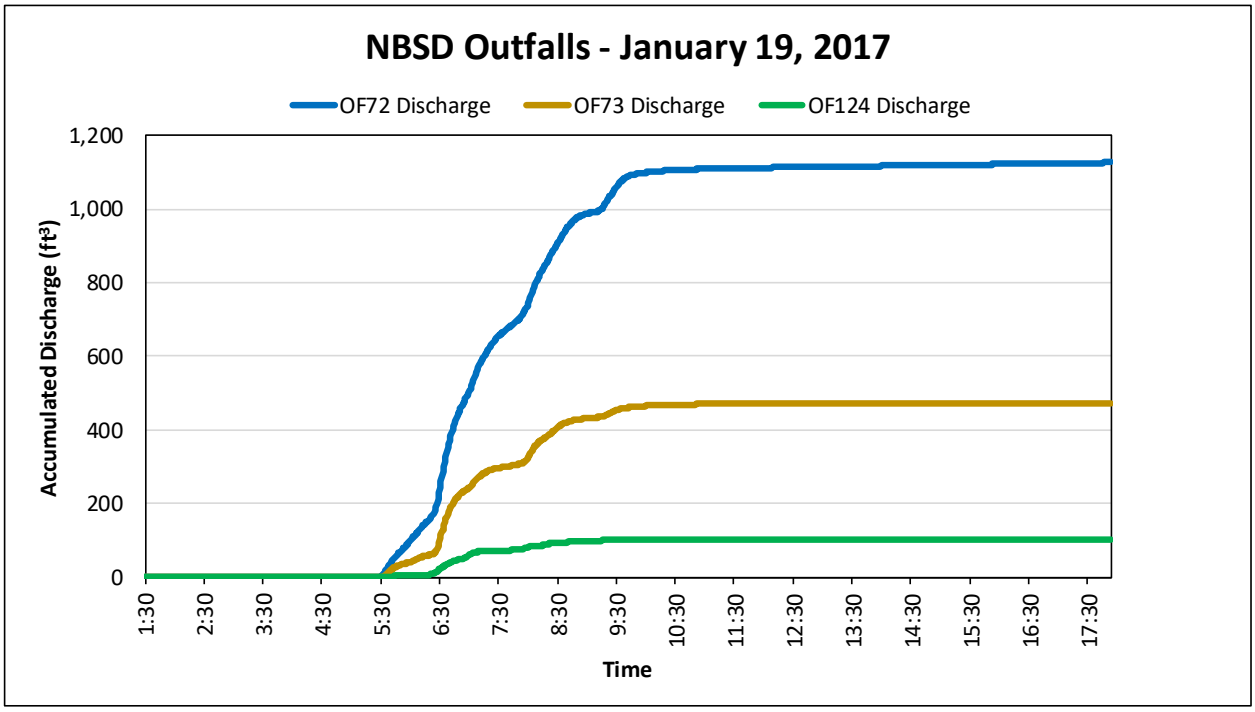

Figure 2-1. Accumulated stormwater discharges as measured from three outfalls from NBSD on 19 January 2017. OF = Outfall.

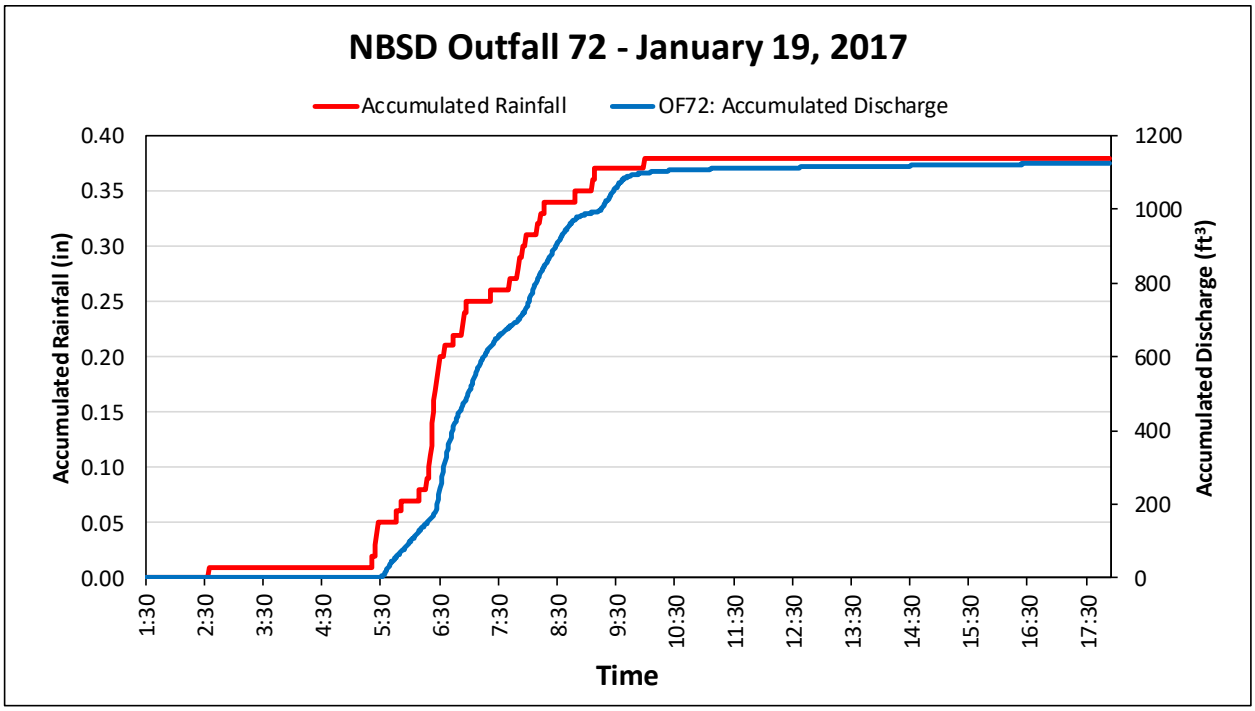

Figure 2-2. Accumulated rainfall and stormwater discharge from Outfall 72 at NBSD on 19 Jan 2017. OF = Outfall.

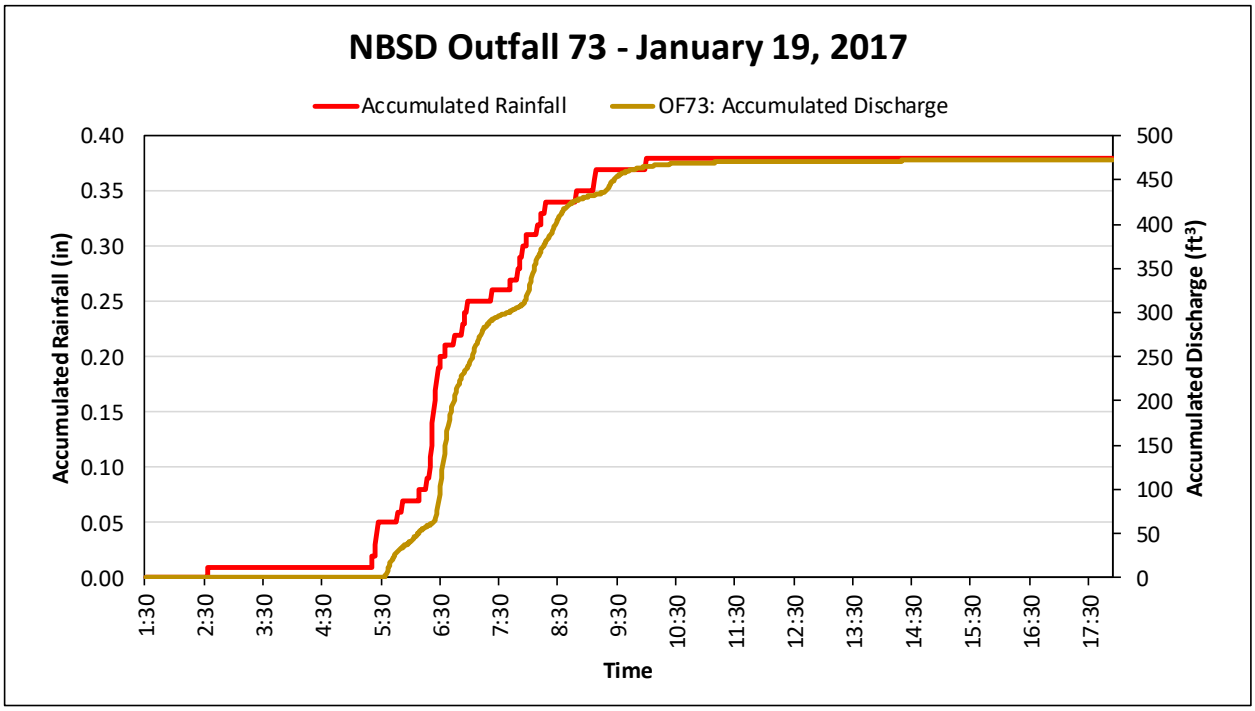

Figure 2-3. Accumulated rainfall and stormwater discharge from Outfall 73 at NBSD on 19 Jan 2017. OF = Outfall.

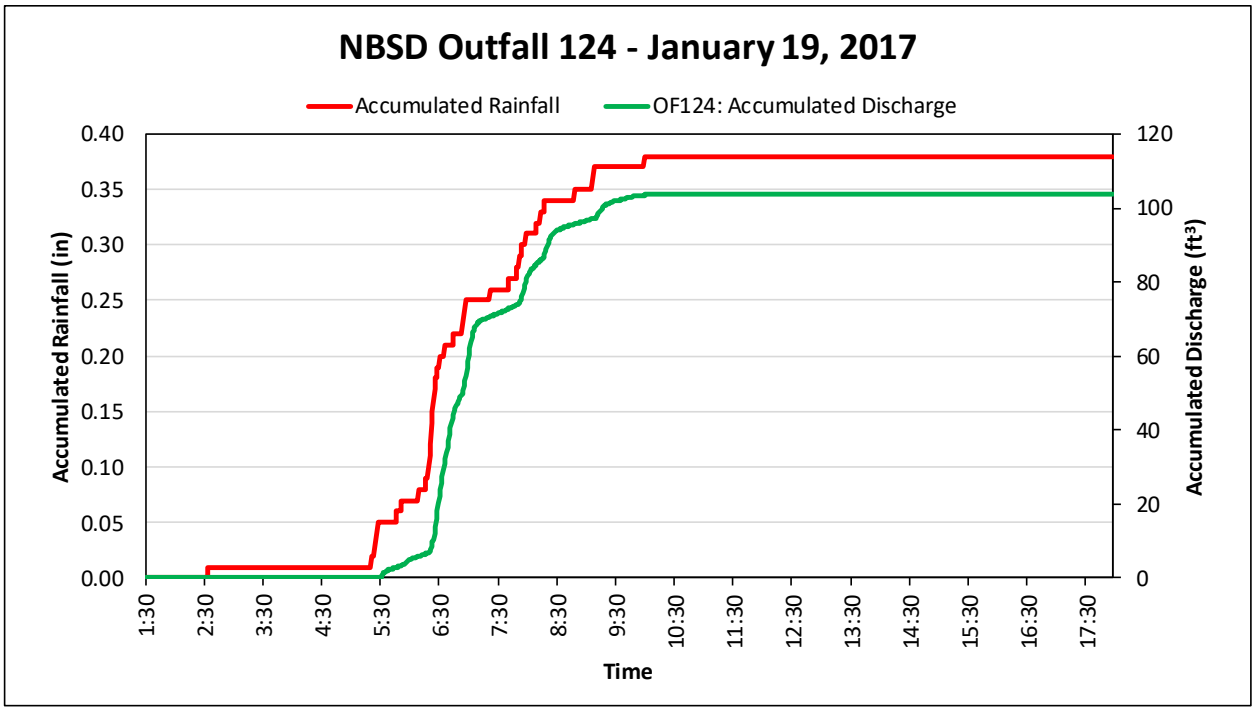

Figure 2-4. Accumulated rainfall and stormwater discharge from Outfall 124 at NBSD on 19 Jan 2017. OF = Outfall.

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3. LOCATION SELECTION FOR RAINFALL ANALYSIS

Site-specific analysis of typical rainfall durations were conducted on twenty-one locations across the U.S and Pacific Ocean. Locations were selected based on their proximity to DoD Installations. Digital data sets covering up to a 20-year period were downloaded from the National Climatic Data Center (NCDC) hosted by NOAA (NOAA 2017) for the locations shown in Table 3-1. Locations were categorized by climatic region as defined by NOAA (Figure 3-1, Karl and Koss 1984).

Table 3-1. Locations and Respective Regions Selected for Rainfall Duration Analysis

Region	City, State
Northeast	Boston, MA
Northwest	Seattle, WA
Southeast	Charleston, SC
	Jacksonville, FL
	Norfolk, VA
	Pensacola, FL*
Southwest	Tucson, AZ
West	San Diego, CA
	San Francisco, CA
	Paso Robles, CA*
Central	Chicago, IL
	Louisville, KY
South	Corpus Christi, TX
	New Orleans, LA
Pacific	Honolulu, HI
	Piti, Guam*
East North Central	Detroit, MI
	St. Paul, MN
West North Central	Rapid City, SD
	Great Falls, MT
Other	Anchorage, AK

*All locations had 20yr of data, exceptions: Paso Robles, CA – 11yr; Pensacola, FL – 15yr; Piti, Guam – 2yr.

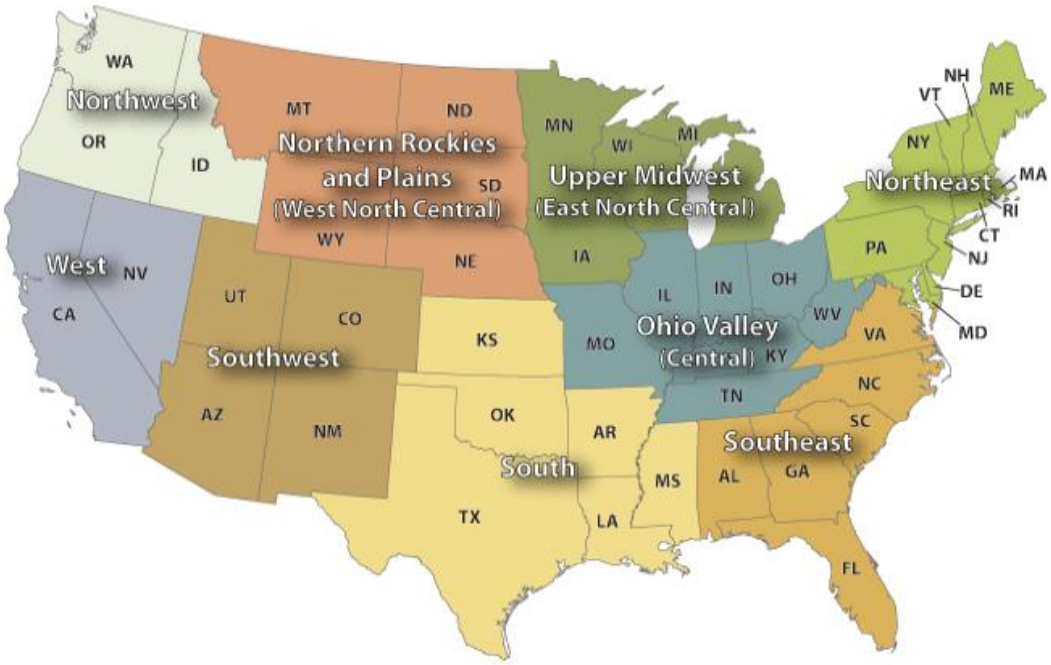

Figure 3-1. Defined climatic regions of the United States (Karl and Koss 1984).

For all but three locations as noted in Table 3-1, data were acquired for a period of 20-years. Rainfall data for all sites consisted of hourly rainfall measurements, detected to a hundredth of an inch (e.g., 0.01" rainfall/hr).

Note that considerable variability in rainfall averages can exist within any given climatic region (e.g. the Mohave Desert in southern California (average of 5" rainfall/yr), and the coastal redwood rainforests of northern California (average > 40" rainfall/yr).

4. METHODS, RESULTS OF ANALYSIS AND RECOMMENDATIONS

Two analyses were performed on each of the data sets obtained from the NCDC. Total rainfall duration was determined for both any given rolling 24-hr period and 96-hr continuous basis at the onset of a qualifying rain event.

4.1 24-HR ANALYSIS

The total number of hours of rainfall that was detected in any given rolling 24-hr period was summed (i.e., 0000–2400). The mean, standard deviation and the 50th, 75th and 95th percentile of rainfall duration was calculated for each location. For example, the 95th percentile of rainfall duration for Chicago, IL is 13hr. Only 5% of the rainfall observations exceeded 13hr during a given 24-hr period. The calculated values of rainfall duration could be continuous or discrete during the 24-hr period, as there is no distinction between discrete or continuous observations in this analysis.

Results of the analysis are shown in Table 4-1. As expected, variability is observed across the different climatic regions with relatively short rainfall durations in locales such as the Southwest and relatively longer rainfall durations in locales such as the Pacific Northwest.

Table 4-1. Rainfall analysis results over a 24 hour period.

Location	Region	Average	SD	50th Percentile	75th Percentile	95th Percentile
Chicago, IL	Central	4.5	3.9	3	6	13
Louisville, KY	Central	4.9	4.2	4	7	14
Detroit, MI	East North Central	4.5	3.8	3	6	13
St. Paul, MN	East North Central	4.2	3.7	3	6	12
Boston, MA	Northeast	5.5	4.7	4	8	15
Seattle, WA	Northwest	6.1	4.7	5	9	16
Anchorage, AK	Other	5.0	4.3	4	7	14
Honolulu, HI	Pacific	2.7	2.7	2	3	8
Piti, Guam	Pacific	4.4	3.7	3	5	12
Corpus Christi, TX	South	3.5	3.2	2	4	10
New Orleans, LA	South	3.9	3.4	3	5	11
Charleston, NC	Southeast	4.1	3.6	3	6	12
Jacksonville, FL	Southeast	3.8	3.5	3	5	11
Norfolk, VA	Southeast	4.8	4.1	3	7	14
Pensacola, FL	Southeast	4.0	3.5	3	5	11
Tucson, AZ	Southwest	3.2	2.9	2	4	9
Paso Robles, CA	West	4.8	4.1	3	7	13

Table 4-1. Rainfall analysis results over a 24 hour period. (Continued)

Location	Region	Average	SD	50th Percentile	75th Percentile	95th Percentile
San Diego, CA	West	4.2	3.8	3	5	11
San Francisco, CA	West	5.9	4.6	5	8	15
Great Falls, MT	West North Central	4.2	4.0	3	6	13
Rapid City, SD	West North Central	3.9	3.9	2	5	13
GRAND MEAN (hrs)		4.4	3.8	3.1	6.0	12.4

4.2 96-HR ANALYSIS

Additionally, following the onset of a qualifying rain event, the total duration of rainfall that was observed over the subsequent 96-hr period was calculated and the mean, standard deviation, and the 50th, 75th and 95th percentile of rainfall duration was derived. The 96-hr period was evaluated to be reflective of typical acute (lethal) and certain chronic (sublethal) toxicity testing durations (USEPA 1995, 2002). Similar to the analysis conducted over a 24-hr period, the number of hours that rainfall was detected in a 96-hr period was summed. However, the analysis of a given 96-hr period only commenced when two conditions for a qualifying event were met. First, an antecedent dry period of at least 12-hr was a requirement prior to the summing of rainfall duration during the subsequent 96-hr period. Second, a total of 0.05" cumulative rainfall must be observed prior to the summing of rainfall duration to account for surface saturation to allow for runoff to occur.

Again, the calculated values of rainfall duration could be continuous or discrete during the 96-hr period, as there is no distinction between discrete or continuous observations in this analysis. In addition, the relative contribution of rainfall duration for each day during the 96-hr period was determined as well as the cumulative rainfall over each qualifying storm event. The latter analysis helps to understand the magnitude of rain events and when the majority volume of rainfall is observed.

Results of the 96-hr analysis are shown in Table 4-2. As expected, climatic regions like the Northwest show some of the longest mean rainfall durations for the 96hr analysis; while Southern and Southwestern regions showed relatively short mean rainfall durations. As caveated previously, larger climatic regions may exhibit highly variable rainfall characteristics, so more refined smaller-scale assessments will be required for appropriate site-specific considerations. For example, the 95th percentile of rainfall duration for San Francisco is quite different than San Diego, 39-hr and 26-hr, respectively.

Table 4-3 shows the results of the analysis to determine the relative contribution of rainfall duration for each day during the 96hr period. On average across all sites, over 70% of the rainfall is observed during the first 24hrs of a given 96-hr monitoring period. For regions like the southwest, more rainfall is observed (80%) within the first 24hrs of the 96-hr period; whereas for the northwest, only 50% of the rainfall on average is observed during the first 24hrs of a 96-hr observation period.

This analysis suggests that a single pulse at the onset of an exposure period would best represent typical rainfall patterns following the onset of a storm event. A recommendation to start a pulsed exposure with water collected at the beginning of a storm at the onset of a testing period is also conservative with regard to capturing the notion of a 'first flush' of contaminants where observed concentrations are generally elevated at the onset of a storm event and decrease over time (Birch and Rochford, 2010; Katz et al., 2006; Kayhanian et al., 2008; Sabin et al., 2005; Soller et al., 2005; Schiff and Tiefenthaler, 2011).

Cumulative rainfall observed in shown in Table 4-4. On average across all sites, over 70% of the total accumulated rainfall over the storm falls in the first 24hr of a given 96-hr period. There are some differences apparent between regions. For example, 79% of the accumulated rainfall was observed in the first 24hr in Tucson, AZ, whereas 53% of the accumulated rainfall was observed in the first 24hr of the 96-hr period for Seattle, WA. This supporting analysis further suggests that a single pulse at the onset of an exposure period would be representative of typical conditions and thus appropriate for a test methodology in a laboratory setting.

Due to the observed variability across and within climatic regions, site-specific pulsed exposure durations for toxicity testing may be more appropriate. Analyses conducted on the above shown sites are shown in more detail in Appendix A.

Table 4-2. Rainfall analysis results over a 96 hour period following onset of qualifying storm.

Location	Region	Average	SD	50th Percentile	75th Percentile	95th Percentile
Chicago, IL	Central	9.1	7.3	7	13	24
Louisville, KY	Central	11.2	8.9	9	16	29
Detroit, MI	East North Central	9.3	7.4	7	13	24
St. Paul, MN	East North Central	9.0	7.7	7	13	24
Boston, MA	Northeast	10.9	9.2	9	15	28
Seattle, WA	Northwest	18.2	13.7	15	26	45
Anchorage, AK	Other	11.6	9.7	9	17	32
Honolulu, HI	Pacific	7.1	7.7	4	9	24
Piti, Guam	Pacific	15.0	11.2	13	20	35
Corpus Christi, TX	South	7.7	7.4	5	11	22
New Orleans, LA	South	8.6	8.5	6	11	23
Charleston, NC	Southeast	9.1	7.7	7	12	25
Jacksonville, FL	Southeast	9.4	8.9	7	12	28
Norfolk, VA	Southeast	9.9	8.5	8	14	26
Pensacola, FL	Southeast	8.7	7.6	7	12	23
Tucson, AZ	Southwest	6.1	5.6	5	8	18
Paso Robles, CA	West	10.7	10.2	8	15	34
San Diego, CA	West	8.9	8.6	6	12	26
San Francisco, CA	West	16.0	12.1	13	23	39
Great Falls, MT	West North Central	9.0	9.3	6	12	29
Rapid City, SD	West North Central	9.0	9.1	6	12	27
GRAND MEAN (hrs)		10.2	8.9	7.8	14.1	27.9

Table 4-3. Rainfall analysis results over a 96 hour period following onset of qualifying storm.

Location	Region	Day 1	Day 2	Day 3	Day 4
Chicago, IL	Central	73%	9%	9%	9%
Louisville, KY	Central	69%	11%	10%	11%
Detroit, MI	East North Central	70%	11%	9%	10%
St. Paul, MN	East North Central	72%	9%	9%	10%
Boston, MA	Northeast	70%	9%	9%	11%
Seattle, WA	Northwest	54%	17%	14%	15%
Anchorage, AK	Other	70%	11%	10%	9%
Honolulu, HI	Pacific	79%	9%	6%	6%
Piti, Guam	Pacific	48%	19%	16%	17%
Corpus Christi, TX	South	77%	10%	7%	7%
New Orleans, LA	South	71%	11%	9%	10%
Charleston, NC	Southeast	72%	11%	9%	9%
Jacksonville, FL	Southeast	68%	12%	10%	10%
Norfolk, VA	Southeast	71%	10%	9%	10%
Pensacola, FL	Southeast	71%	11%	9%	10%
Tucson, AZ	Southwest	80%	8%	6%	6%
Paso Robles, CA	West	74%	11%	8%	7%
San Diego, CA	West	77%	9%	7%	7%
San Francisco, CA	West	61%	14%	13%	12%
Great Falls, MT	West North Central	78%	8%	7%	8%
Rapid City, SD	West North Central	77%	9%	7%	7%
GRAND MEAN (hrs)		70%	11%	9%	10%

Table 4-4. Cumulative daily rainfall proportions over a 96 hour period following onset of qualifying storm.

Location	Region	Day 1	Day 2	Day 3	Day 4
Chicago, IL	Central	72%	9%	9%	10%
Louisville, KY	Central	67%	11%	11%	11%
Detroit, MI	East North Central	70%	9%	9%	11%
St. Paul, MN	East North Central	71%	9%	9%	10%
Boston, MA	Northeast	69%	9%	9%	12%
Seattle, WA	Northwest	53%	18%	14%	15%
Anchorage, AK	Other	68%	12%	11%	9%
Honolulu, HI	Pacific	78%	9%	6%	7%
Piti, Guam	Pacific	45%	19%	17%	18%
Corpus Christi, TX	South	76%	10%	7%	7%
New Orleans, LA	South	70%	11%	9%	10%
Charleston, NC	Southeast	71%	11%	9%	9%
Jacksonville, FL	Southeast	67%	12%	10%	10%
Norfolk, VA	Southeast	69%	10%	10%	11%
Pensacola, FL	Southeast	70%	11%	9%	10%
Tucson, AZ	Southwest	79%	9%	7%	6%
Paso Robles, CA	West	73%	11%	9%	7%
San Diego, CA	West	76%	10%	8%	7%
San Francisco, CA	West	59%	15%	14%	12%
Great Falls, MT	West North Central	78%	8%	7%	8%
Rapid City, SD	West North Central	76%	10%	7%	8%
GRAND MEAN (hrs)		69%	11%	10%	10%

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US EPA. 2002c. Short-Term Methods for Estimating the Chronic Toxicity of Effluents and Receiving Waters to Marine and Estuarine Organisms. Washington DC.

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APPENDIX A
SITE SPECIFIC ANALYSES

RAINFALL MEASURMENTS BY CITY

Items included in this section are:

RAINFALL MEASURMENTS: ANCHORAGE, ALASKA

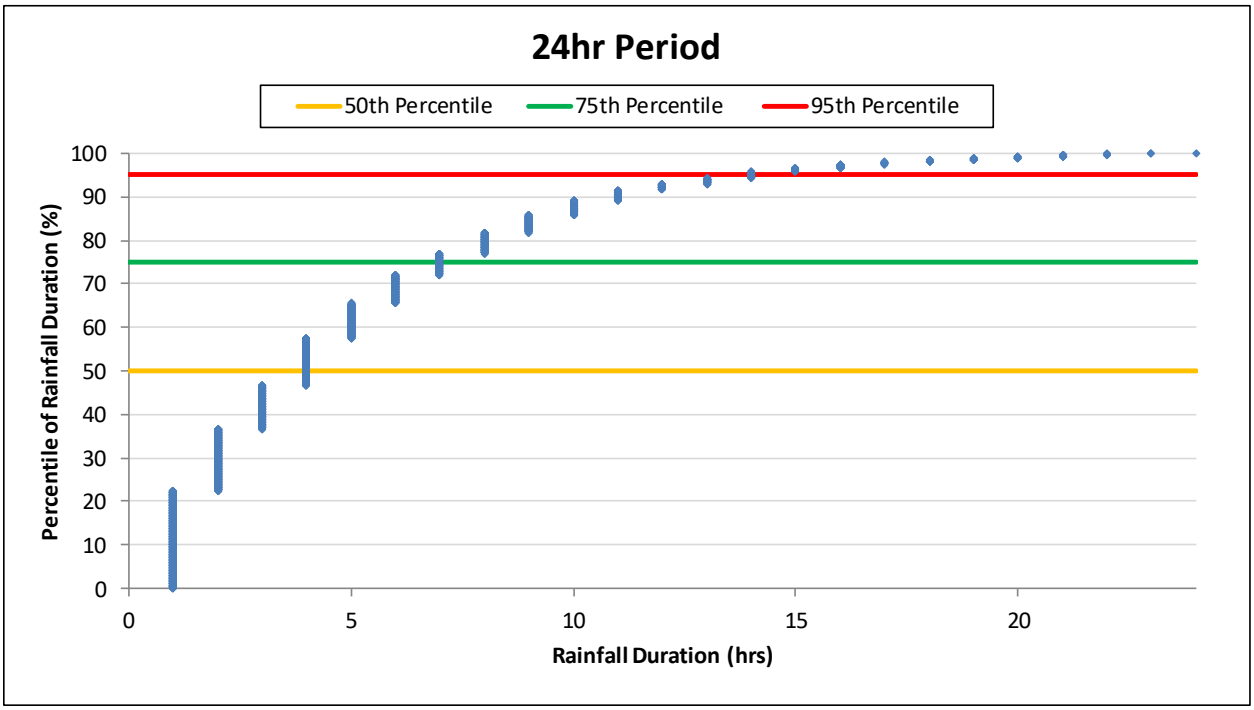

Figure A-1. Anchorage, Alaska 24 hour period rainfall measurements.

Table A-1. Anchorage, Alaska 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	24
Mean	5.0
SD	4.3
50%	4
75%	7
95%	14

*Maximum duration of rainfall in a given period.

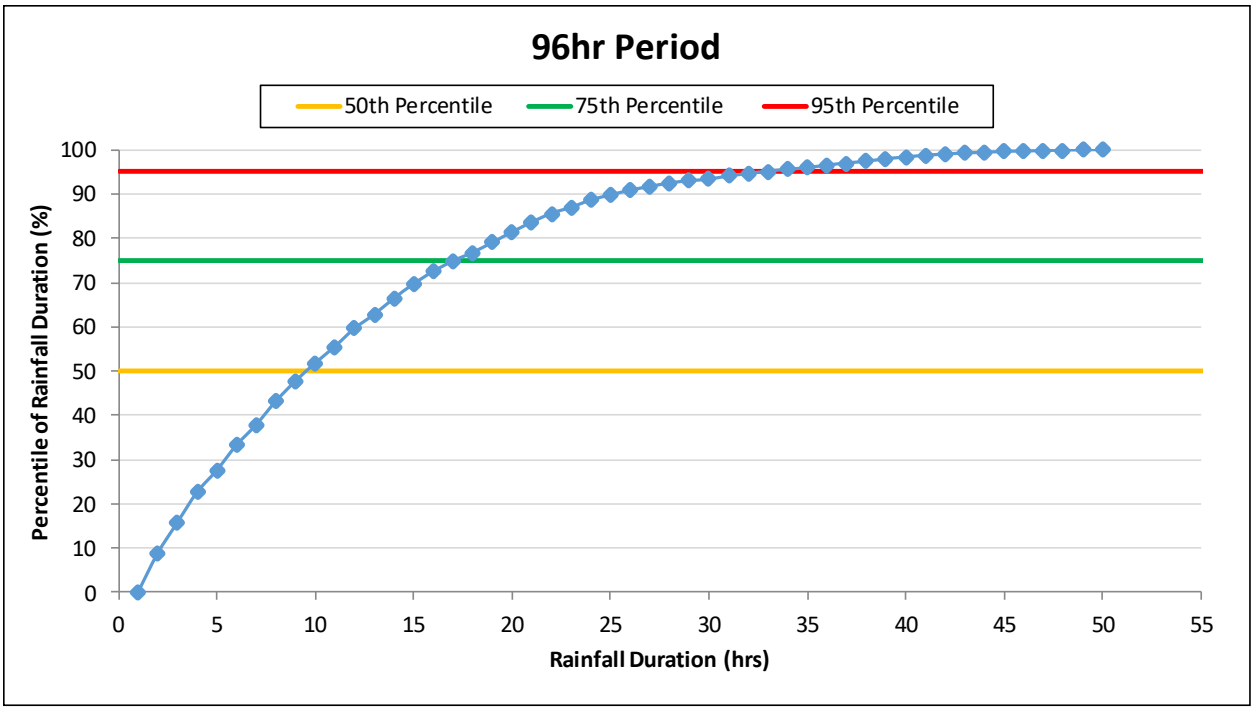

Figure A-2. Anchorage, Alaska 96 hour period rainfall measurements.

Table A-2. Anchorage, Alaska 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	51
Mean	11.6
SD	9.7
50%	9
75%	17
95%	32

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: BOSTON, MASSACHUSETTS

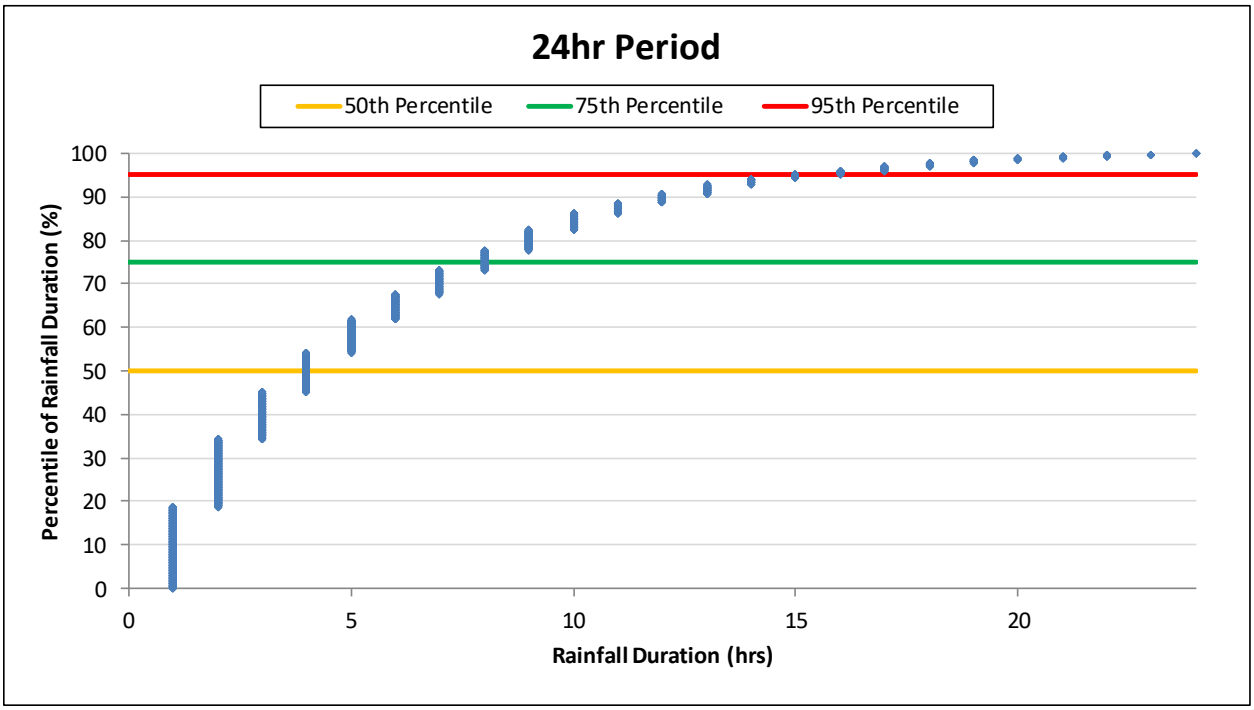

Figure A-3. Boston, Massachusetts 24 hour period rainfall measurements.

Table A-3. Boston, Massachusetts 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	24
Mean	5.5
SD	4.7
50%	4
75%	8
95%	15

*Maximum duration of rainfall in a given period.

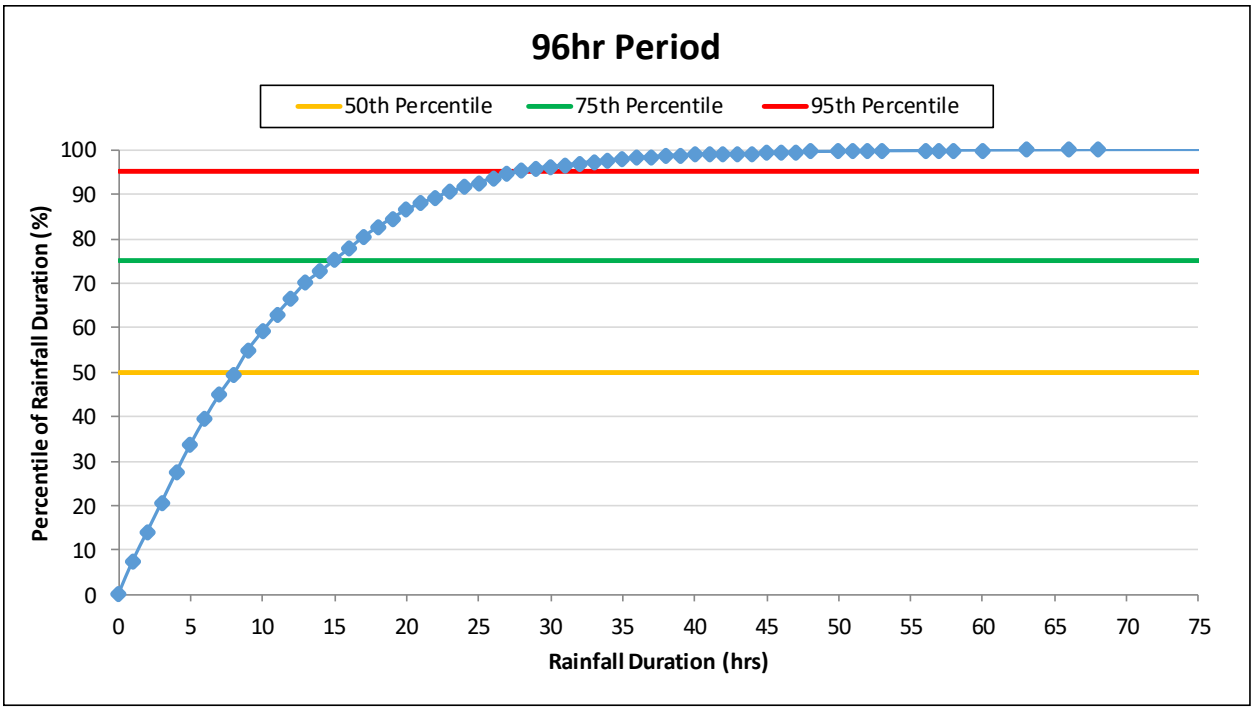

Figure A-4. Boston, Massachusetts 96 hour period rainfall measurements.

Table A-4. Boston, Massachusetts 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	76
Mean	10.9
SD	9.2
50%	9
75%	15
95%	28

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: CHARLESTON, NORTH CAROLINA

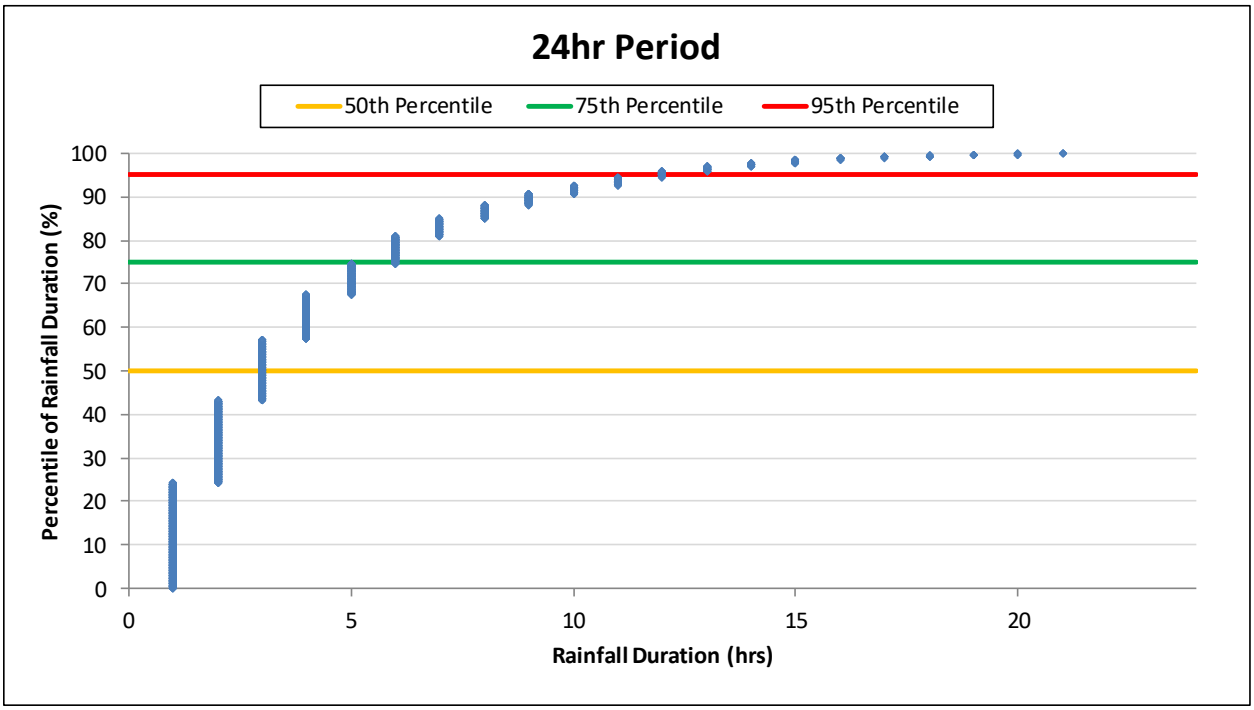

Figure A-5. Charleston, North Carolina 24 hour period rainfall measurements.

Table A-5. Charleston, North Carolina 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	21
Mean	4.1
SD	3.6
50%	3
75%	6
95%	12

*Maximum duration of rainfall in a given period.

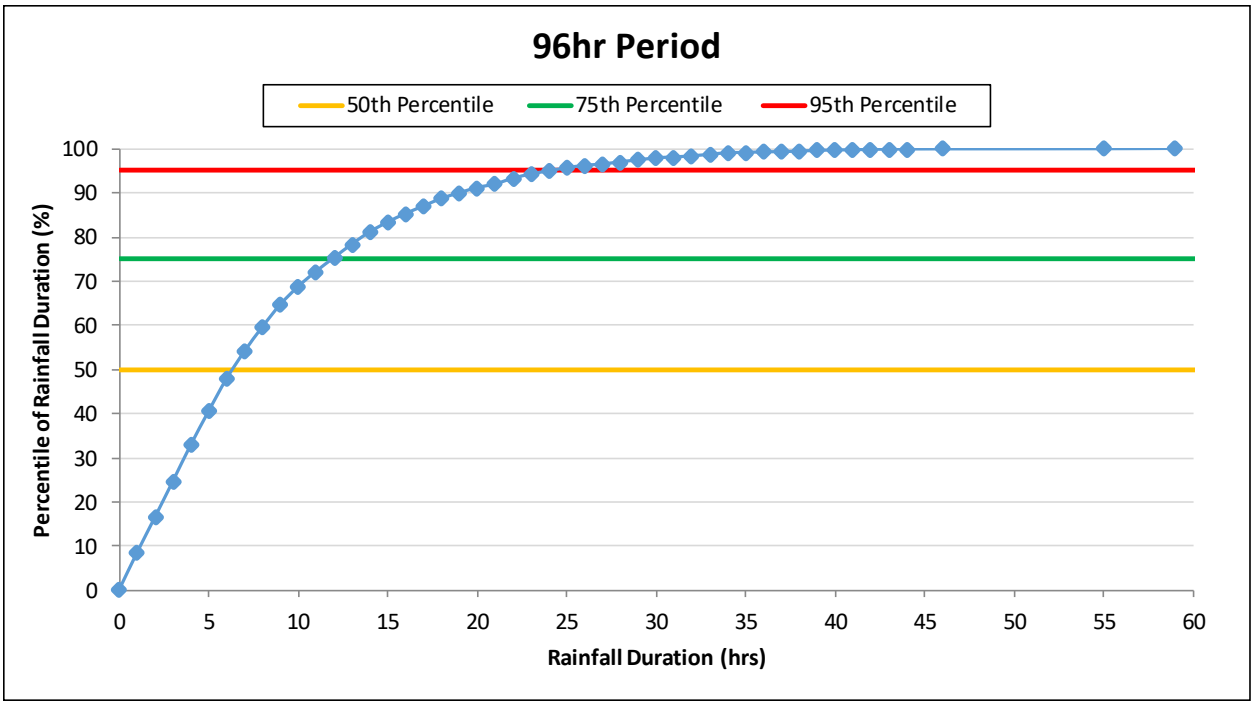

Figure A-6. Charleston, North Carolina 96 hour period rainfall measurements.

Table A-6. Charleston, North Carolina 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	59
Mean	9.1
SD	7.7
50%	7
75%	12
95%	25

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: CHICAGO, ILLINOIS

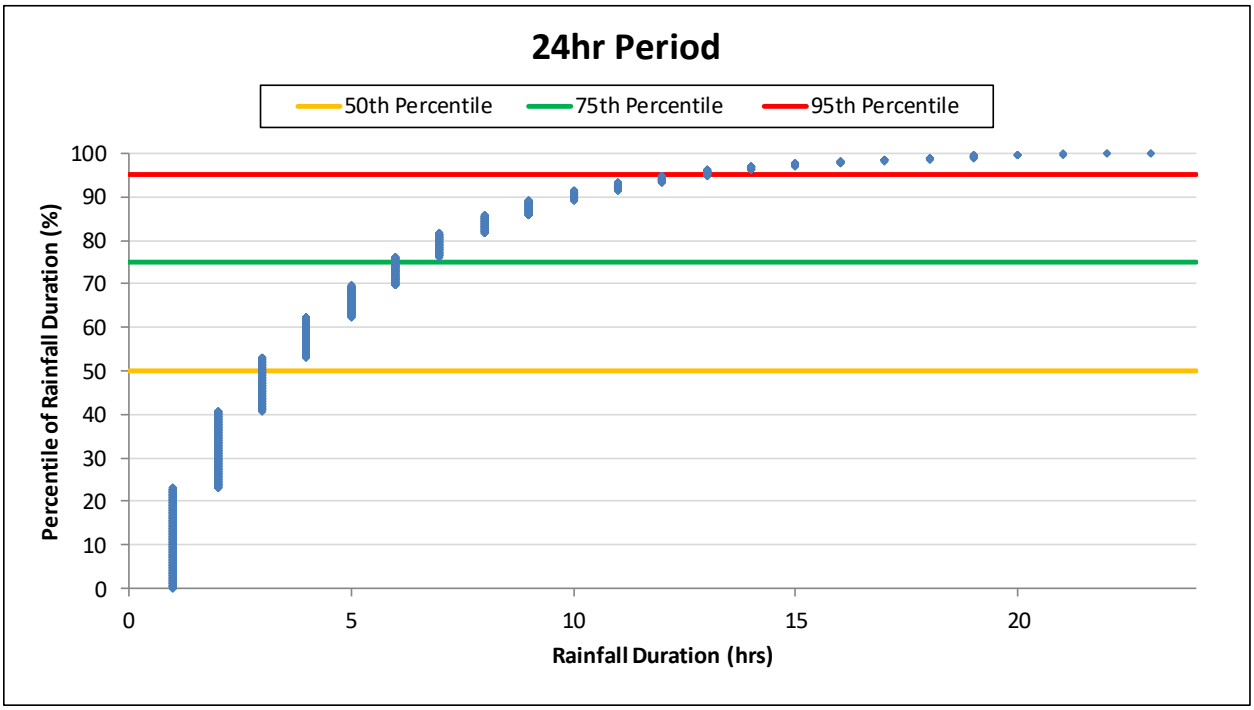

Figure A-7. Chicago, Illinois 24 hour period rainfall measurements.

Table A-7. Chicago, Illinois 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	23
Mean	4.5
SD	3.9
50%	3
75%	6
95%	13

*Maximum duration of rainfall in a given period.

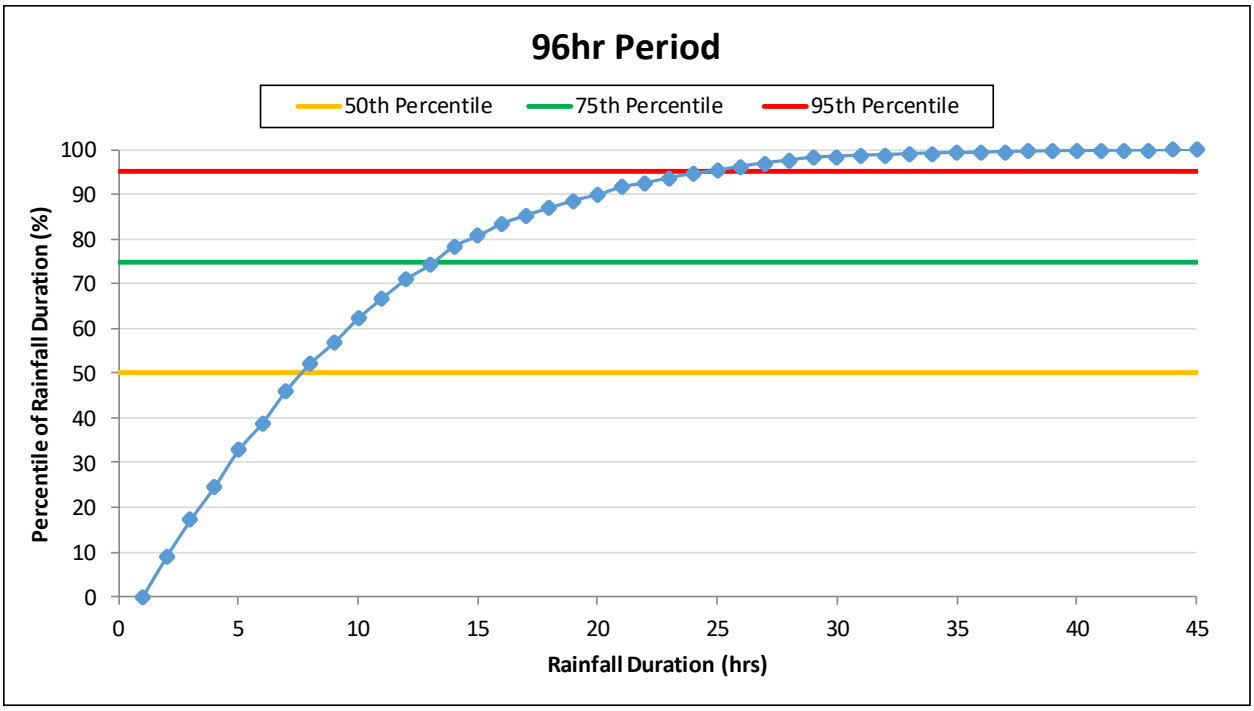

Figure A-8. Chicago, Illinois 96 hour period rainfall measurements.

Table A-8. Chicago, Illinois 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	45
Mean	9.1
SD	7.3
50%	7
75%	13
95%	24

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: CORPUS CHRISTI, TEXAS

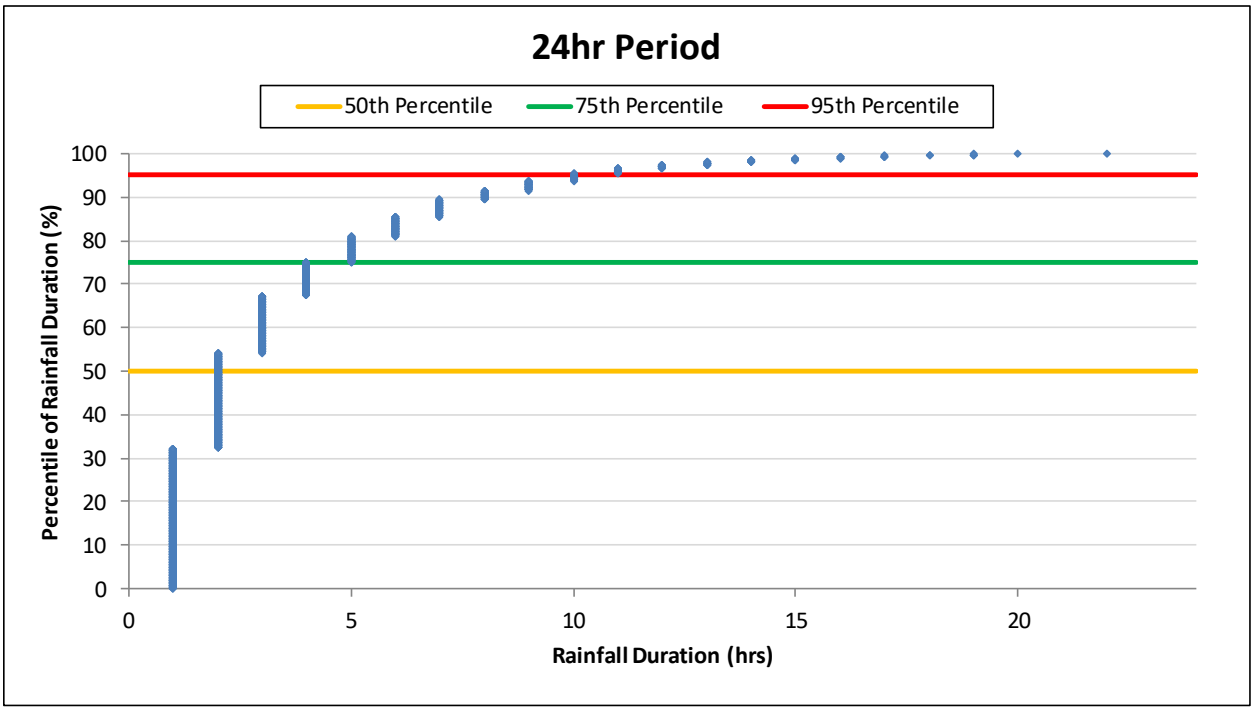

Figure A-9. Corpus Christi, Texas 24 hour period rainfall measurements.

Table A-9. Corpus Christi, Texas 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	22
Mean	3.5
SD	3.2
50%	2
75%	4
95%	10

*Maximum duration of rainfall in a given period.

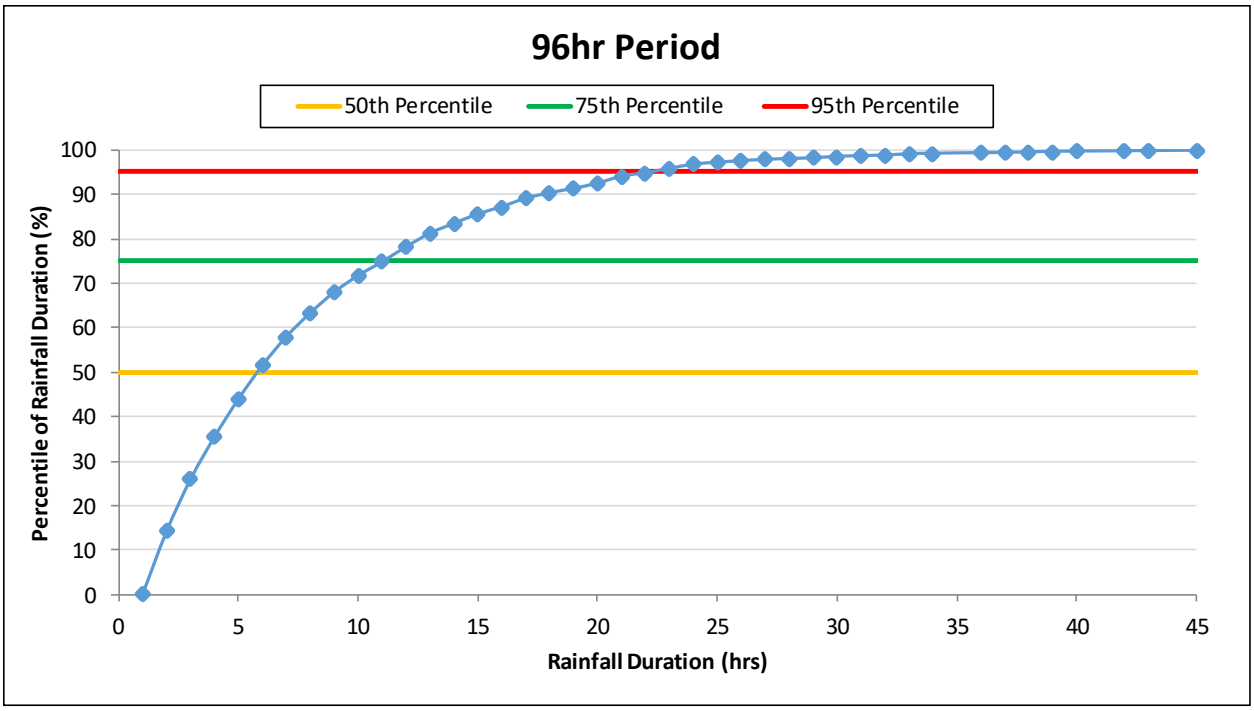

Figure A-10. Corpus Christi, Texas 96 hour period rainfall measurements.

Table A-10. Corpus Christi, Texas 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	55
Mean	7.7
SD	7.4
50%	5
75%	11
95%	22

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: DETROIT, MICHIGAN

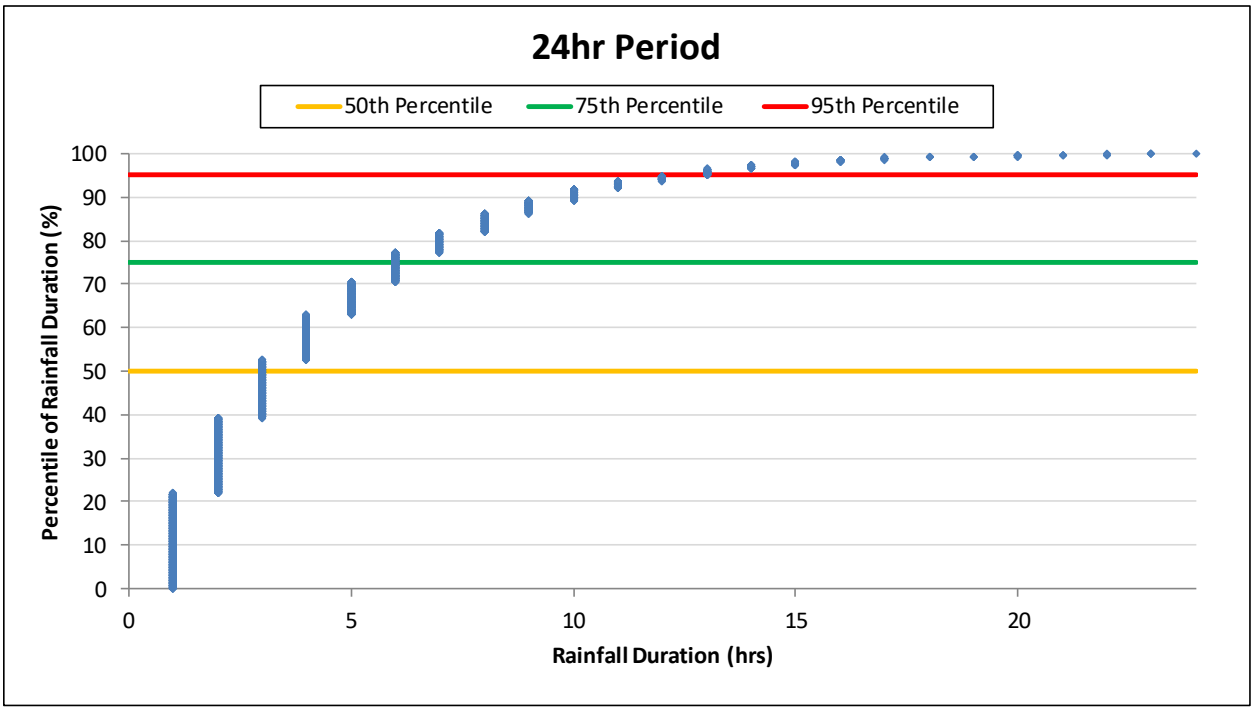

Figure A-11. Detroit, Michigan 24 hour period rainfall measurements.

Table A-11. Detroit, Michigan 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	24
Mean	4.5
SD	3.8
50%	3
75%	6
95%	13

*Maximum duration of rainfall in a given period.

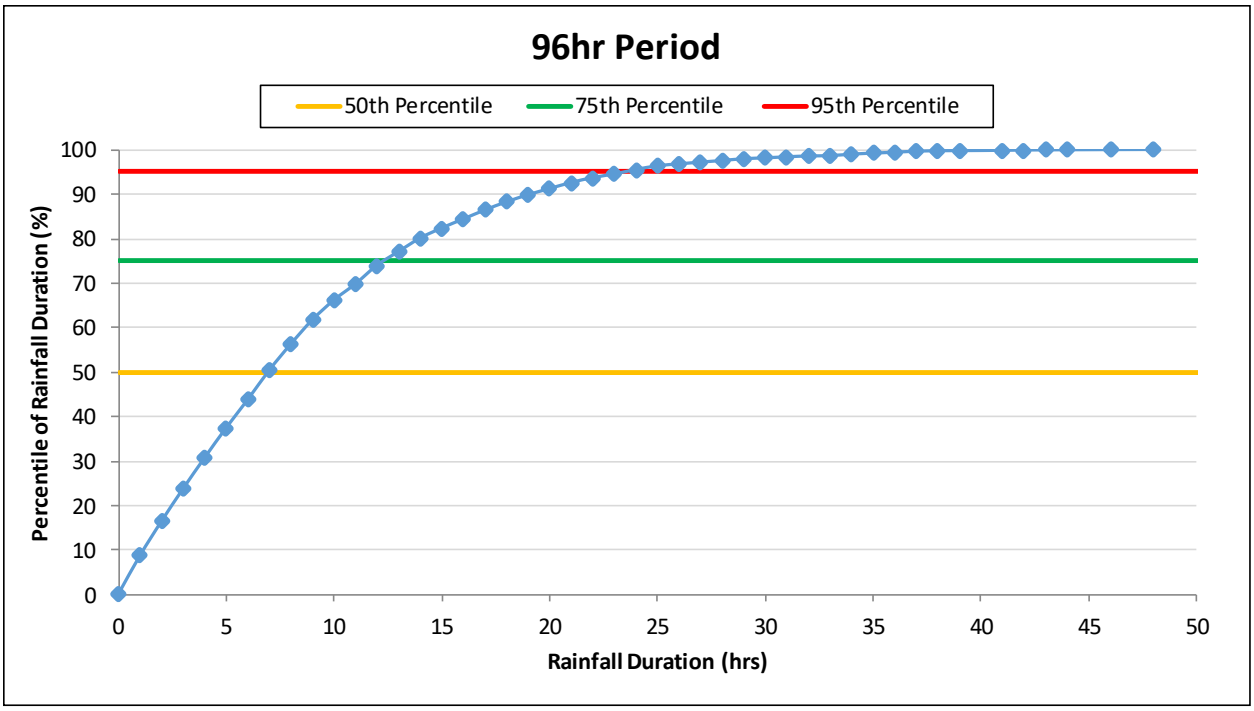

Figure A-12. Detroit, Michigan 96 hour period rainfall measurements.

Table A-12. Detroit, Michigan 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	48
Mean	9.3
SD	7.4
50%	7
75%	13
95%	24

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: PITI, GUAM

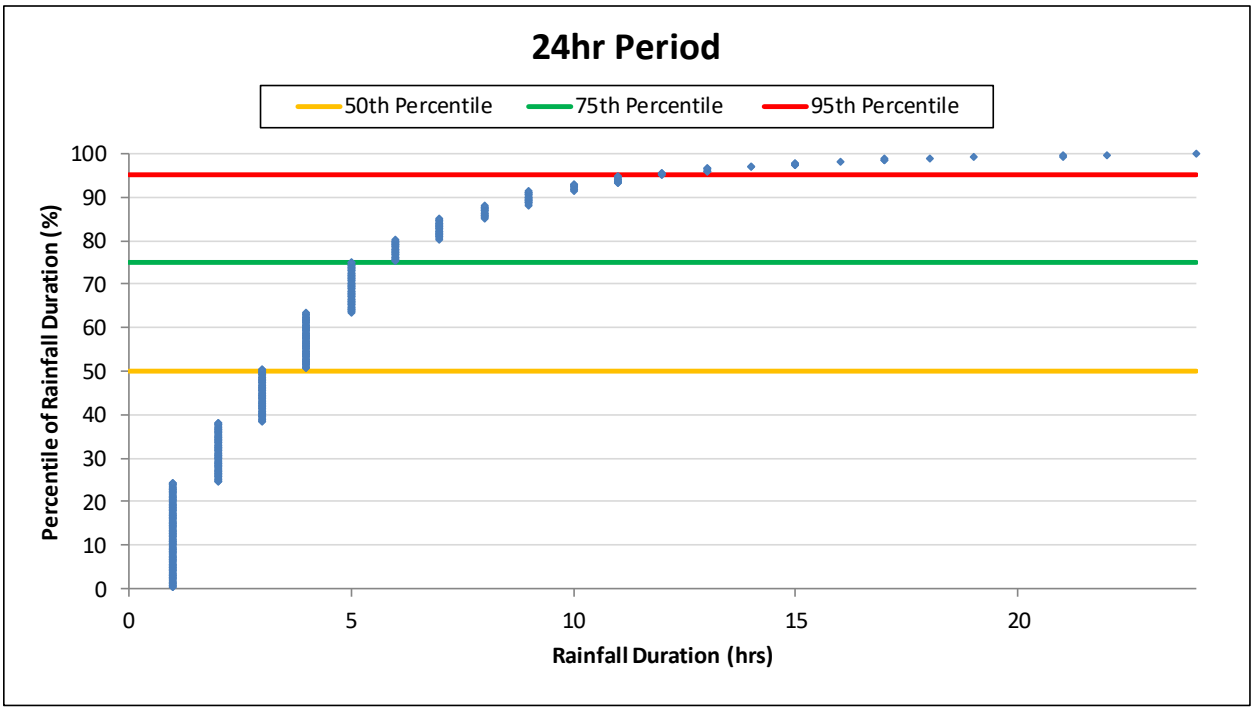

Figure A-13. Piti, Guam 24 hour period rainfall measurements.

Table A-13. Piti, Guam 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	24
Mean	4.4
SD	3.7
50%	3
75%	5
95%	12

*Maximum duration of rainfall in a given period.

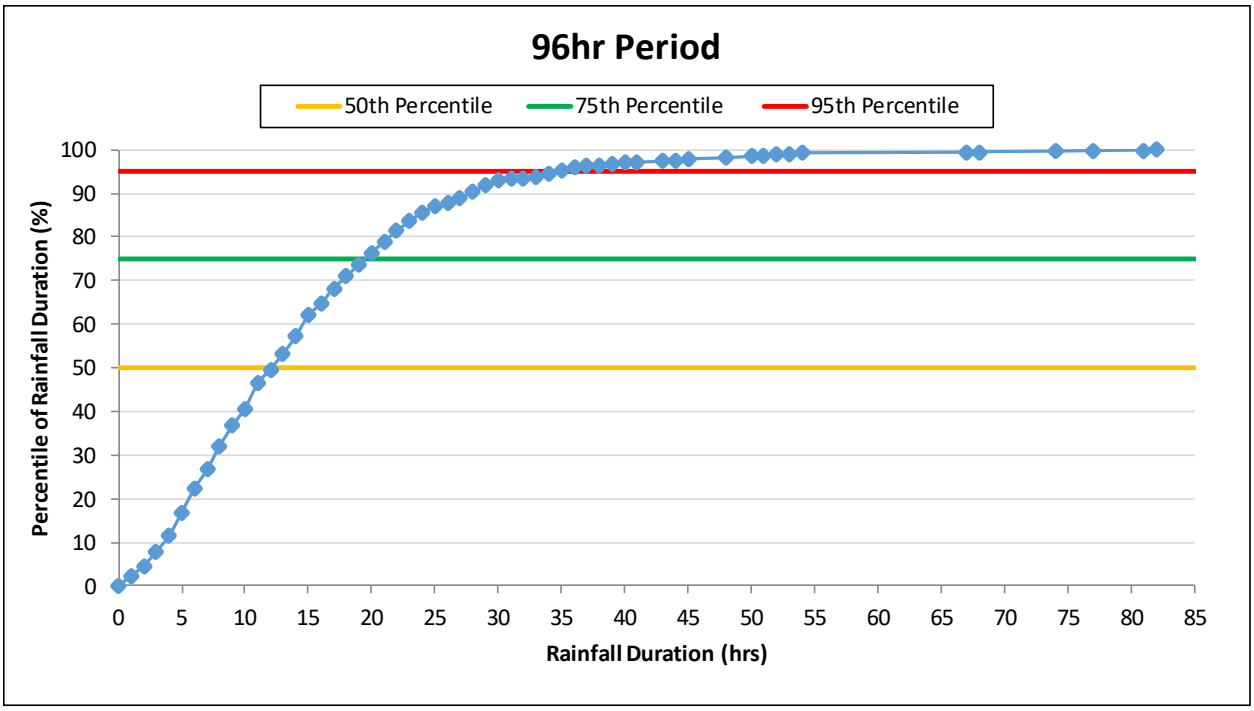

Figure A-14. Piti, Guam 96 hour period rainfall measurements.

Table A-14. Piti, Guam 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	82
Mean	15.0
SD	11.2
50%	13
75%	20
95%	35

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: HONOLULU, HAWAII

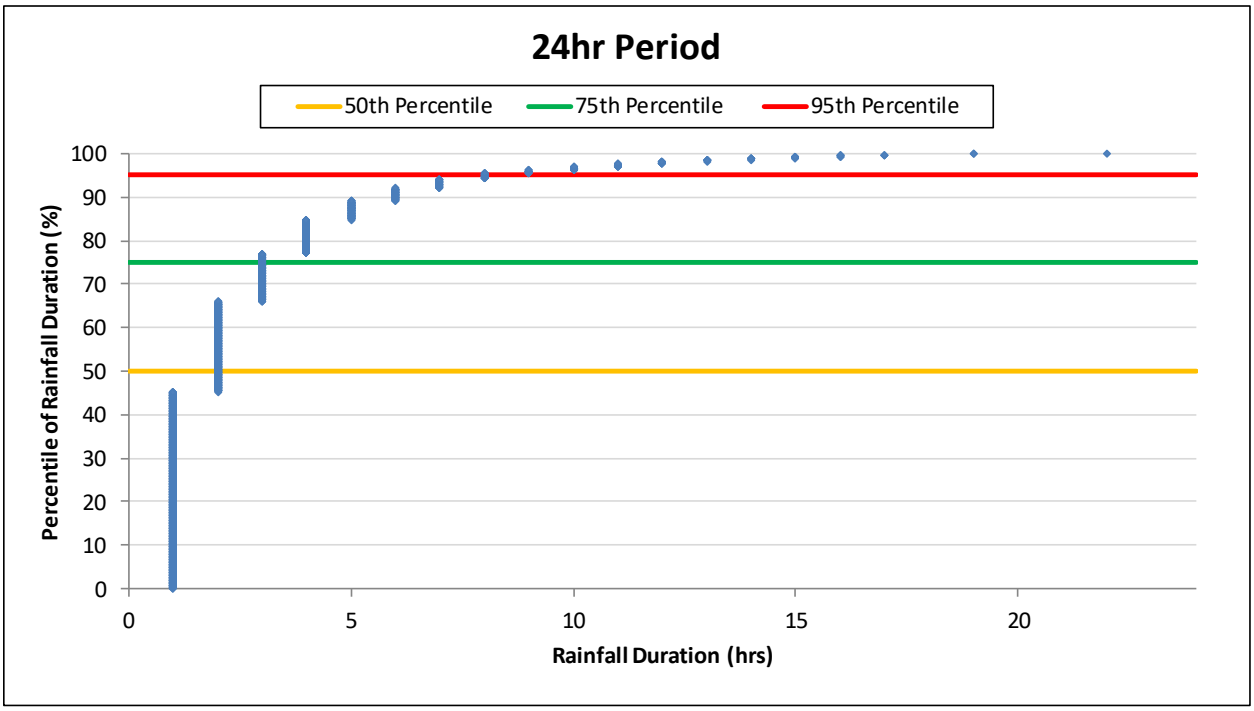

Figure A-15. Honolulu, Hawaii 24 hour period rainfall measurements.

Table A-15. Honolulu, Hawaii 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	22
Mean	2.7
SD	2.7
50%	2
75%	3
95%	8

*Maximum duration of rainfall in a given period.

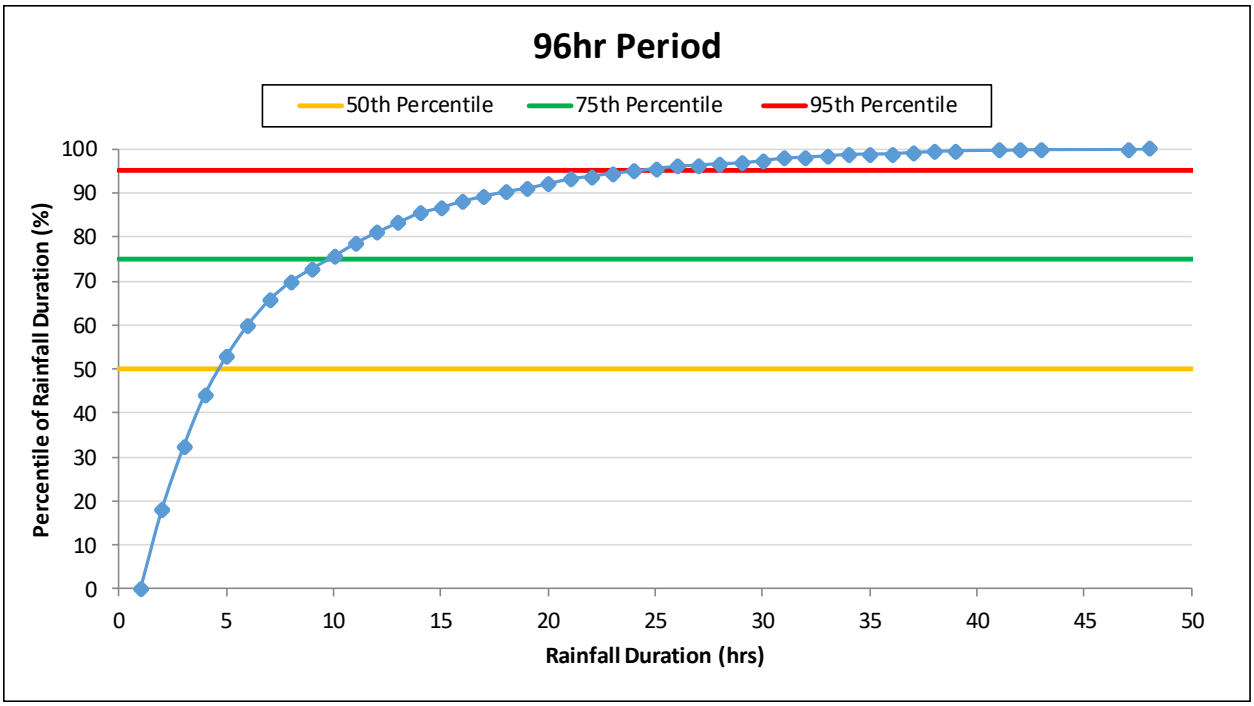

Figure A-16. Honolulu, Hawaii 96 hour period rainfall measurements.

Table A-16. Honolulu, Hawaii 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	48
Mean	7.1
SD	7.7
50%	4
75%	9
95%	24

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: JACKSONVILLE, FLORIDA

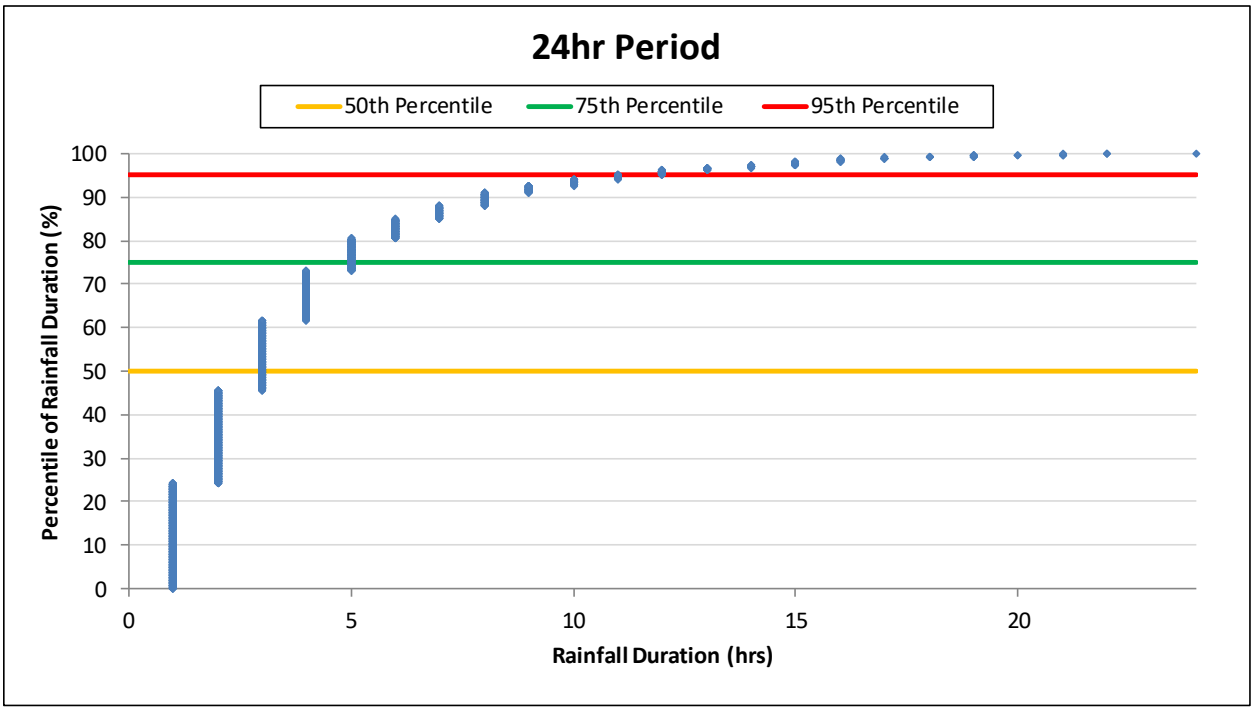

Figure A-17. Jacksonville, Florida 24 hour period rainfall measurements.

Table A-17. Jacksonville, Florida 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	24
Mean	3.8
SD	3.5
50%	3
75%	5
95%	11

*Maximum duration of rainfall in a given period.

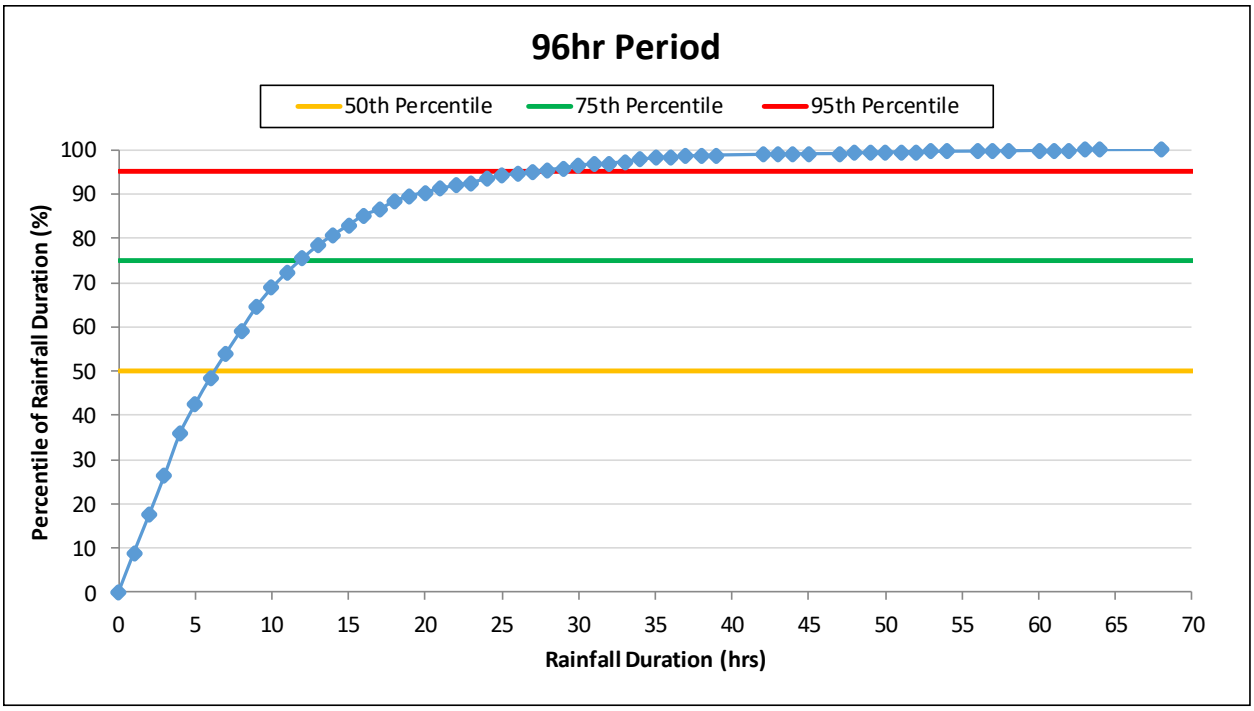

Figure A-18. Jacksonville, Florida 96 hour period rainfall measurements.

Table A-18. Jacksonville, Florida 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	68
Mean	9.4
SD	8.9
50%	7
75%	12
95%	28

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: LOUISVILLE, KENTUCKY

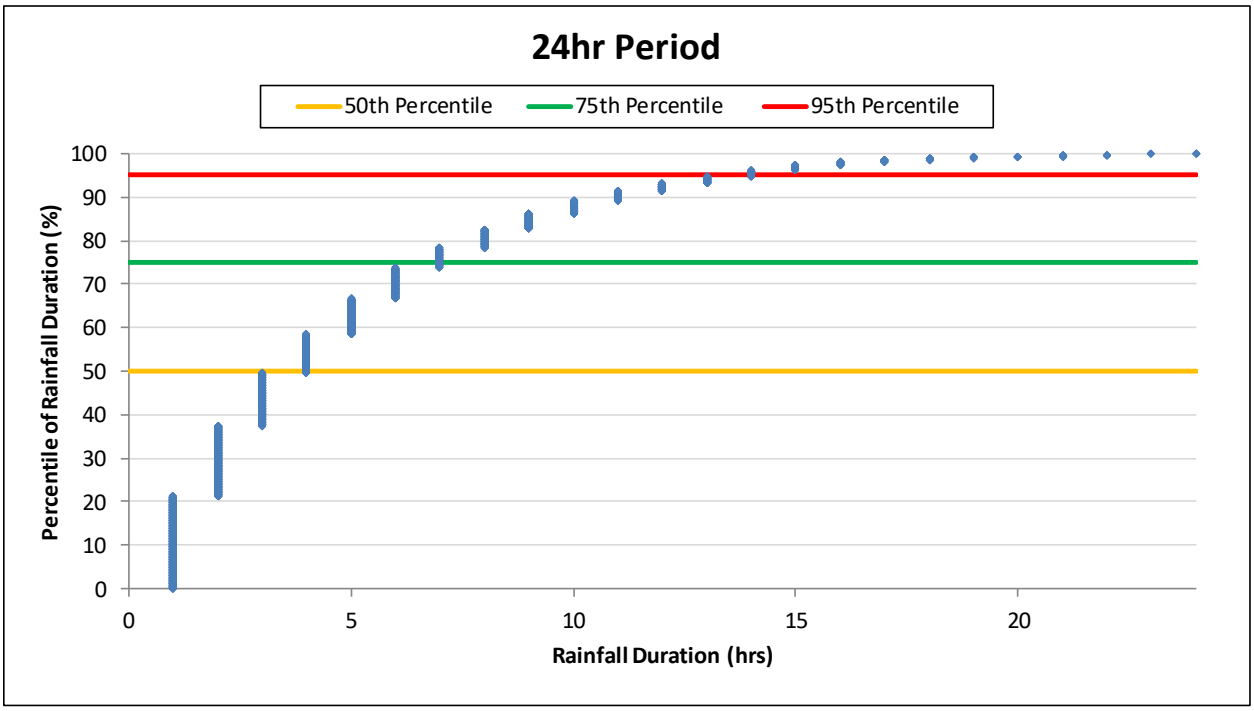

Figure A-19. Louisville, Kentucky 24 hour period rainfall measurements.

Table A-19. Louisville, Kentucky 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	24
Mean	4.9
SD	4.2
50%	4
75%	7
95%	14

*Maximum duration of rainfall in a given period.

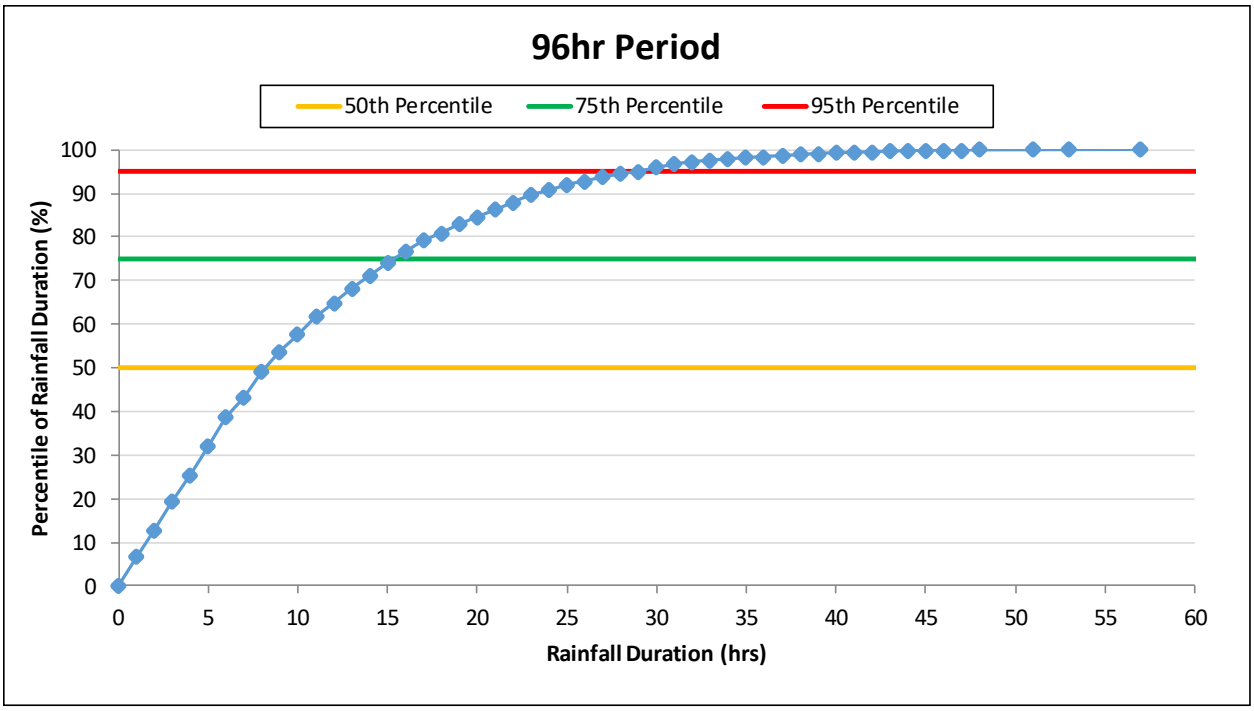

Figure A-20. Louisville, Kentucky 96 hour period rainfall measurements.

Table A-20. Louisville, Kentucky 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	57
Mean	11.2
SD	8.9
50%	9
75%	16
95%	29

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: GREAT FALLS, MONTANA

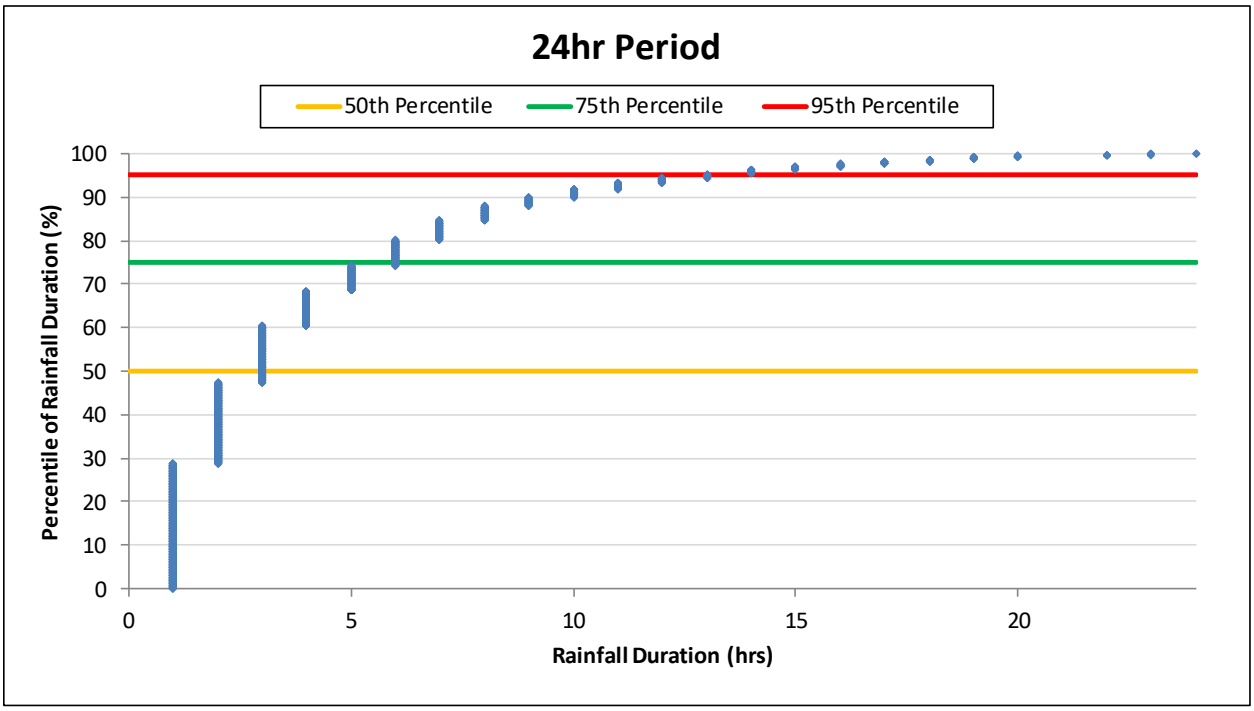

Figure A-21. Great Falls, Montana 24 hour period rainfall measurements.

Table A-21. Great Falls, Montana 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	24
Mean	4.2
SD	4.0
50%	3
75%	6
95%	13

*Maximum duration of rainfall in a given period.

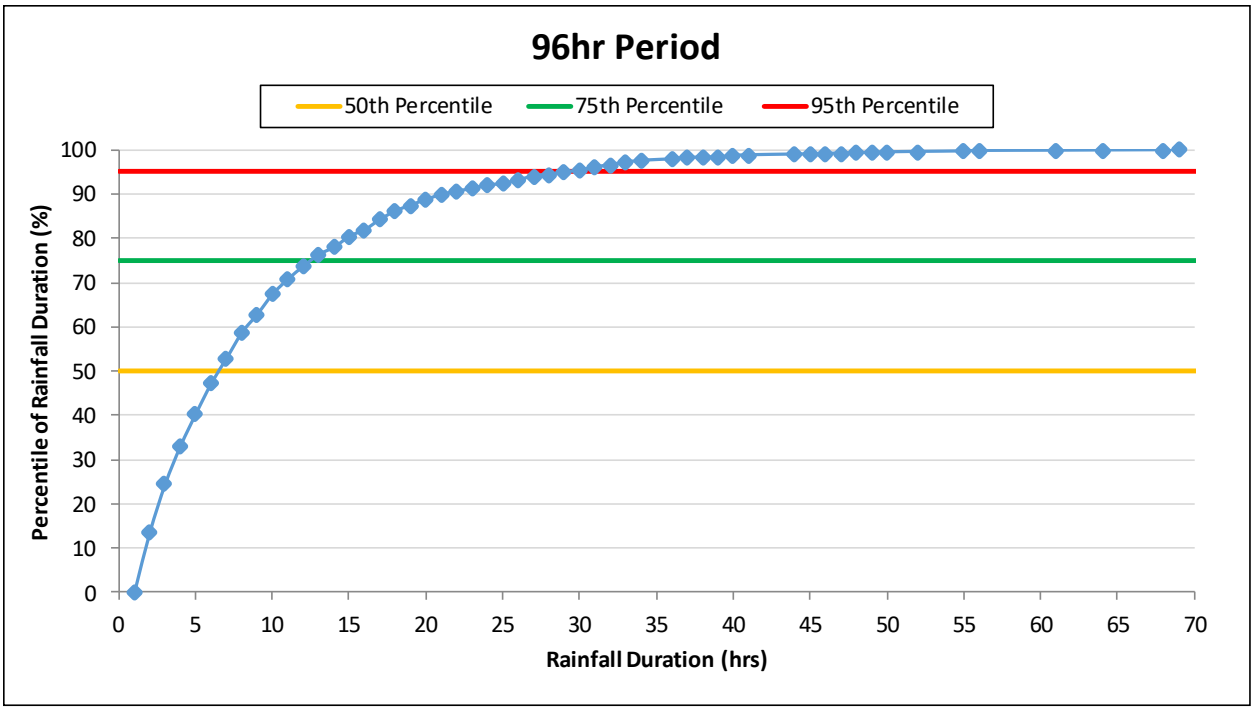

Figure A-22. Great Falls, Montana 96 hour period rainfall measurements.

Table A-22. Great Falls, Montana 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	69
Mean	9.0
SD	9.3
50%	6
75%	12
95%	29

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: NEW ORLEANS, LOUISIANA

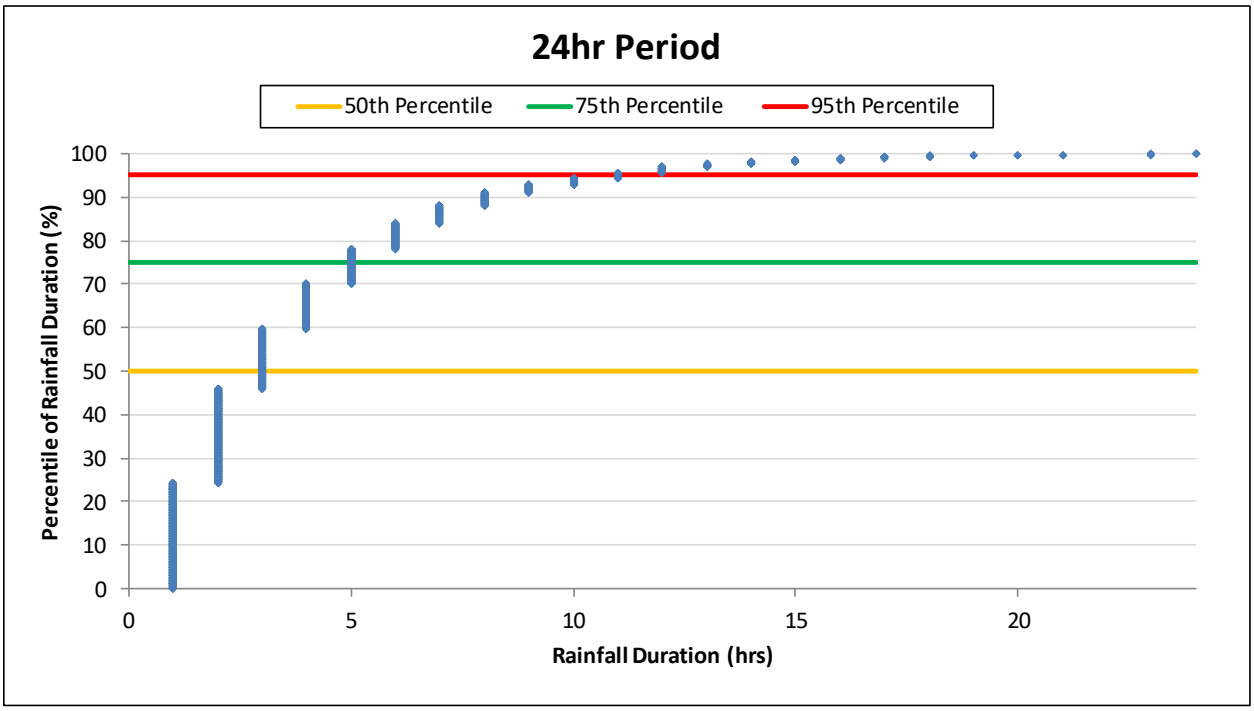

Figure A-23. New Orleans, Louisiana 24 hour period rainfall measurements.

Table A-23. New Orleans, Louisiana 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	24
Mean	3.9
SD	3.4
50%	3
75%	5
95%	11

*Maximum duration of rainfall in a given period.

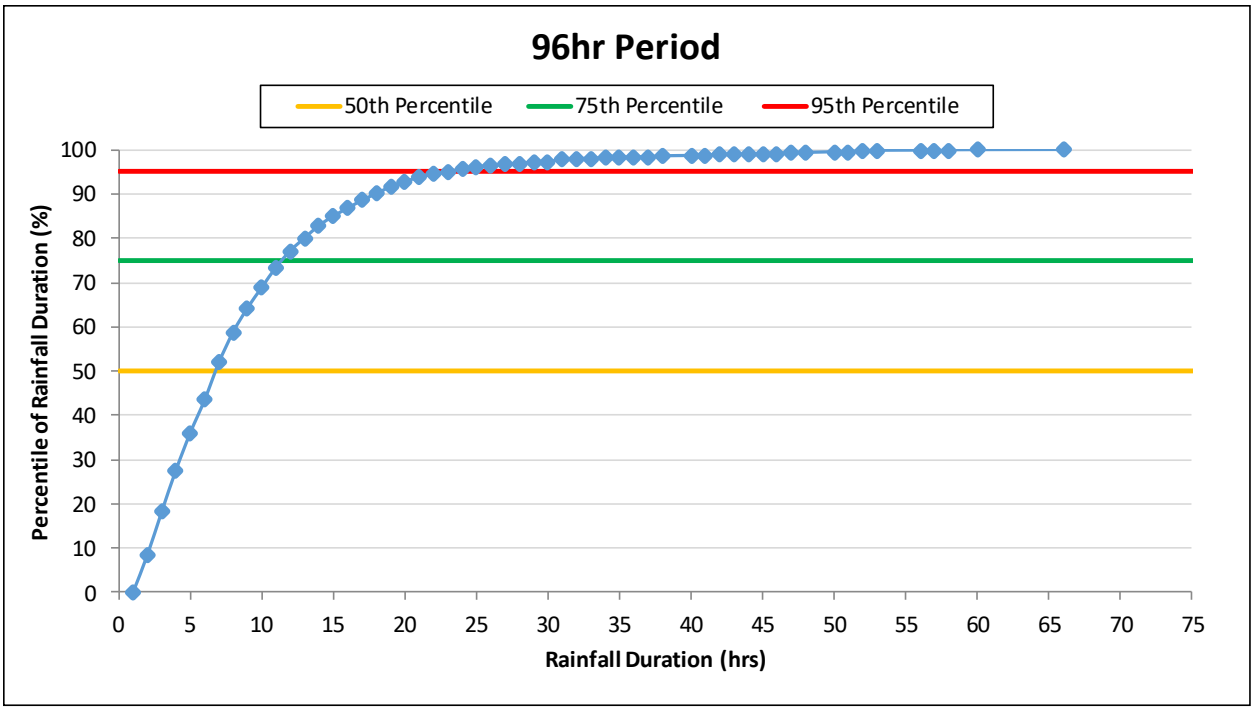

Figure A-24. New Orleans, Louisiana 96 hour period rainfall measurements.

Table A-24. New Orleans, Louisiana 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	67
Mean	8.6
SD	8.5
50%	6
75%	11
95%	23

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: NORFOLK, VIRGINIA

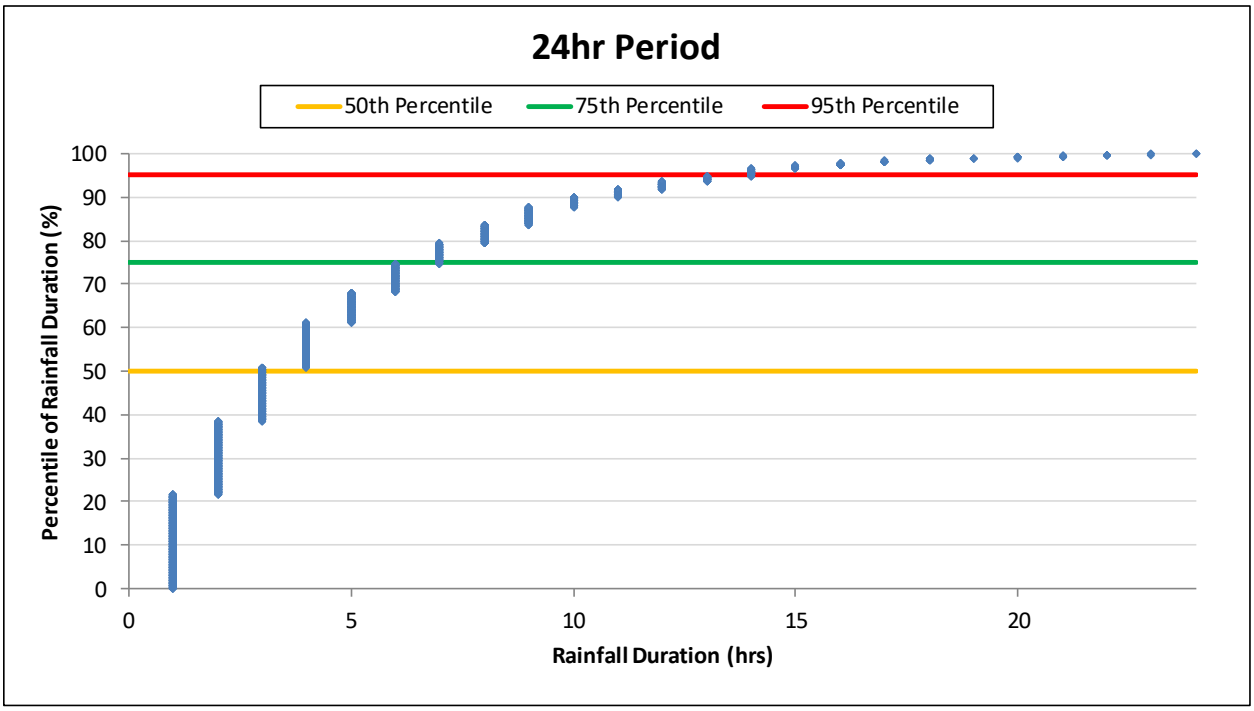

Figure A-25. Norfolk, Virginia 24 hour period rainfall measurements.

Table A-25. Norfolk, Virginia 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	24
Mean	4.8
SD	4.1
50%	3
75%	7
95%	14

*Maximum duration of rainfall in a given period.

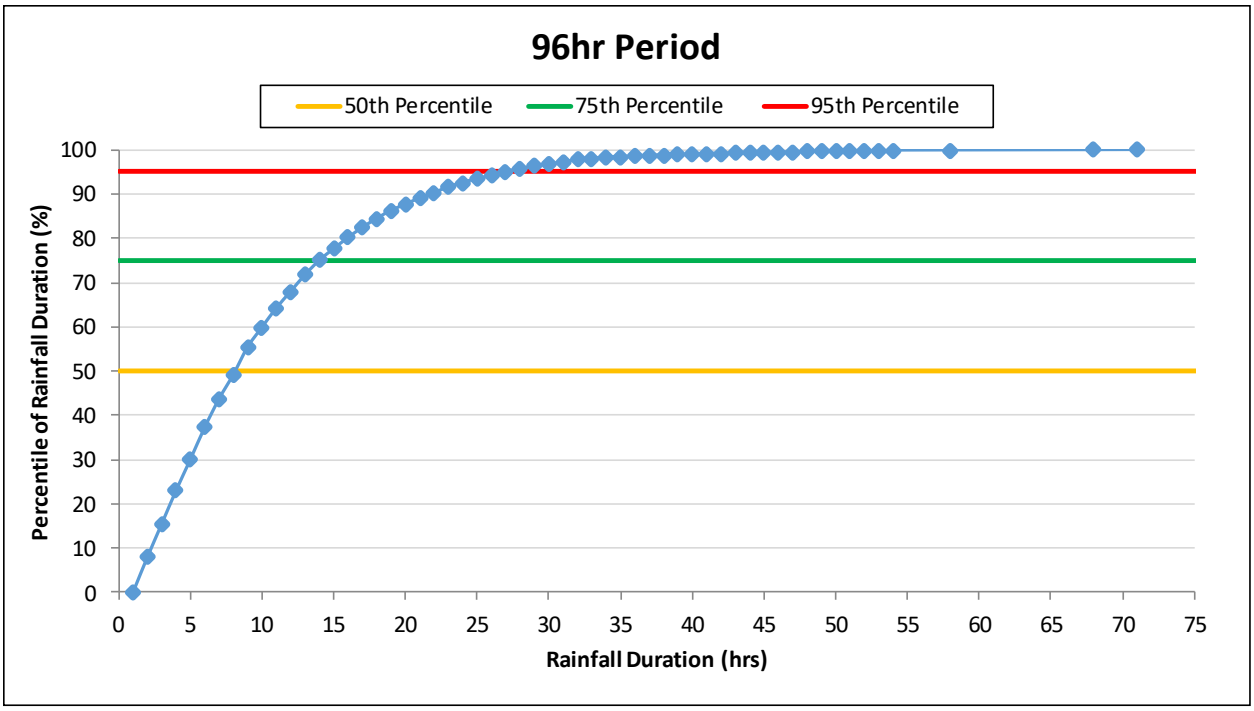

Figure A-26. Norfolk, Virginia 96 hour period rainfall measurements.

Table A-26. Norfolk, Virginia 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	71
Mean	9.9
SD	8.5
50%	8
75%	13.5
95%	26

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: PASO ROBLES, CALIFORNIA

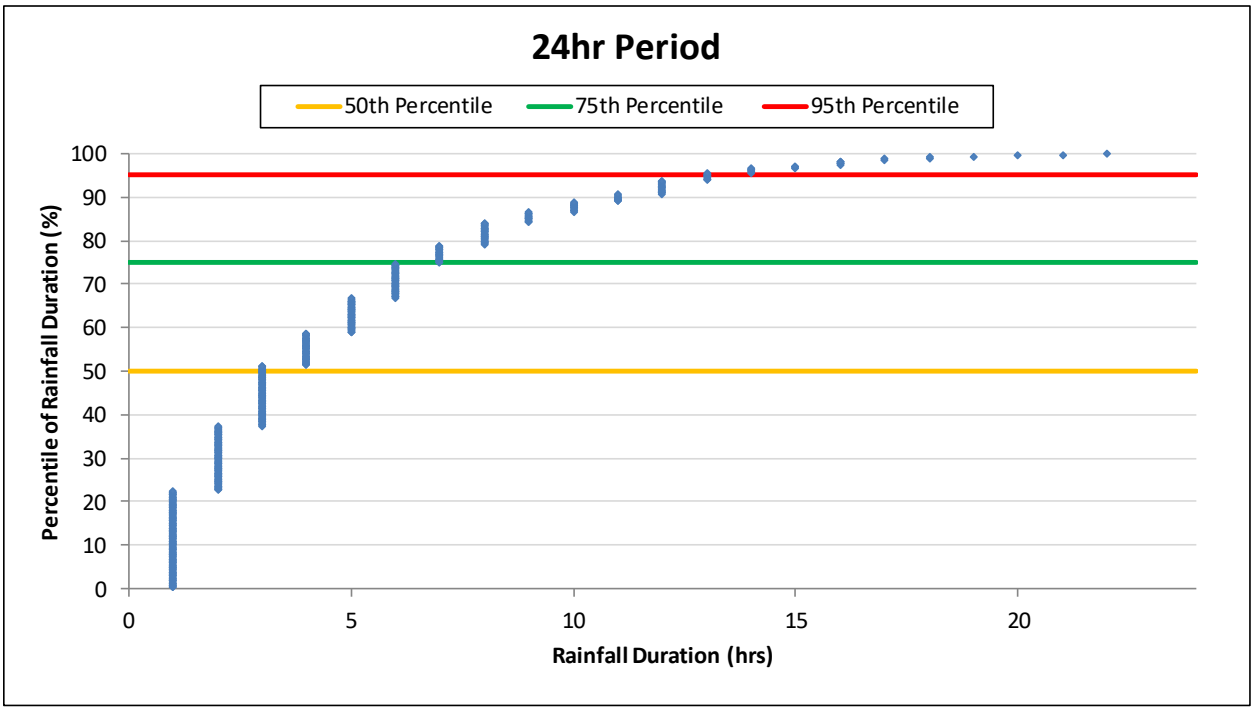

Figure A-27. Paso Robles, California 24 hour period rainfall measurements.

Table A-27. Paso Robles, California 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	22
Mean	4.8
SD	4.1
50%	3
75%	7
95%	13

*Maximum duration of rainfall in a given period.

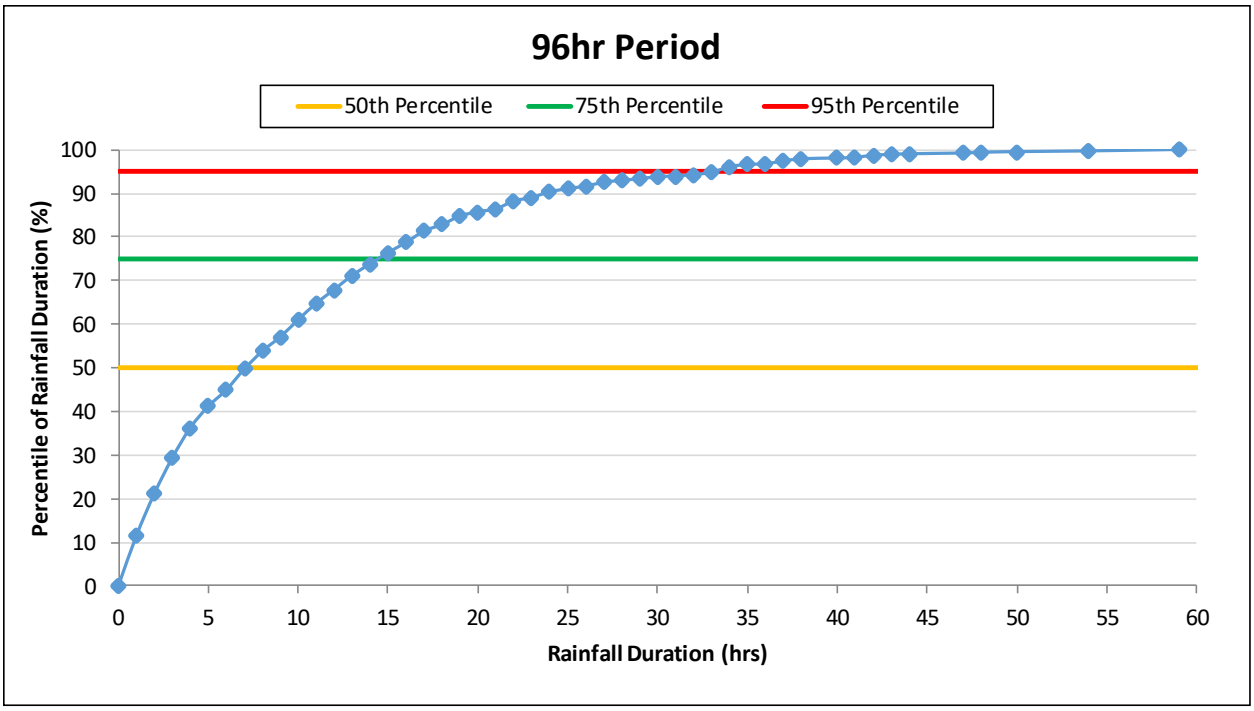

Figure A-28. Paso Robles, California 96 hour period rainfall measurements.

Table A-28. Paso Robles, California 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	59
Mean	10.7
SD	10.2
50%	8
75%	15
95%	34

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: PENSACOLA, FLORIDA

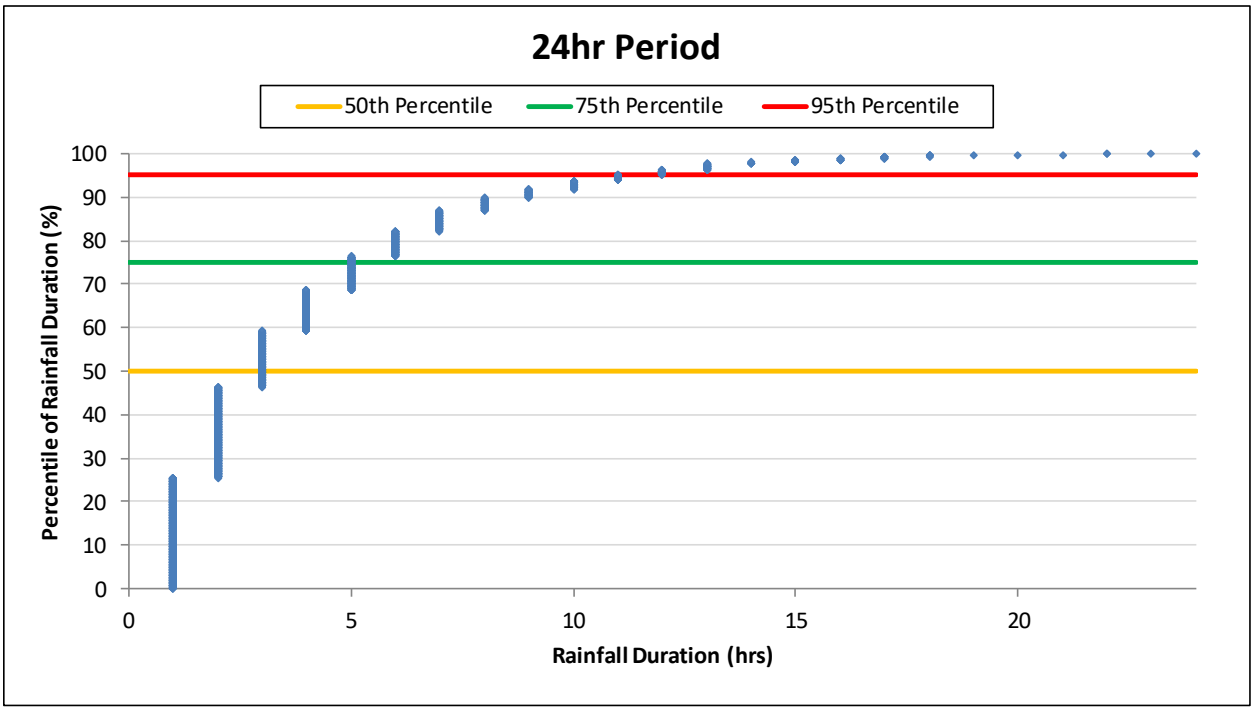

Figure A-29. Pensacola, Florida 24 hour period rainfall measurements.

Table A-29. Pensacola, Florida 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	24
Mean	4.0
SD	3.5
50%	3
75%	5
95%	11

*Maximum duration of rainfall in a given period.

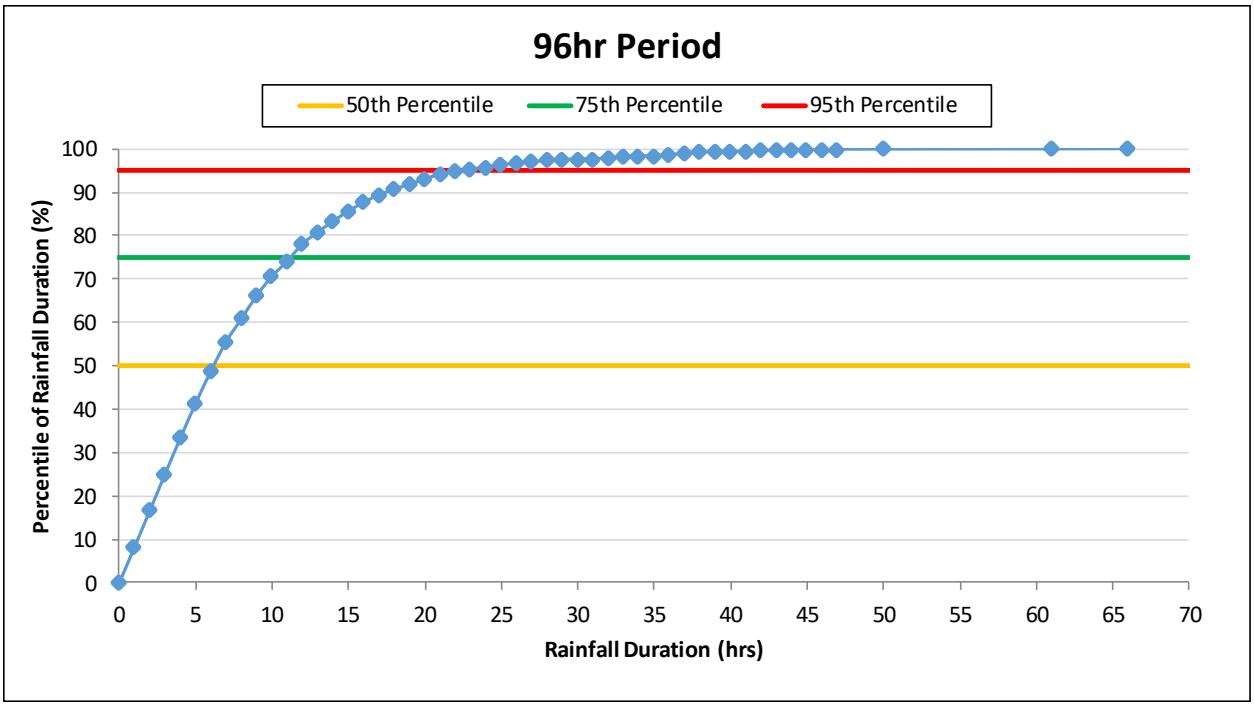

Figure A-30. Pensacola, Florida 96 hour period rainfall measurements.

Table A-30. Pensacola, Florida 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	66
Mean	8.7
SD	7.6
50%	7
75%	12
95%	23

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: SAN DIEGO, CALIFORNIA

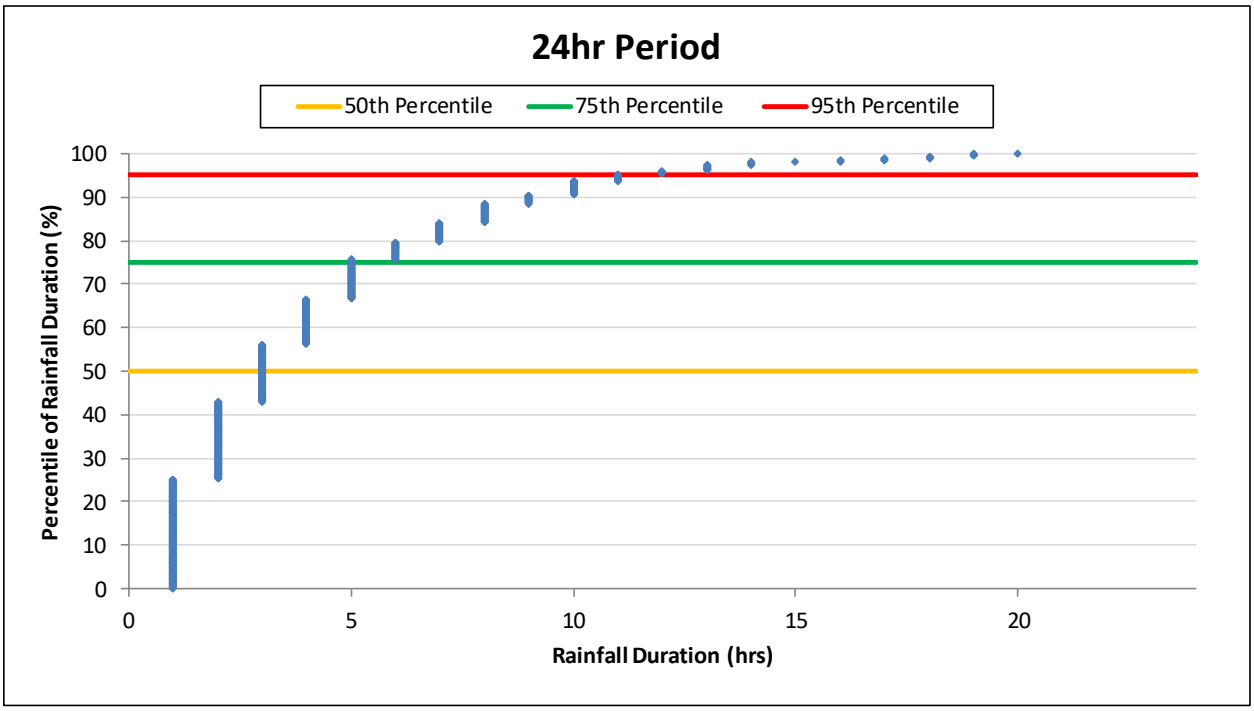

Figure A-31. San Diego, California 24 hour period rainfall measurements.

Table A-31. San Diego, California 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	24
Mean	4.2
SD	3.5
50%	3
75%	5
95%	11

*Maximum duration of rainfall in a given period.

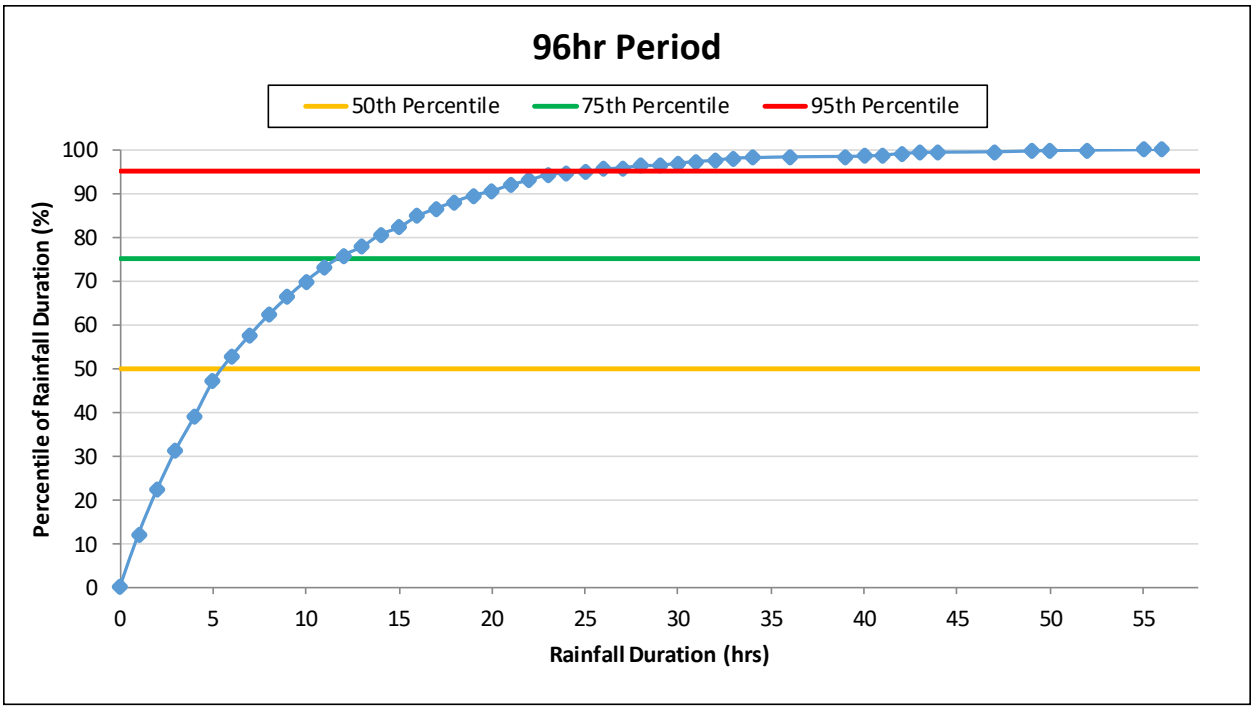

Figure A-32. San Diego, California 96 hour period rainfall measurements.

Table A-32. San Diego, California 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	56
Mean	8.9
SD	8.6
50%	6
75%	12
95%	26

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: SAN FRANCISCO, CALIFORNIA

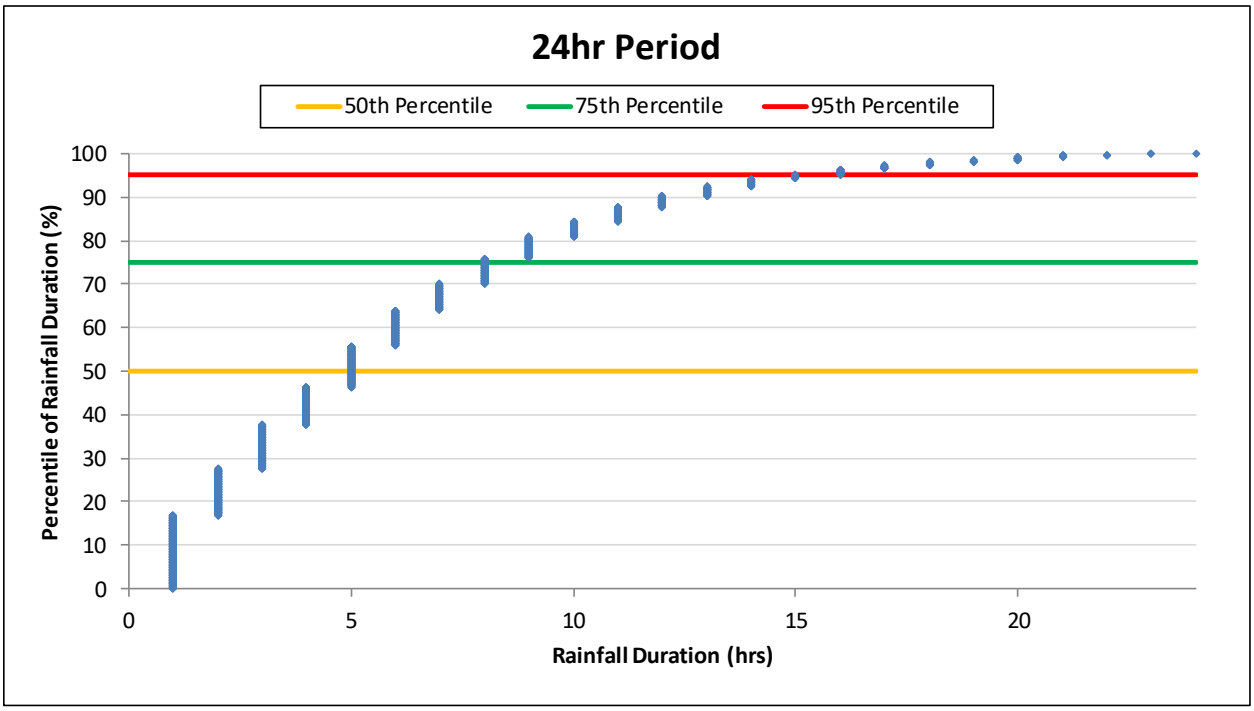

Figure A-33. San Francisco, California 24 hour period rainfall measurements.

Table A-33. San Francisco, California 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	24
Mean	5.9
SD	4.6
50%	5
75%	8
95%	15

*Maximum duration of rainfall in a given period.

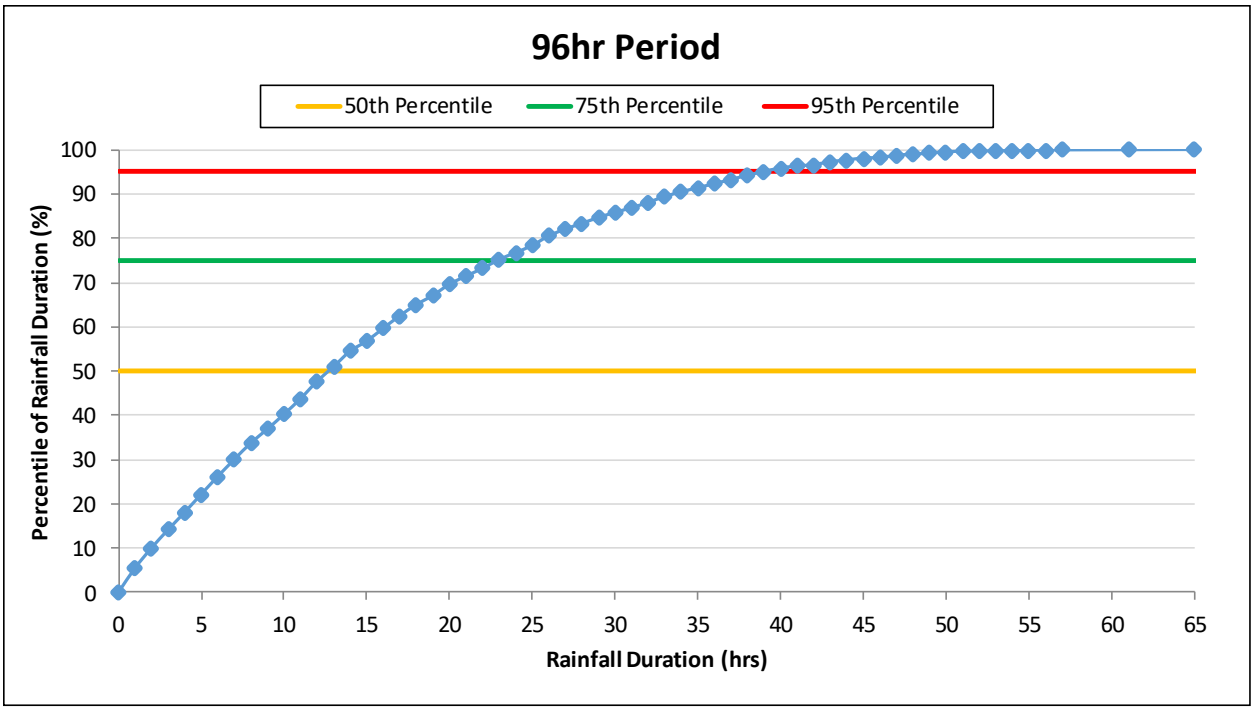

Figure A-34. San Francisco, California 96 hour period rainfall measurements.

Table A-34. San Francisco, California 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (Hours)
Max*	65
Mean	16.0
SD	12.1
50%	13
75%	23
95%	39

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: SEATTLE, WASHINGTON

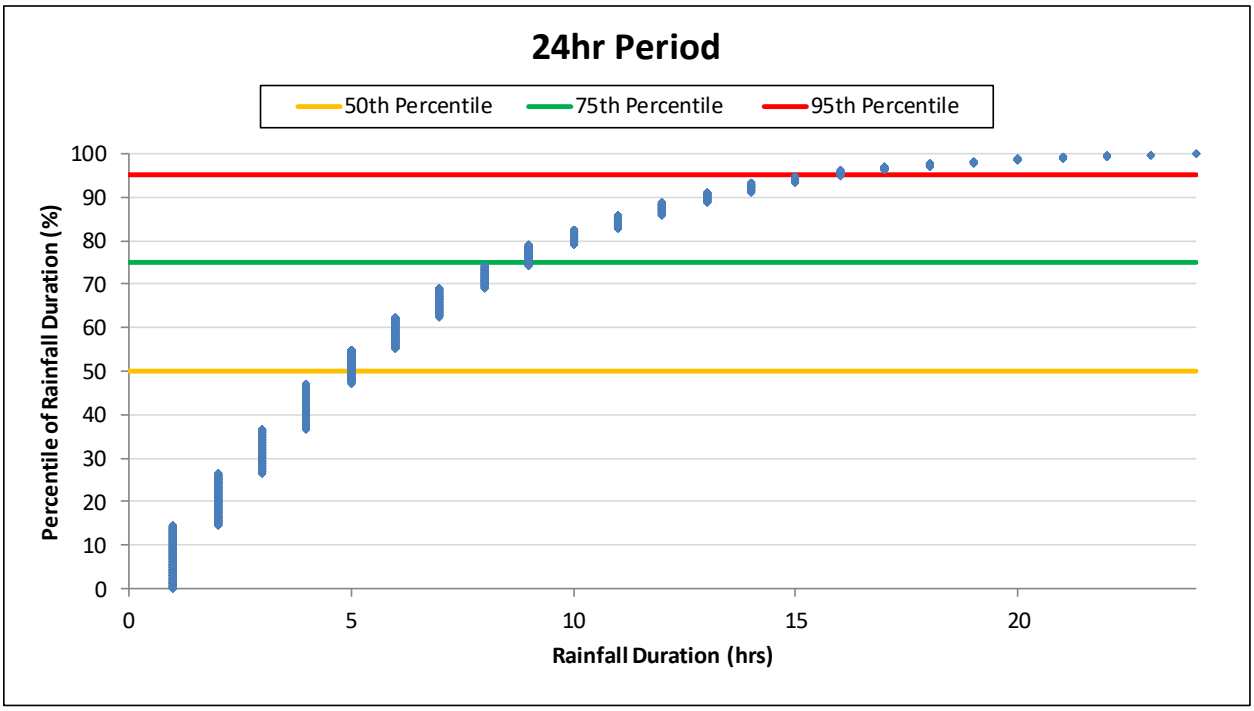

Figure A-35. Seattle, Washington 24 hour period rainfall measurements.

Table A-35. Seattle, Washington 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	24
Mean	6.1
SD	4.7
50%	5
75%	9
95%	16

*Maximum duration of rainfall in a given period.

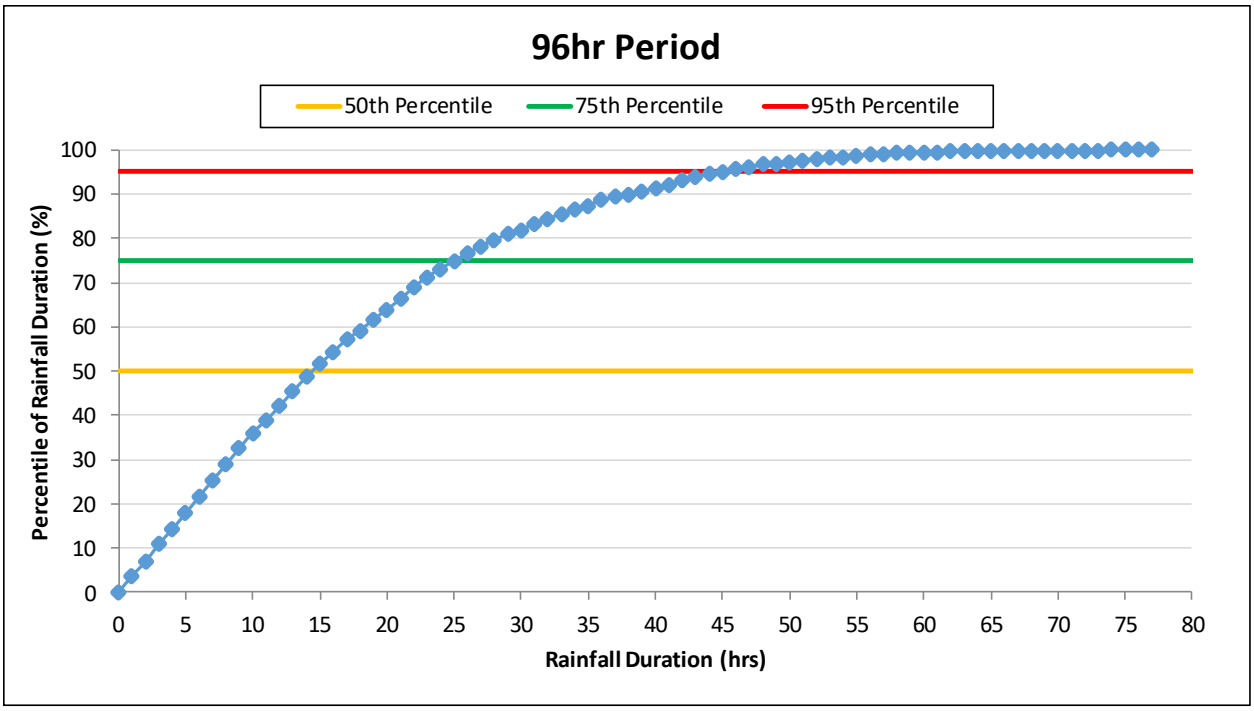

Figure A-36. Seattle, Washington 96 hour period rainfall measurements.

Table A-36. Seattle, Washington 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	77
Mean	18.2
SD	13.7
50%	15
75%	26
95%	45

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: RAPID CITY, SOUTH DAKOTA

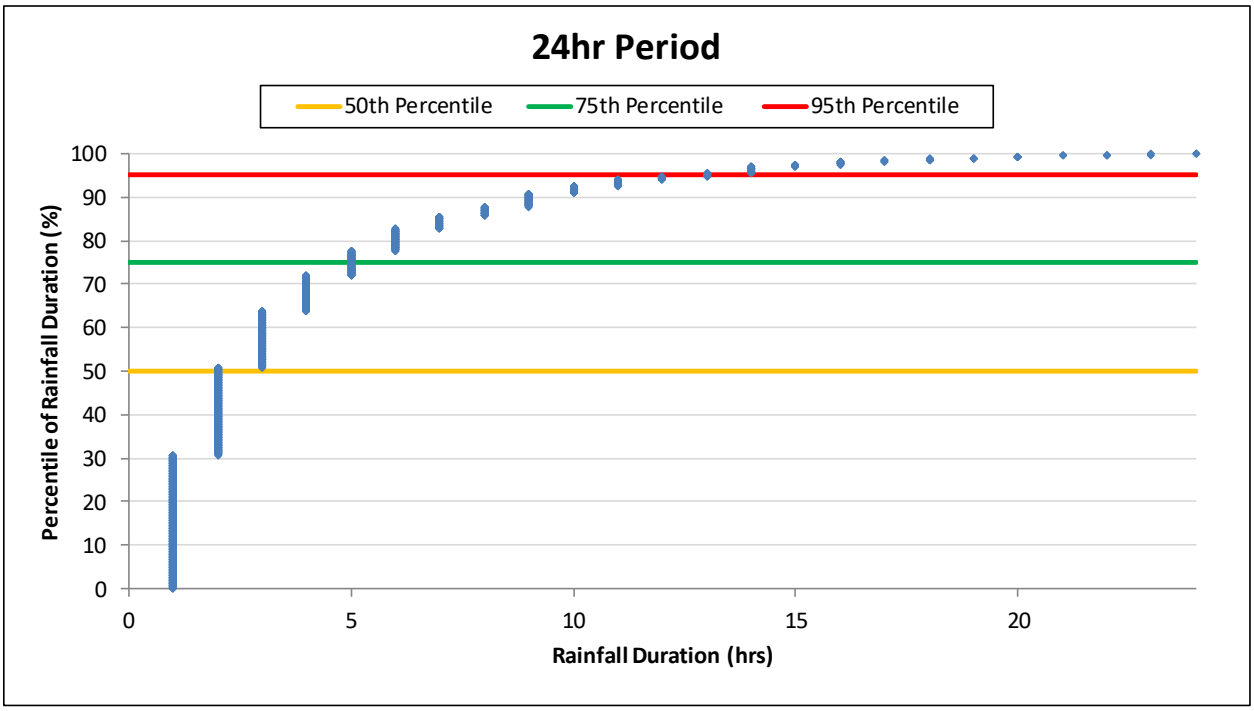

Figure A-37. Rapid City, South Dakota 24 hour period rainfall measurements.

Table A-37. Rapid City, South Dakota 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	24
Mean	3.9
SD	3.9
50%	2
75%	5
95%	13

*Maximum duration of rainfall in a given period.

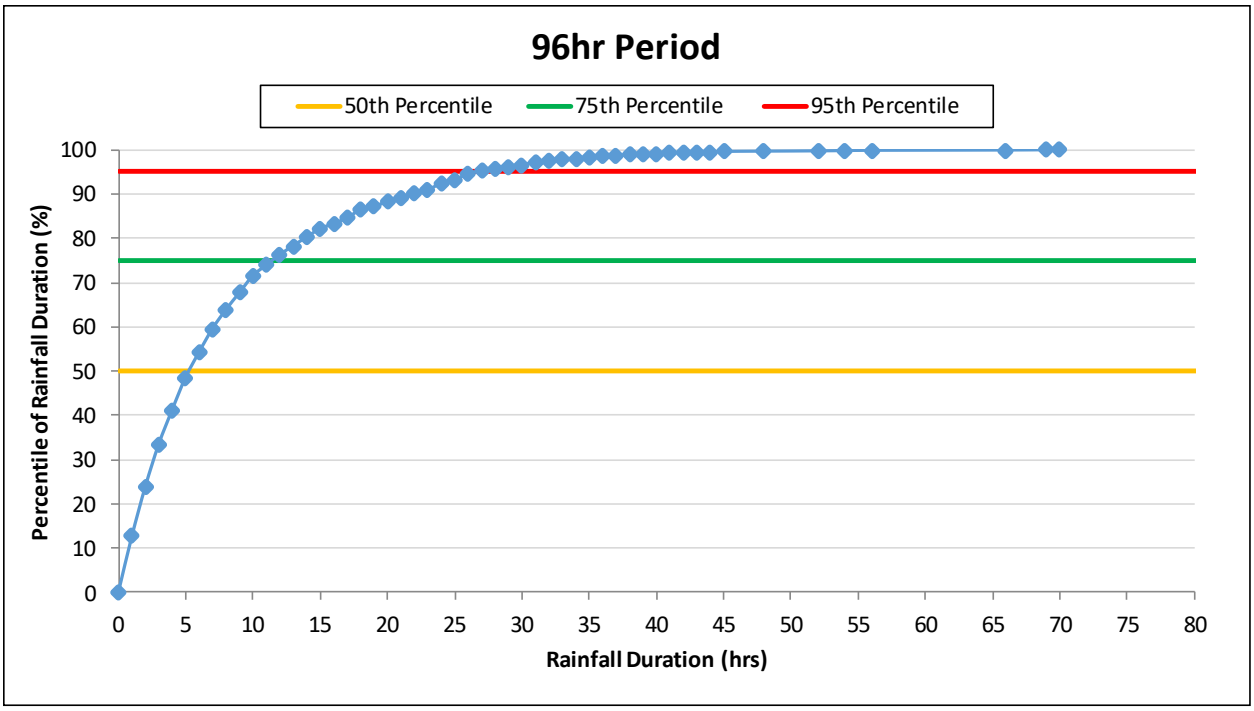

Figure A-38. Rapid City, South Dakota 96 hour period rainfall measurements.

Table A-38. Rapid City, South Dakota 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	70
Mean	9.0
SD	9.1
50%	6
75%	12
95%	27

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: ST. PAUL, MINNESOTA

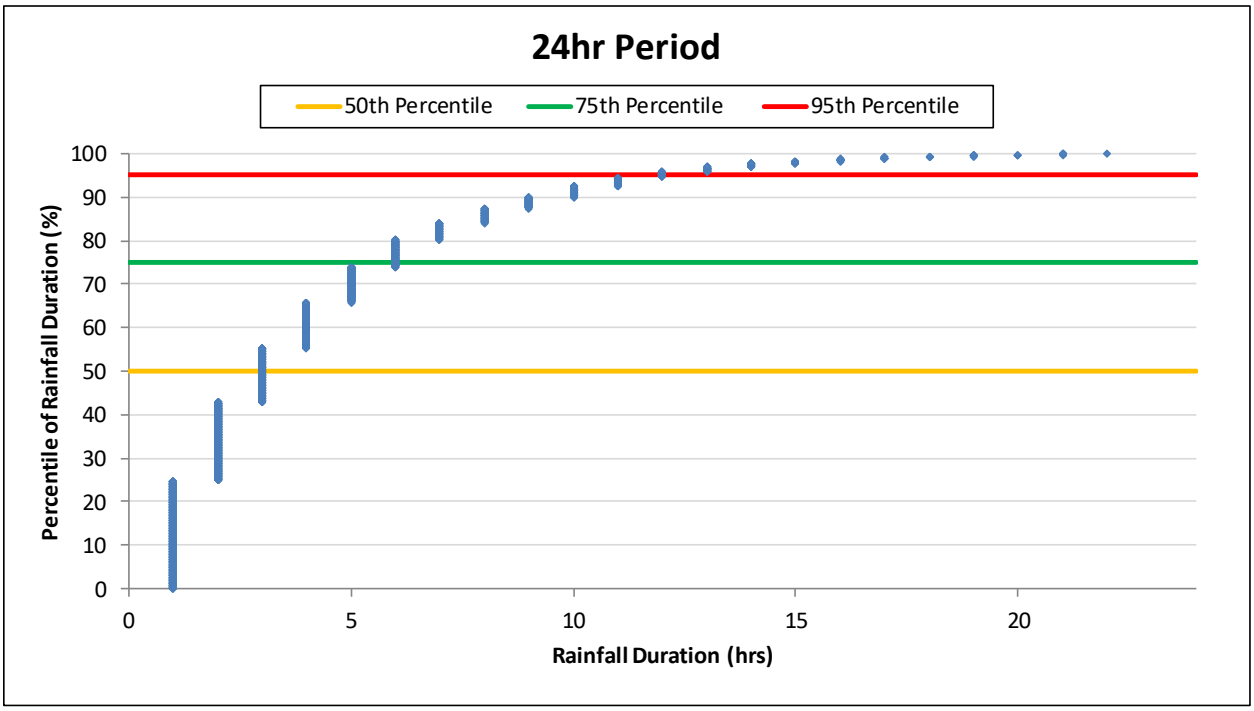

Figure A-39. St. Paul, Minnesota 24 hour period rainfall measurements.

Table A-39. St. Paul, Minnesota 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	22
Mean	4.2
SD	3.7
50%	3
75%	6
95%	12

*Maximum duration of rainfall in a given period.

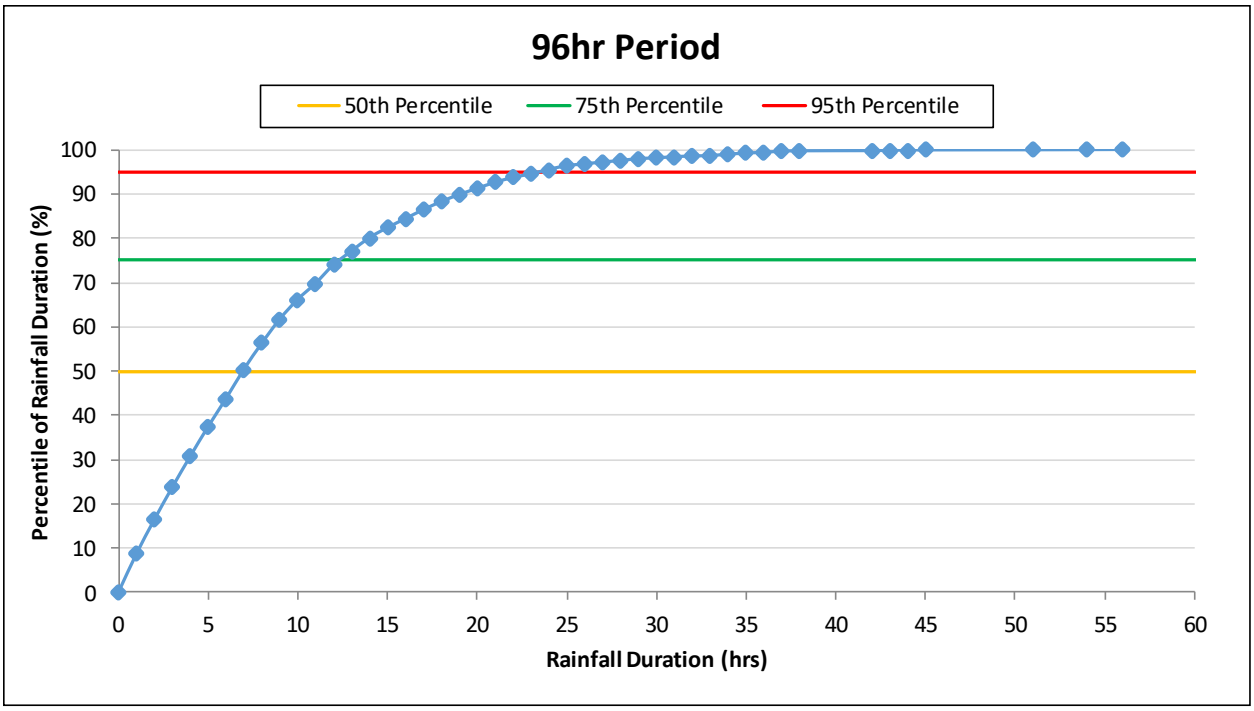

Figure A-40. St. Paul, Minnesota 96 hour period rainfall measurements.

Table A-40. St. Paul, Minnesota 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	57
Mean	9.0
SD	7.7
50%	7
75%	13
95%	24

*Maximum duration of rainfall in a given period.

RAINFALL MEASURMENTS: TUCSON, ARIZONA

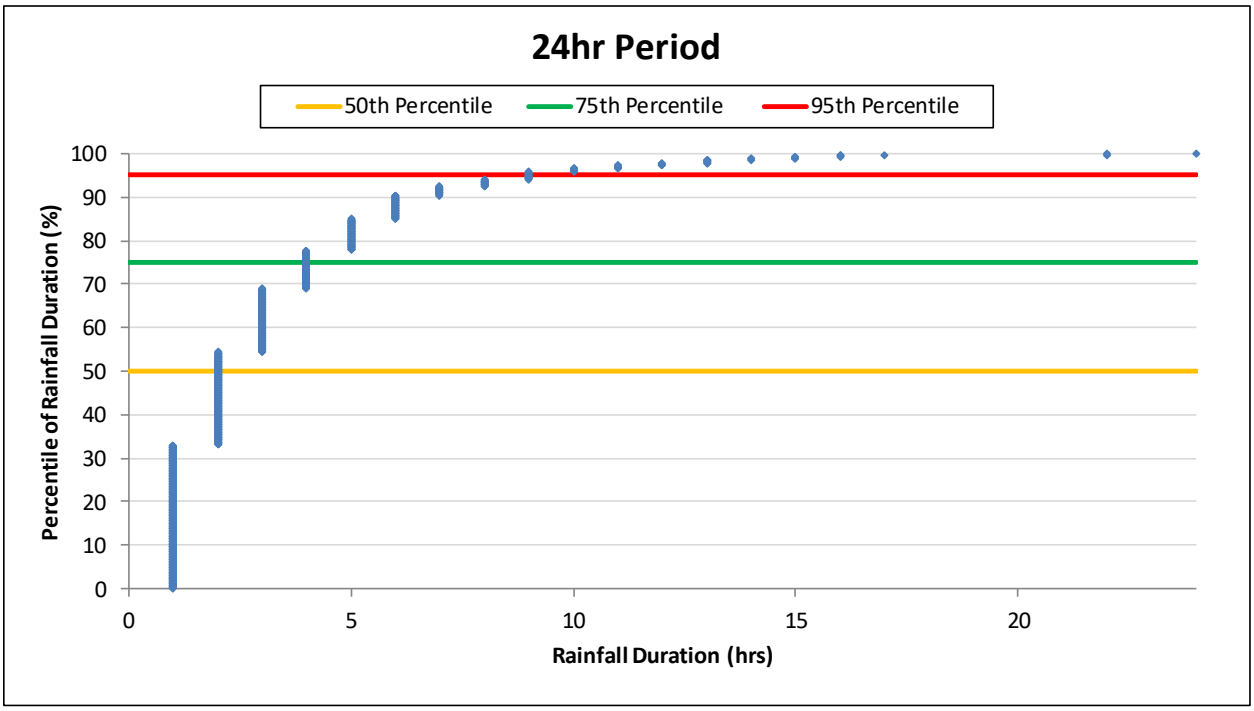

Figure A-41. Tucson, Arizona 24 hour period rainfall measurements.

Table A-41. Tucson, Arizona 24 hour period rainfall measurements.

24-hr Period	
Statistic	Pulse Duration (hrs)
Max*	24
Mean	3.2
SD	2.9
50%	2
75%	4
95%	9

*Maximum duration of rainfall in a given period.

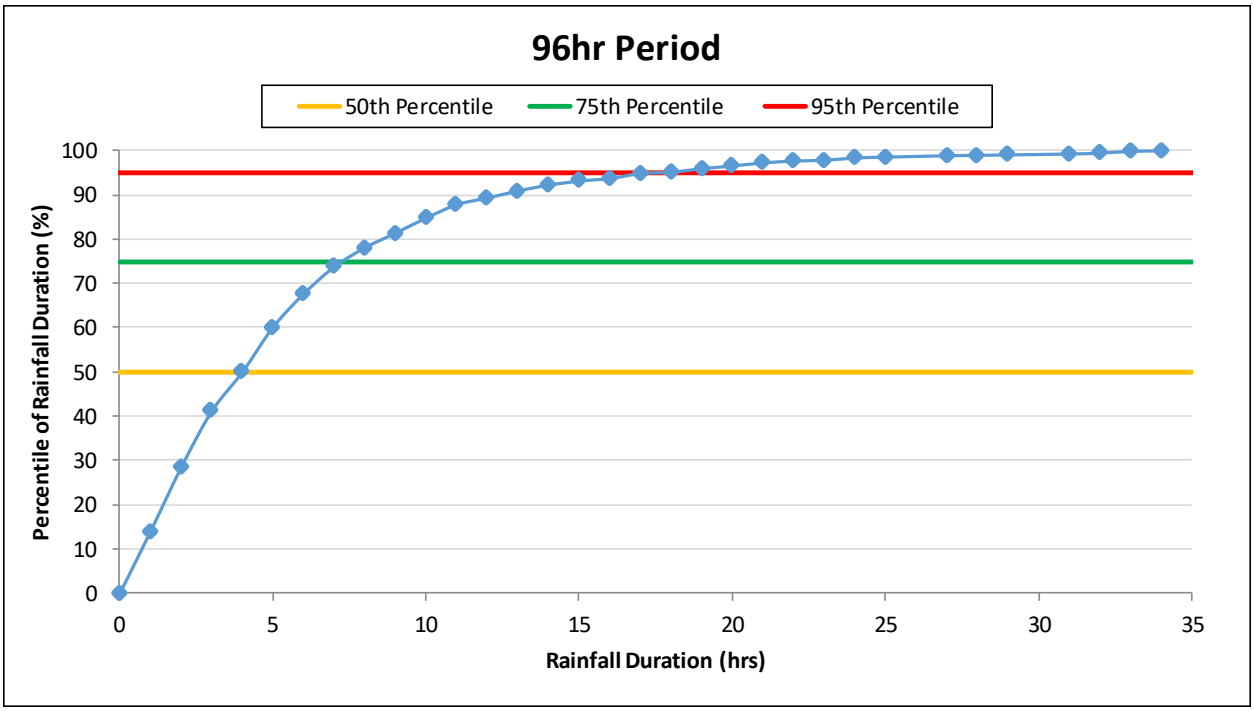

Figure A-42. Tucson, Arizona 96 hour period rainfall measurements.

Table A-42. Tucson, Arizona 96 hour period rainfall measurements.

96-hr Period	
Statistic	Pulse Duration (hrs)
Max*	34
Mean	6.1
SD	5.6
50%	4.5
75%	8
95%	18

*Maximum duration of rainfall in a given period.

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14. ABSTRACT

This document details analyses conducted on historical rainfall data at numerous locations across the United States in order to develop site-specific recommendations for exposure durations for laboratory toxicity testing specifically for assessment of stormwater discharges. If applied properly, a modification to generate more realistic exposure conditions for toxicity testing will still provide an appropriate level of protection, particularly given that the exposure at the end-of-pipe will be further reduced once it mixes in the receiving environment.

15. SUBJECT TERMS

rainfall analysis; whole effluent toxicity; national pollutant discharge elimination system

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