U.S. Department of Transportation
Federal Highway Administration
Office of Project Development and Environmental Review

Overview of Studies Characterizing Storm-Event Precipitation Statistics

By Gregory E. Granato

Appendix 3 *in*

Granato, G.E., 2010, Methods for development of planning-level estimates of stormflow at unmonitored sites in the conterminous United States: Washington, D.C., U.S. Department of Transportation, Federal Highway Administration, FHWA-HEP-09-005, 90 p. with CD-ROM

Prepared by the
U.S. Department of the Interior
U.S. Geological Survey
Northborough Massachusetts, 2010

Foreword

The mission of the Federal Highway Administration (FHWA) is to continually improve the quality of our Nation’s highway system and intermodal connections in a manner that protects and enhances the natural environment and communities affected by transportation. The FHWA must develop and disseminate research products that help FHWA and its partners implement surface transportation programs in a manner that protects and enhances the natural and human environment. More specifically, the Office of Office of Project Development and Environmental Review of the FHWA strives to develop and disseminate skills, tools, and information to redesign Federal environmental and transportation decisionmaking, and to ensure an integrated process at the Federal, State, tribal, and local levels. These tools, techniques and methods are designed to reduce direct and indirect adverse impacts of highways on water quality, habitat, and ecosystems to preserve and enhance human health, biological productivity, and ecological diversity.

This report, the associated computer applications, and data provide tools and techniques for developing planning-level estimates of stormflows at sites receiving highway runoff. This information is vital for assessing the potential for adverse effects of runoff on receiving waters throughout the Nation and it should provide transportation agencies with the tools and information to improve project delivery without compromising environmental protection.

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For more information on FHWA-USGS Runoff-Quality Studies:

World Wide Web: http://ma.water.usgs.gov/fhwa/
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Suggested citation

Granato, G.E., 2010, Overview of studies characterizing storm-event precipitation statistics--Appendix 3 in Granato, G.E., 2010, Methods for development of planning-level estimates of stormflow at unmonitored sites in the conterminous United States: Washington, D.C., U.S. Department of Transportation, Federal Highway Administration, FHWA-HEP-09-005, 90 p. with CD-ROM

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Introduction

The stochastic empirical loading and dilution model (SELDM) uses storm-event precipitation statistics to estimate storm-flow statistics for a highway-site of interest and the associated upstream basin. The average, standard deviation, and lower bound of precipitation statistics are used in SELDM to generate a random population of stormflow volumes. The precipitation statistics are the number of storm of events per year, the annual precipitation volume, the storm-event precipitation volumes, the storm-event durations, and the time between storm-event midpoints. Precipitation statistics are used with selected probability distributions to generate a random population of storm-events, which are coupled with a random population of runoff coefficients to estimate storm-flow volumes from the highway site of interest and the associated upstream basin. Conceptually, this approach is based on the assumption that the highway and the upstream basin will be affected by the same storm. This appendix is a brief review of the literature that describes methods for estimating precipitation statistics and related probability distributions that were considered for use in the SELDM development process.

Characterizing Storm-Event Precipitation Statistics

For more than 30 years, many researchers have examined methods for statistical characterization of the occurrence and properties of storm events. T**able 3-1** is a summary of information from 42 reports published during the period 1971-2006 that document approaches for quantifying precipitation-event statistics for various uses in hydrologic studies. In general, storm event arrivals are modeled as a Poisson process; individual storm events are modeled with right-skewed probability distributions; and storm-event hyetographs are modeled with various geometric shapes.

Table 3-1. Summary of studies characterizing storm-event precipitation statistics.

[Abbreviations: Heading: IET minimum interevent time; Avg. average; TBS time between storms; Scope: A annual; D daily; SE storm event. Time Step: Min. minutes. Statistical distributions for event characterization: B beta distribution; E one-parameter exponential; 2E two-parameter exponential; G two-parameter gamma; 3G three-parameter gamma; GM geometric; GP generalized Pareto; K four parameter Kappa distribution; L two-parameter lognormal; LEV log-extreme value; N Normal distribution; PIII Pearson type III (three-parameter gamma); R regression based cumulative distribution function; W Weibull. Comments: CV coefficient of variation; SD standard deviation; SK skew; K Kurtosis. USEPA United States Environmental Protection Agency.]

Reference	Site(s)	Time period	Number of sites	Event characterization									Comments
				Scope	Time step	IET	Volume	Duration	Intensity		TBS	Hyetograph	
									Avg.	Peak			
Adams and others, 1986	Canada	1957-1975	1	SE	Min.	1-6Hr	E,G	E,G	E,G	--	E,G	rectangular	Number of events and statistics depend on IET. Volume and duration are highly correlated. Use USEPA SYNOP program. Mean, SD, and SK provided.
Adams and Papa, 2000	Canada	1938-1983	30	SE	Hourly	1-12Hr	E,G	E,G	E,G	--	E,G	rectangular	Number of events and statistics depend on IET. Use exponential distribution as an approximation to facilitate analytical solutions for BMP planning models. Examine covariance. Mean provided.
Alexanderson, 1985	Sweden	1836-1982	2	SE	Hourly Daily	--	E	--	E	--	--	rectangular	Storm arrival is Poisson process. Mean and variance provided.
Asquith and others, 2006	NM OK, TX	1990-2005	774	SE	Hourly	6-72	K,PIII,E	K,PIII,E	--	--	E	triangular L-gamma	Storm arrival is Poisson process. IET influences statistics and choice of distribution. Mean, SD, and SK provided. L-moments and ratios provided. Moment diagrams indicate four-parameter-kappa distribution, but parameters not intuitive or manually tractable.
Bardsley, 1984	--	--	--	SE	--	--	E	--	--	--	E	--	Theoretical examination. Storm arrival is Poisson process.

Table 3-1. Summary of studies characterizing storm-event precipitation statistics (continued).

[Abbreviations: Heading: IET minimum interevent time; Avg. average; TBS time between storms; Scope: A annual; D daily; SE storm event. Time Step: Min. minutes. Statistical distributions for event characterization: B beta distribution; E one-parameter exponential; 2E two-parameter exponential; G two-parameter gamma; 3G three-parameter gamma; GM geometric; GP generalized Pareto; K four parameter Kappa distribution; L two-parameter lognormal; LEV log-extreme value; N Normal distribution; PIII Pearson type III (three-parameter gamma); R regression based cumulative distribution function; W Weibull. Comments: CV coefficient of variation; SD standard deviation; SK skew; K Kurtosis. USEPA United States Environmental Protection Agency.]

Reference	Site(s)	Time period	Number of sites	Event characterization									Comments
				Scope	Time step	IET	Volume	Duration	Intensity		TBS	Hyetograph	
									Avg.	Peak			
Bonta and Rao, 1998	OH	40yr record	3	SE	Min.	8-9 Hr	--	--	--	--	E	--	Storm arrival is Poisson process.
Cameron and others, 2000	England Scotland Wales	1949-1993	3	SE	Hourly	1Hr	E,GP G	E,GP G	E,GP G	--	E	rectangular	Storm arrival is Poisson process. Different models perform well. except for extreme events. Minimum event volume 0.1 mm Mean, and SD provided.
Chen and Adams, 2005	Canada	1963-1997	1	SE	Hourly	4 Hr	E	E	E	--	E	--	IET determines an event and affects event statistics. Exponential approximation used to facilitate analytical solutions. Mean provided.
Cowperwait and others, 1996	England	20yr record	27	SE	Hourly Daily	--	--	E	E,W	--	--	rectangular pulses	Mean, variance and covariance Provided.
Driscoll and others, 1979	USA	1948-1975	11	SE	Hourly	4-6 Hr	E,G	E,G	--	--	E	rectangular	Storm arrival is Poisson process. Choice of IET affects event statistics
Driscoll and others, 1989	USA	1949-1987	136	A,SE	Hourly	6 Hr	E,G	E,G	E,G	--	E,G	rectangular	Minimum event volume 0.1 inch for runoff producing event. Statistics depend on IET and minimum event volume. Use USEPA SYNOP program. National contour maps and 15 rain zones. Mean and CV provided.

Table 3-1. Summary of studies characterizing storm-event precipitation statistics (continued).

[Abbreviations: Heading: IET minimum interevent time; Avg. average; TBS time between storms; Scope: A annual; D daily; SE storm event. Time Step: Min. minutes. Statistical distributions for event characterization: B beta distribution; E one-parameter exponential; 2E two-parameter exponential; G two-parameter gamma; 3G three-parameter gamma; GM geometric; GP generalized Pareto; K four parameter Kappa distribution; L two-parameter lognormal; LEV log-extreme value; N Normal distribution; PIII Pearson type III (three-parameter gamma); R regression based cumulative distribution function; W Weibull. Comments: CV coefficient of variation; SD standard deviation; SK skew; K Kurtosis. USEPA United States Environmental Protection Agency.]

Reference	Site(s)	Time period	Number of sites	Event characterization									Comments
				Scope	Time step	IET	Volume	Duration	Intensity		TBS	Hyetograph	
									Avg.	Peak			
Driscoll and others, 1990a,b	USA	1949-1987	62	SE	Hourly	6 Hr	E,G	E,G	E,G	--	E,G	rectangular	1990 FHWA Model Minimum event volume 0.1 inch for runoff producing event. Use USEPA SYNOP program. 9 rain zones. Mean and CV provided.
Duckstein, And others, 1972	AZ, IL LA	--	3	SE	Min.	--	GM	--	--	--	--	--	Storm arrival is Poisson process. Areal precipitation volume has geometric distribution. Mean and variance provided.
Dunn, 2004	Australia	1882-1994	2	SE	--	--	G	--	--	--	--	--	Storm arrival is Poisson process. Shape and scale of gamma distribution provided.
Eagleson, 1978	MA, CA	1956-1965	3	SE	Hourly Daily	7 Hr	G	E	E	--	E	rectangular	Storm arrival is Poisson process. Mean and variance provided.
Eilers, 1991	--	--	--	SE	Hourly	--	G,L	G,L	G,L	--	G,L	--	Provides cumulative gamma function for storm-event analysis.
Goforth and others, 1983	GA	1948-1972	1	SE	Hourly	8 Hr (3-12)	E	E	E	--	E	--	Storm arrival is Poisson process. Mean and CV provided.
Gottschalk and Weingartner, 1998	Swiss	--	17	SE	Hourly	--	G	--	--	--	--	--	Shape and scale of gamma distribution provided.
Guo and Adams, 1998	Canada	--	1	SE	Hourly	6 Hr	E	E	E	--	E	rectangular	Storm arrival is Poisson process. Mean, SD, and SK provided.

Table 3-1. Summary of studies characterizing storm-event precipitation statistics (continued).

[Abbreviations: Heading: IET minimum interevent time; Avg. average; TBS time between storms; Scope: A annual; D daily; SE storm event. Time Step: Min. minutes. Statistical distributions for event characterization: B beta distribution; E one-parameter exponential; 2E two-parameter exponential; G two-parameter gamma; 3G three-parameter gamma; GM geometric; GP generalized Pareto; K four parameter Kappa distribution; L two-parameter lognormal; LEV log-extreme value; N Normal distribution; PIII Pearson type III (three-parameter gamma); R regression based cumulative distribution function; W Weibull. Comments: CV coefficient of variation; SD standard deviation; SK skew; K Kurtosis. USEPA United States Environmental Protection Agency.]

Reference	Site(s)	Time period	Number of sites	Event characterization									Comments
				Scope	Time step	IET	Volume	Duration	Intensity Avg.	Intensity Peak	TBS	Hyetograph	
Guo and Urbonas, 2002	AZ, CA CO, FL MA, OH	20-30Yr	7	SE	Hourly	6 Hr	E	--	--	--	--	rectangular	Storm arrival is Poisson process. Minimum event volume 0.1 inch Mean, SD, and SK provided.
Guttorp, 1988	NY, PA	1976-1982	2	SE	Hourly	12 Hr	2L,G 1E,W	--	--	--	--	--	Storm arrival is Poisson process. No correlation between TBS and duration. Mean and SD provided.
Harremos, 1988	Denmark	38 year record	1	SE	10 min.	--	L	--	L	L	--	--	Minimum event volume 0.3 mm Mean and SD provided.
Imhoff and Davis, 1983	NC,	1951-1981	76	Weeks	Weekly	--	G	--	--	--	--	--	Shape and scale of gamma distribution provided.
Ison and others, 1971	KS	1900-1966	3	Weeks	Daily	--	G	--	--	--	--	--	Storm arrival by Markov Chain Shape and scale of gamma distribution provided.
Kottegoda and others, 2000	Italy	--	3	SE	Daily	5 Days	G,E,2E	GM	--	--	--	--	Storm arrival by Markov Chain Shape and scale of gamma distribution provided.
Marien and Vandewiele, 1986	Belgium	1967-1980	1	SE	10 min.	10 min.	W	G	B	--	Mixed	triangular	Minimum event volume 0.4 mm Mean and SD provided.
Nguyen and Rousselle, 1981	Canada	32 year record	1	SE	Hourly	1 Hour	E	--	--	--	--	rectangular pulses	Storm arrival by Markov Chain Mean provided.

Table 3-1. Summary of studies characterizing storm-event precipitation statistics (continued).

[Abbreviations: Heading: IET minimum interevent time; Avg. average; TBS time between storms; Scope: A annual; D daily; SE storm event. Time Step: Min. minutes. Statistical distributions for event characterization: B beta distribution; E one-parameter exponential; 2E two-parameter exponential; G two-parameter gamma; 3G three-parameter gamma; GM geometric; GP generalized Pareto; K four parameter Kappa distribution; L two-parameter lognormal; LEV log-extreme value; N Normal distribution; PIII Pearson type III (three-parameter gamma); R regression based cumulative distribution function; W Weibull. Comments: CV coefficient of variation; SD standard deviation; SK skew; K Kurtosis. USEPA United States Environmental Protection Agency.]

Reference	Site(s)	Time period	Number of sites	Event characterization										Comments
				Scope	Time step	IET	Volume	Duration	Intensity		TBS	Hyetograph		
									Avg.	Peak				
Onof and others, 2000	England	--	3	SE	Hourly	0.5-24 hours	E,G	E,G	--	--	--	rectangular pulses		Storm arrival by various methods, Poisson model has fewest parameters Mean and SD provided.
Palecki and Others, 2005	USA	1972-2002	3,700	SE	15 min	6 Hr	R	R	R	R	--	--		Minimum event volume 0.1 inch Mean provided. Seasonal values but no annual values. 9 statistically determined rain zones. Trends in precipitation statistics detected.
Rao and Chenchayya, 1984	IN	--	2	SE	Hourly 10 min.	--	G,E	G,E,W	G	--	E,W	--		Explored regression and bivariate gamma distributions for storm volumes and durations; weak relationships exist. Mean, SD, SK, K, minimum and maximums provided.
Restrepo-Posada and Eagleson, 1982	Saudi-Arabia, Columbia Az, CA, NM, OH	5-27 yr	17	SE	Hourly	1-132 Hr	E	--	--	--	E	rectangular pulses		Storm arrival is Poisson process. Mean and SD provided.
Salvucci and Song, 2000	MA, CA	1948-1993	2	SE	Hourly	6-30 Hr	G	--	--	--	--	--		Storm arrival is Poisson process.
Strecker and others, 1989	USA	1949-	--	SE	Hourly	3-24 Hr	L	--	L	--	E,G	rectangular		Storm arrival is Poisson process. Storm statistics depend on IET and minimum event volume (compare 0.0 and 0.1 inch) Mean and COVs provided.

Table 3-1. Summary of studies characterizing storm-event precipitation statistics (continued).

[Abbreviations: Heading: IET minimum interevent time; Avg. average; TBS time between storms; Scope: A annual; D daily; SE storm event. Time Step: Min. minutes. Statistical distributions for event characterization: B beta distribution; E one-parameter exponential; 2E two-parameter exponential; G two-parameter gamma; 3G three-parameter gamma; GM geometric; GP generalized Pareto; K four parameter Kappa distribution; L two-parameter lognormal; LEV log-extreme value; N Normal distribution; PIII Pearson type III (three-parameter gamma); R regression based cumulative distribution function; W Weibull. Comments: CV coefficient of variation; SD standard deviation; SK skew; K Kurtosis. USEPA United States Environmental Protection Agency.]

Reference	Site(s)	Time period	Number of sites	Event characterization									Comments
				Scope	Time step	IET	Volume	Duration	Intensity		TBS	Hyetograph	
									Avg.	Peak			
Swift and Schreuder, 1981	NC	1936-1974	1	Day	Daily	--	3L,G, L,W,B	--	--	--	--	--	Median, shape, scale and maximum provided. Minimum event volume 0.5 mm
Tsakiris and Agrafiotis, 1988,	Greece	6 years	1	SE	Hourly	2 Hr	E,3G, 3L	--	--	--	E	--	Storm arrival is Poisson process. Mean volume and TBS provided.
Tucker and Bras, 2000	OR, GA	--	2	SE	Hourly	--	E	E	E	--	E	rectangular	Storm arrival is Poisson process. Mean provided.
Tucker, 2004	USA	--	76	SE	Hourly	--	--	E	E	--	E	rectangular	Storm arrival is Poisson process. Mean provided.
USEPA, 1986	USA	2-30 years	57	SE	Hourly	--	G	G	G	--	G	rectangular	Mean and COVs provided.
Werner and Kaldec, 2000	IL	20 years	1	SE	--	--	--	LEV	E	--	LEV	--	Mean provided.
Wu and others, 2006	Hong Kong China	1884-1990	1	SE	Hourly	--	L,G,E, N	L,G,E, N	--	--	G,L,E, N	various	Storm arrival is Poisson process. Provide Median, SD,SK, K L-moments and ratios.
Yen, 1993	IL, OH	--	2	SE	Hourly	--	--	--	--	--	G	--	Mean and COVs provided.
Zimmerman, 2006	Argentina	--	4	D	Daily	--	E	--	--	--	--	--	Storm arrival is Poisson or Erlang process. Mean and SD provided.

The Poisson process

Although various approaches are documented in these and many other reports on precipitation statistics, a common approach is to model the occurrence of precipitation events as a Poisson process. The Poisson process is a statistical description of the probability of occurrence of discrete, independent events on a continuous time-scale (Haan, 1977; Chow and others, 1988; Salas, 1993). A Poisson process is commonly used to define the occurrence of events and the number of storms per year (**table 3-1**). In a Poisson process the number of events is an integer, but the probability that an event will occur during a given time interval (the time between events) is continuous. The probability distribution of the number of events during a given time interval is the Poisson distribution. As the number of events in a given time period increases the Poisson distribution approximates a truncated histogram for a normal distribution with a standard deviation that equals the average number of events (Saucier, 2000). Application of statistics for the Poisson process has been used successfully for analysis of precipitation data from many sites with different climates that represent conditions found throughout the United States (**table 3-1**).

In a Poisson process the time between event arrivals is an exponential distribution. Many studies in the literature have modeled event arrivals as an exponential distribution and various event statistics with one or more right-skewed probability distributions (**table 3-1**). The standard deviation of the exponential distribution is equal to the mean, resulting in a COV of one (Haan, 1977; Chow and others, 1988). The right-skewed probability distributions that are commonly used to characterize storm-event statistics include various parameterizations of the exponential, gamma, generalized Pareto, lognormal, Pearson type 3, and Weibull distributions. These right-skewed probability distributions are used because they generally include only positive nonzero values and these distributions have a relatively large number of small values and relatively few extreme values. The properties of and parameters for these distributions are well defined, documented, and readily available in hydrological and statistical texts (for example: Haan, 1977; Chow and others, 1988; Stedinger and others, 1993; Saucier, 2000; National Institute of Science and Technology, 2004).

Probability Distributions for Modeling Storm-Event Statistics

A number of right-skewed probability distributions have been used to analyze and model storm-event statistics in the literature (**table 3-1**); each may be considered an approximation for characterizing the properties of local storm-event statistics. These distributions include the one-parameter exponential distribution, the two-parameter exponential distribution, the two-parameter lognormal distribution, the two-parameter gamma distribution, the Pearson type 3 distribution, the generalized Pareto distribution, and the Kappa distribution. Each distribution may be considered an approximation for characterizing the properties of local storm-event statistics. Different distributions have been selected based on available data and the purpose of the analysis. Selection of an approximate probability distribution is a balance between theoretical rigor (for example, Asquith and others, 2006) and practical and tractable estimation techniques that will be acceptable to practitioners, planners, and decision makers (U.S. Environmental Protection Agency, 1997).

Precipitation studies indicate that further work is needed to update available planning-level storm event statistics to provide greater geographic and temporal coverage for future work. Palecki and others (2005) used 15-minute precipitation data from 3,700 rain gage stations in the conterminous United States that were collected during the period 1972-2002 to develop seasonal precipitation-event statistics that include storm totals and storm durations for storms with a 6-hour minimum event time (**table 3-1**). Palecki and others (2005) interpreted statistics from each precipitation gage to identify 9 noncontiguous rain zones. However, they do not provide annual planning-level statistics, statistics for the time between storms, for the number of storms per year, or for individual site statistics. Asquith and others (2006) did a comprehensive statistical analysis of precipitation data collected during the 1990-2005 period at 774 rain-gage locations, but their study was limited to areas in New Mexico, Oklahoma, and Texas (**table 3-1**). Efforts of this magnitude and scope are needed to develop appropriate precipitation statistics for runoff-generating events throughout the United States because spatial variability and temporal trends limit the application of older analyses. Such a comprehensive analysis on a national scale, however, is beyond the scope of the current study.

Storm-Event Hyetographs

A hyetograph is defined as the temporal distribution of rainfall within a storm event (Yen and Chow, 1980; 1983; Chow and others, 1988). Highway, urban, and BMP studies commonly use a rectangular hyetograph to represent storm events for planning-level analysis because these studies are focused on results from complete events rather than within-event processes (Driscoll and others, 1979; Goforth and others, 1983; Adams and others, 1986; Driscoll, Shelley, and others, 1989; Strecker and others, 1989; Driscoll and others, 1990a; b; Adams and Papa, 2000). Use of a rectangular hyetograph provides an estimate of the average precipitation intensity during the storm as the quotient of total volume and total duration. In reality, storm-event hyetographs are highly variable and the average intensity will substantially under-represent the peak intensity. Therefore, this approach should not be used for hydraulic design of drainage structures. For example, the safety, hydraulic performance, and water-quality treatment of structural BMPs may be affected by within-storm variations in precipitation intensity and associated variations in runoff flows.

If within-event processes are important for runoff-event analysis or BMP design, then the triangular hyetograph provides a good first-order approximation for these purposes (Yen and Chow, 1980; 1983; Asquith and others, 2003). Yen and Chow (1983) examined a number of design hyetograph methods and developed a nondimensional triangular hyetograph by analyzing 293,946 storm events from 235 precipitation monitoring stations in the United States and determined that the triangular hyetograph serves as a first-order approximation for a design-storm concept. Yen and Chow (1983) also provided a National map of dimensionless time-to-peak ratios indicating that the time-to-peak ranges from about 25 percent of the storm duration in the southeast to 45 percent of the storm duration in the northwest. The time-to-peak is about 30 to 35 percent of the storm duration in most of the conterminous United States. Similarly, Asquith and others (2003) studied more than 1,600 storm events that produced runoff from 91 small watersheds in Texas. They found that the triangular dimensionless hyetograph, with times-to-peak ranging from 23 to 35 percent of the storm duration, is a good design approximation for within-event precipitation patterns. The USEPA tool for managing watershed modeling time-series data (WDMUtil) uses a triangular hyetograph to disaggregate daily precipitation into hourly data if data from available hourly precipitation-stations are not sufficient for watershed modeling (Hummel and others, 2001). The peak intensity of the triangular hyetograph is twice the average intensity, which is a better approximation of peak rainfall intensities than the average intensity provided by a rectangular hyetograph (Yen and Chow, 1983). For example, **figure 3-1** shows seasonal ratios of average 15-minute precipitation intensities to average storm intensities for 9 rain zones. The data in this figure was compiled by Palecki and others (2005) from 30 years of 15-minute data at 3,700 precipitation monitoring stations within the conterminous United States (**table 3-1**). These boxplots indicate that triangular hyetographs are a good first-order design approximation for storm-event characteristics because these peak intensities commonly are between 1.5 and 2.5 times the average storm intensities.

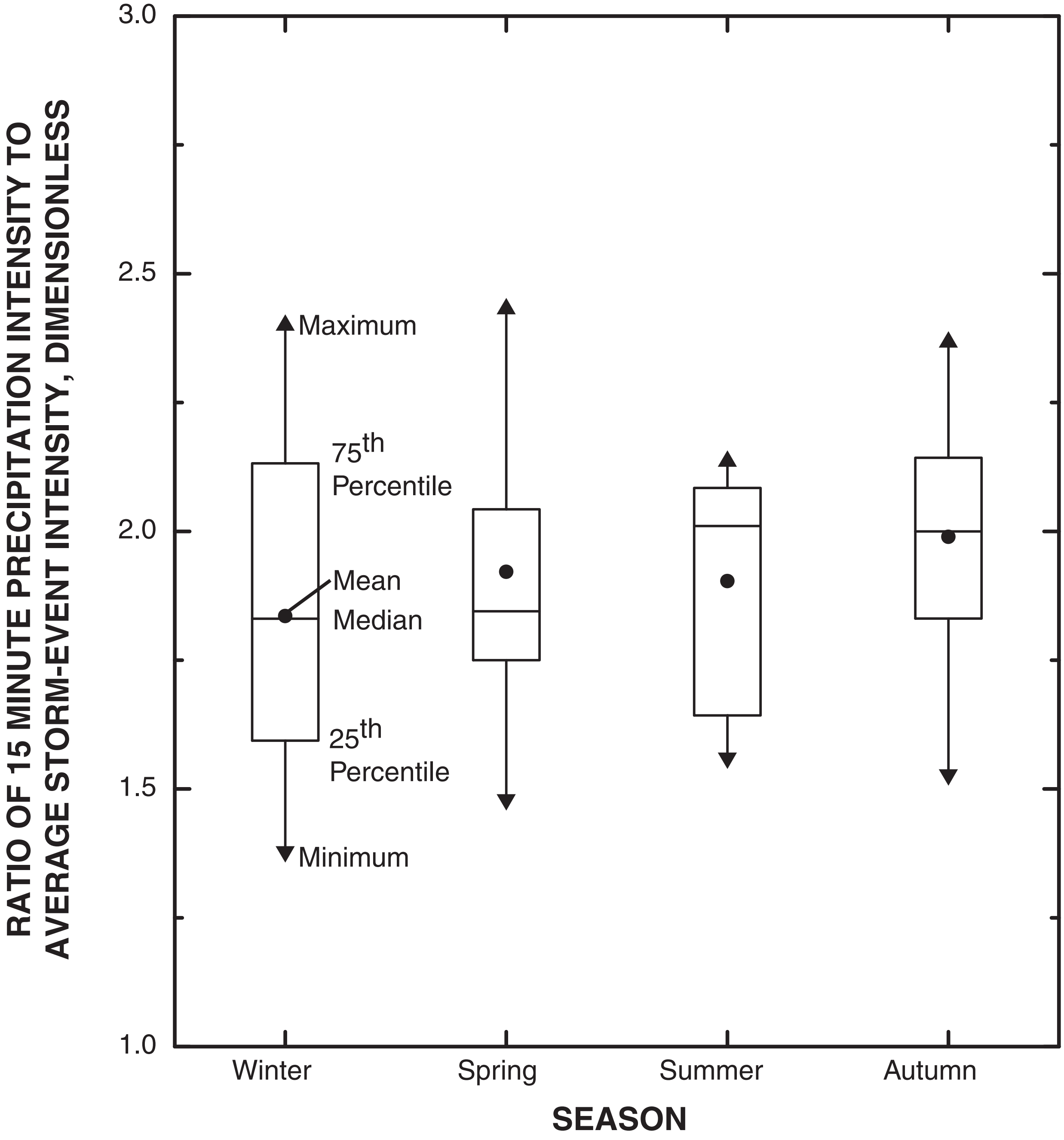

Figure 3-1. Ratio of maximum 15-minute precipitation intensity to the mean storm-event intensity (total storm volume divided by storm duration) indicating the potential sutability for use of the triangular hyetograph (Data from Palecki and others, 2005).

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