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ESTIMATING RUNOFF QUANTITIES FOR FLOW AND VOLUME-BASED BMP DESIGN

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ABSTRACT

In this paper linkage between local 1-hour rainfall data that are used in water quality Best Management Practices (BMP) design, and the rainfall statistics presented in the National Oceanographic Atmospheric Administration (NOAA) Atlas 14 (Bonnin, G.M., et al., 2004), which are used for flood control design is presented. The 50th, 85th and 95th –one-hour rainfall percentile values were correlated to NOAA Atlas 14, 2-yr 1-hour rainfall estimates. This simple to use analysis process can be used in quantifying runoff quantities for flow-based BMP design without conducting expensive hydrologic studies. It was also found that a correlation (better than 95%) between the volume-based BMP design value, P_6 statistic and the NOAA Atlas 14, 2-yr 1-hour rainfall estimates also exists, which greatly reduces BMP design hydrologic study costs.

Keywords – precipitation, runoff, decision support systems, flooding, BMP

INTRODUCTION

Improving storm runoff water quality for the most frequent storm events is an important goal for City, County and State Agencies because large concentrations of pollutants are typically found in runoff from small volume storms (which are typically the most frequently occurring type of event) and from the "first flush" of larger storms. Another goal is to develop simple-to-use analysis processes for use in quantifying the magnitude of runoff in any given area without conducting expensive hydrologic studies. In this research, conducted for the County of San Bernardino, California (Figure 1), such simple-to-use analysis procedures are examined and developed for use throughout the multiple hydrologic regions found in the County. San Bernardino County is the largest county in the contiguous 48 states (County of San Bernardino, 2004). It covers an area of 51,961 square kilometers (20,062 square miles) which is larger than the combined states of Connecticut, Delaware, New Jersey, and Rhode Island 39,671 sq km (15,317 sq mi). About 90% of the County is desert; the remainder consists of the San Bernardino Valley and the San Bernardino Mountains. San Bernardino County provides an ideal area to conduct this type of analysis because the County is made up of urbanized valleys (San Bernardino Valley), high steep mountains (Big Bear and Lake Arrowhead), and elevated desert regions (Mojave Desert), and therefore involves a variety of hydrologic conditions.

A key effort in this study is the development of a linkage between local 1-hour rainfall data that are used in stormwater Best Management Practices (BMP) design, and the rainfall statistics presented in the National Oceanographic Atmospheric Administration (NOAA) Atlas 14 (Bonnin, G.M., et al., 2004), which are used for flood control design. This approach could possibly be applied throughout the United States where NOAA has completed analyses similar to the Atlas 14, which was prepared for the southwestern United States (Bonnin, G.M., et al., 2004). In areas where no rainfall gauges exist, this study provides an approach for establishing a correlation between the NOAA Atlas information and the relevant rainfall statistics used for BMP design.

A BMP design criterion for management of stormwater from rainfall events is broken into two types; namely, volume-based and flow-based (CASQA, 2003). A volume-based BMP design calls for the capture and infiltration or treatment of a certain percentage of the runoff from the project site, usually in the range of the 75th to 85th percentile of average annual runoff volume. To maximize treatment, volume-based BMPs typically retain and then release the treated runoff between a 24 and 72-hour period. The California Stormwater BMP Handbook (CASQA, 2003), states volume-based BMP design standards apply to BMPs whose primary mode of pollutant removal depends on the volumetric capacity of the BMP and recommends a basin draw down time of 48 hours (CASQA, 2003).

The flow-based BMP design criteria calls for the capture and infiltration or treatment of runoff produced by rain events up to a maximum of 0.2 inches/hour. The flow rate is dependent on the type of soil and percentage of impervious area in the development. The California Stormwater BMP Handbook (CASQA, 2003), states flow-based BMP design standards apply to BMPs whose primary mode of pollutant removal depends on the rate of flow of runoff through the BMP. Examples may include swales, sand filters, and screening devices.

According to the California Stormwater BMP Handbook (CASQA, 2003), arbitrarily targeting large, infrequent storm events can potentially lead to a reduced pollutant removal capability of some BMPs. This occurs when BMP systems designed to accommodate usually large volumes and high flows are "over designed". This causes the smaller more frequent stormwaters to move quickly through the BMP and therefore do not receive adequate time for treatment. Based on this reasoning, methods are needed for calculating the stormwater runoff volumes used to design BMPs.

NOAA ATLAS 14 (BONNIN, G.M., ET AL., 2004)

NOAA Atlas 14 (Bonnin, G.M., et al., 2004) contains precipitation frequency estimates with associated confidence limits for the southwestern portion of the US. This is based on the analysis of annual maximum series data with the results converted to represent estimates based on partial duration series. An annual maximum series is constructed by taking the highest accumulated precipitation for a particular duration in each successive year of record. The calendar year is used for all data manipulation. Statistical analysis of the annual maximum series produces estimates of the average period between years when a particular value is equaled or exceeded (i.e., return frequency). Analysis of partial duration series gives the average period between cases of a particular magnitude. The two results are numerically similar at rarer average recurrence intervals but differ significantly at shorter average recurrence intervals, such as below 20 years (Bonnin, G.M., et al., 2004). Both annual maximum series and partial duration series were extracted at each observing station from quality-controlled datasets. To support the regional approach, potential hydrometerologic regions were selected. NOAA Atlas 14 carries its analysis further than NOAA Atlas 2 (Miller, J.F., et al., 1973) in that they provide confidence limits for the precipitation frequency estimates. Monte Carlo simulation was used to produce upper and lower bounds at the 90% confidence level.

NOAA Atlas 14 used the station mean annual maximum values to spatially interpolate the mean annual maximum, or "index flood" (Bonnin, G.M., et al., 2004). A hybrid statistical-geographic approach to mapping climate data was used for this interpolation. The technology was developed by Oregon State University's Spatial Climate Analysis Service (SCAS). SCAS developed PRISM (Parameter-elevation Regressions on Independent Slopes Model); PRISM spatially interpolated the Hydrometeorological Design Studies Center (HDSC)-calculated mean annual maximum values by using a naturally strong relationship with mean annual precipitation (Bonnin, G.M., et al., 2004). Mean annual precipitation was used as the predictor because it is based on a large dataset and accounts for spatial variation of climatic information and is consistent with methods used in the previous NOAA Atlas 2.

Of particular relevance in the NOAA Atlas 14, are the 2-yr 1-hour rainfall estimates, which typically envelop almost all of the 1-hour rainfall data collected at the rain gauge over the gauge's period of record. Additionally, the 2-yr 1-hour rainfall estimates are the most statistically stable of statistics developed by NOAA as this closely represents the median of the data.

STATISTICAL APPROACH

Rainfall data was collected from several sources including; NOAA (2004), County of San Bernardino (personal communication with Bill Raisner, December, 2004; Water Resources-Hydrology Section, San Bernardino County Flood Control District), and the California Irrigation Management Information System (CIMIS, 2004). A total of 655 rainfall gauges were identified within the study area (Table 1). Data consists of daily rainfall totals, hourly measurements, and 15-minute readings from 27 rainfall stations. Stations may record rainfall at a multitude of intervals (hourly, daily, and 15-

minute). For the purpose of this study, the hourly rainfall totals were used as the primary source of data for statistical analysis.

Data Verification and Filtering

Data were collected from these various sources and sorted into daily and hourly record sets. This database was further sorted to reflect the continuous nature of the data. Most rainfall measurements were recorded to the nearest hundredths of an inch (0.01 inch), with an occasional station recording to the nearest 0.10 inches. Several other anomalies within the database include "99999" values and cumulative storm values. The "99999" values represent questionable data or time frames for which the station was down. These values were filtered out of the datasets. Some cumulative storm values are rainfall totals associated with a single time interval, not necessarily hourly readings. These values were also filtered out of the dataset used for all statistics except for the P_6 statistical analysis (estimate of mean storm depth). The reason behind the elimination of these data is that the exact time of the rainfall and the associated magnitude is unclear.

Record Length Analysis

This study chose to use only stations that had 20 or more years of data, despite a large number of rainfall stations scattered throughout the County of San Bernardino. California Stormwater Quality Association (CASQA, 2003) chose to use stations of 15 or more years of data for their analysis for inclusion in the Stormwater BMP Handbook (CASQA, 2003). NOAA chose to use the more conservative 20 or more years of record threshold for their Atlas 14 statistical analysis (Bonnin, G.M., et al., 2004). A total of 90 stations were used for this statistical analysis.

Analysis of Yearly Maximum Hourly Readings

We statistically analyzed the yearly maximum hourly readings from San Bernardino County. Unlike the other analyses, only the 6 stations having the longest records (>20 years) were selected from the available 90. This analysis was done in order to test for sensitivity of statistical results in using data based on the water year (July 1 – June 30) (San Bernardino County water year) versus using data based on the standard calendar year (January 1 – December 31). The water year maximum hourly reading versus the calendar year maximum hourly readings for these 6 stations using the 50^{th} percentile values which correspond to the 2-yr 1-hour rainfall estimate are presented in Table 2. The 2-yr 1-hour rainfall estimates based upon calendar years do not significantly differ from similar estimates based on water years for record lengths of 20 years or greater.

COMPARISON OF 2-YR 1-HOUR ESTIMATES: NOAA VERSUS COUNTY DATA

A comparison was made of the 2-yr, 1 hour rainfalls estimates developed from use of the County data versus the NOAA Atlas 14 2-yr, 1-hour rainfall estimates (Figure 2). For this analysis, 30 of the 90 rainfall stations were used. These stations were selected at random throughout the County. From Figure 2, a close comparison exists between the NOAA and County data statistically.

Mean versus Median

In order to evaluate the distribution of the County 1-hr rainfall data, a comparison of the mean and median estimates of the yearly maximum rainfall data for a selection of 30 rainfall stations was conducted. From Figure 3, the considered mean and median are shown to be statistically comparable.

Sensitivity Analysis for Rainfall Intensity

Several stations were selected at random to analyze for the sensitivity of the cumulative frequency statistics due to the selection of a threshold value. Because use of threshold values is reported in the literature (Miller, J.F., et al., 1973; Bonnin, G.M., et al., 2004; and CASQA, 2003), the sensitivity of statistical estimates was considered in this study. Percentile plots for one representative rain gauge is shown in Figure 4; also shown are the corresponding percentile plots of one-hour rainfall values based upon use of the minimum threshold values of 0.01, 0.02, 0.03, 0.04, 0.05, 0.10, and 0.20 inches of rainfall. The observed variation is shift of the curves to the right (increased 1-hour rainfall values). This observation was seen in all subsequent analysis conducted.

The use of the 0.01 inch threshold value is customary for this type of analysis (Miller, J.F., et al., 1973; Bonnin, G.M., et al., 2004; and CASQA, 2003). Therefore, for all subsequent analysis, except P_6 calculations and statistics, the 0.01 inch threshold value is used (all values less than 0.01 were eliminated from the datasets).

Flow-based Methodology (Analysis of Percentile Ratios)

Hourly rainfall was organized by station with respect to percentile rank. The data were then normalized with respect to the 95^{th}-percentile value of each station. The resulting percentage ratios were then plotted as a normalized frequency graph (histogram). This established distribution curves for the 25, 50, 70, 75, 85, and 90^{th} percentiles. All graphs suggest a possible normal distribution. The 50^{th}-percentile was used to conduct further analysis to see if any regional patterns in data could be discerned. The 50^{th}-percentile graph corresponds to a resistant statistic (median) and therefore is not subject to effects in the changes of magnitude in the largest and smallest values.

Using the 50^{th}-percentile normalized frequency histogram, the data appear to be grouped into two separate subsets ($\Omega 1$ and $\Omega 2$); namely, those stations with 50^{th}-percentile versus 95^{th}-percentile ratios that followed an approximately normal distribution curve ($\Omega 1$), and those stations with 50^{th}-percentile versus 95^{th}-percentile ratios greater than 0.33 ($\Omega 2$) (Figure 5). The data in subset $\Omega 1$ were further subdivided. The mean and standard deviation of the $\Omega 1$ subset were calculated. This provided a mechanism for dividing the data into ranges of mean ± one standard deviation ($\mu \pm \sigma$).

Evidence for Correlation between Percentile Plots and Rainfall Data

Regional trends in the percentile ratios were examined by plotting the data onto a regional map according to the four ranges of percentile ratio values identified in the previous discussion (Figure 6). As seen in Figure 6, there exists some overlap; however, for the most part three distinct regions appear to fall according to well-known hydrometerologic regions namely; Valley, Mountain and Desert. These regional effects are also observed in the NOAA Atlas 14 (Bonnin, G.M., et al., 2004).

Justification for these regions can be further described by the homogeneity of the valley region in that almost all the stations fall in the range of values within one standard deviation of the mean. This is true except for four individual rainfall stations scattered throughout the valley region. These four stations are, however, completely surrounded by stations with the lower values. The Mountain and Desert regions are not homogenous but rather heterogeneous in that they have values representing all four ranges of percentile ratios.

Relationship of NOAA Atlas 14, 2-yr 1-hour Rainfall Estimates to Percentile Estimates

Using all the data versus NOAA Atlas 14, 2-yr 1-hour rainfall, it was found that nearly all the hourly rainfall data (99.6%) is less than that of NOAA Atlas 14, 2-yr 1-hour rainfall values. A linear correlation between various rainfall percentiles and NOAA Atlas 14, 2-yr 1-hour rainfall estimates was developed. Figure 7 shows this linear correlation for the 85^{th}-percentile for the Valley region. Standard deviation statistical plots were also constructed for the 50^{th}, 85^{th} and 95^{th}-percentile versus NOAA Atlas 14, 2-yr 1-hour rainfalls. These plots provided further evidence of a correlation between the datasets.

Regression Coefficient Determination

Based on the analysis of percentile values versus NOAA Atlas 14, 2-yr 1-hour rainfall, it was determined that upper confidence limits could be estimated. Table 3 provides regression coefficients as calculated for each region corresponding to the 50% and 85% upper confidence limits, where the linear relationship of Equation 1, is used.

$$Y = \alpha X \qquad [1]$$

where: Y = independent variable (50^{th} or 85^{th}-percentile value)
α = relevant regression coefficient as determined by this study for the 50^{th} or 85^{th}-upper confidence limit
X = NOAA Atlas 14, 2-yr 1-hour rainfall value

Observations Associated with Percentile Value Regression Analysis

Some observations associated with regression coefficient calculations are as follows:

i) The variability between target percentiles versus NOAA Atlas 14 2-yr 1-hour rainfall estimates is least for the valley region and greatest for the desert region. This potentially could be due to the relative number of rainfall stations. However, it should be noted that the desert region is observed to have a greater amount of rainfall variability than that of the valley region.

ii) As expected, the difference in magnitude between the 50^{th} and 85^{th}-upper confidence limit estimates increases in magnitude as the target rainfall percentile value increases from the 50^{th} to the 95^{th}-percentile.

Further analysis was conducted on the desert region to look at the impact of adding stations with 5 or more years versus rainfall stations with the previously considered stations that have 20 or more years of record. This analysis added an additional 34 rainfall stations to the original 15. Table 4 shows that a slight change in the regression coefficients occurred when the gauge record length was reduced to 5 years of rainfall data.

Volume-based Methodology (P_6 – Mean Storm Precipitation Volume)

The P_6 statistic is useful in describing the mean storm precipitation volume (Driscoll, E.D., et. al., 1986). The P_6 value is used as a basis for calculating stormwater capture volumes (ASCE and WEF, 1998). P_6 values were defined as discrete rain events separated by a dry (no rainfall) period of a minimum of 6 hours. In this study, P_6 values were calculated based upon the inclusion of cumulative event records and another analysis was made by excluding these cumulative event records. Cumulative event records are defined as events that are recorded over an extended period of time (not hourly) but are given a total rainfall accumulation for the period of record. The reason for running calculations for both inclusion and exclusion of these data is that these data cannot be defined for a specific rain event.

Possible errors could be introduced into the P_6 calculation based upon the inclusion of the cumulated storm event data. This is due to the unknown storm duration or the potential for multiple storms within the timeframe of the subject event. Since only total accumulation is known and the exact time of this event(s) or the nature of this event(s) are unknown, it is difficult to include these events.

Based on these discrete events separated by a dry inter-event period, calculations of rainfall (storm) totals were made. Small rainfall events, defined as events whose depth was less than or equal to 0.10 inches, were deleted from the record as such events tend to produce little if any runoff (CASQA, 2003). Then, the remaining storm rainfall totals were averaged, producing the P_6 value.

Sensitivity Test for P_6 Values with and Without Cumulative Event Records

A comparative analysis of estimated P_6 values (including or excluding the subject cumulative event data) to those of published values in the California Stormwater BMP Handbook, Appendix D (CASQA, 2003), can be made. The results of the two P_6 analyses are shown in Table 5. The first is a calculation of P_6 without cumulative event records and the second is the inclusion of such data.

Calculations made with the included cumulated storm data provided the closer fit to the published calculations. Thus, for this study's P_6 analysis, we included the cumulative storm data.

Regression Coefficients for P_6 Statistic

For each of the subject 90 rainfall stations, regressions of P_6 versus NOAA Atlas 14, 2-yr 1-hour rainfall estimates were made. This was accomplished for all stations on a hydrologic region basis, using the same relationship of Equation 1, and associated upper confidence limit estimation (Figure 8).

From Table 6, the P_6 regression coefficients are highest in the Mountain region and lowest in the Desert region. This can be attributed to a higher storm totals typically observed in the Mountains.

Application: Comparison of Volume Based BMP Design Runoff Estimates

Volume-based BMP design, according to the California Stormwater BMP Handbook (CASQA, 2003), is based upon two different approaches to calculating required runoff volumes. These are the California Stormwater BMP Handbook Approach (CASQA, 2003) and the Urban Runoff Quality Management Approach (ASCE and WEF, *and references therein*, 1998). The California Stormwater BMP Handbook approach is based on results from a continuous simulation computer model, such as the computer program STORM, developed by the Hydrologic Engineering Center of the US Corps of Engineers. Normalized curves were developed for use in localities that are considered hydrometeorologically similar to the rain gauges where such analyses were conducted. Use of theses curves consists of identifying the BMP tributary drainage area, a composite runoff coefficient and a desired drawdown time (either 24 or 48 hours). A 48-hour drawdown time is recommended, with caution given to BMP designs of greater than 48-hours (CASQA, 2003).

The Urban Runoff Quality Management Approach (ASCE and WEF, *and references therein*, 1998) is similar to the California Stormwater BMP Handbook (CASQA, 2003) approach in that it is based on the translation of rainfall to runoff. This approach is based on two regression equations. The first is a regression equation that relates rainfall to runoff, whereas, the second regression equation relates mean annual runoff-producing rainfall depths to the "Maximum Water Quality Capture Volume" that corresponds to the so-called "knee of the cumulative probability curve". The Maximized Water Quality Capture Volume corresponds to the approximate 85th-percentile runoff event, and ranges typically from 82% to 88% (CASQA, 2003). This "knee of the curve" maybe somewhat subjective in determination and thus may lead to difficulties in its interpretation. (Note: Design criteria for water quality control BMPs are set to coincide with the "knee of the curve", that is, the point of inflection where the magnitude of the event increases rapidly as compared to the number of events captured (CASQA, 2003).)

The two regression equations (Equation 2 and 3) that form the Urban Runoff Quality Management Approach are as follows (CASQA, 2003):

$$C = 0.858i^3 - 0.78i^2 + 0.774i + 0.04 \qquad [2]$$

where: C = runoff coefficient; and
i = watershed imperviousness ratio which is equal to the percent total imperviousness divided by 100
and

$$P_0 = (a \cdot C) \cdot P_6 \qquad [3]$$

where: P_0 = Maximized Detention Volume, in watershed inches
a = regression constant from least-squares analysis; where a = 1.582
and a = 1.963 for 24 and 48 hour draw down,
C = runoff coefficient; and
P_6 = mean storm precipitation volume, watershed (inches)

Based on Equation 3, and the calculated P_6 values from this study, a comparison of P_0 values was made and compared to relevant percent capture curves found in the California Stormwater BMP Handbook, Appendix D (CASQA, 2003). Table 7 shows the P_0 calculations for both the 24 and 48 hour drawdown based on the published P_6 value in the California Stormwater BMP Handbook (CASQA, 2003), for the Victorville Pump Station (9325). Table 8 shows the same calculation for Victorville Pump Station (9325) using this study's calculated P_6 value for the same drawdown times.

Figure 9 illustrates that after plotting these storage volumes on the percentile curves for percent capture versus storage volume for the same Victorville Pump Plant (9325) and rainfall station (CASQA, 2003), the values estimated using this study's procedures are near the 90% runoff capture threshold. Since the ranges for these calculations are typically between 82% and 88%, which corresponds to approximately the 85th-percentile runoff event, this study's approach appears to be slightly conservative.

Since the "knee of the curve" analysis appears to be difficult to determine for some volume-based curves and this study's method of using P_6 values is easy-to-use and produces reproducible results, use of the P_6 method may avoid conflicts in interpretation of the "knee of the curve", among other issues.

Furthermore, calibration of this P_6 value to the existing volume curves could be addressed through a simple coefficient multiplier (i.e., 0.95) to better match the "knee of the curve" values. Evaluations of such an arbitrary coefficient are a policy statement of the regulatory agencies that should include the inherent uncertainties of the available sampling rainfall data.

Finally, the above P_6 approach appears to be slightly conservative in estimating the relevant runoff volumes, which corresponds to about a 3% impact on holding pond dimensions, and less than about 3% in costs.

CONCLUSION

Based on the statistical analysis presented in this paper for calculating rainfall runoff volumes and flow rates for use in BMP design, it is seen that a simple approach can be developed that is an efficient alternative to the use of costly hydrologic modeling such as continuous computer simulation. It is shown that one can correlate 1-hour rainfall data trends that are used for stormwater BMP design to the standard well-known NOAA Atlas 14, 2-yr 1-hour rainfall estimates. A web-based interactive map, combining both the NOAA Atlas 14 rainfall estimates and the calculated regression coefficients is being developed for the County. With the use of the regression coefficients developed herein for the County of San Bernardino, California and the NOAA Atlas rainfall statistics, one can quickly calculate the quantity of runoff for use in flow or volume-based BMP design and therefore, the BMP design size, without the aid of conducting a costly hydrologic model.

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NOTE

The views expressed herein are those of the author and do not purport to reflect the position of the United States Military Academy, The Department of the Army, or the Department of Defense.

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FIGURES AND TABLES

Total Number of rainfall stations	Total number of daily stations	Total number of hourly stations	Total number of 15 minute stations	Total number of hourly stations used in study
655	544	227	27	90

Table 1. General Rainfall Station Information, San Bernardino County, Ca.

Station ID	Calendar Year	Water Year
NCDC 41272	0.393	0.377
NCDC 42164	0.727	0.695
NCDC 42255	0.294	0.298
NCDC 44297	0.416	0.406
NCDC 45218	0.771	0.758
NCDC 45632	0.711	0.674

Table 2. Values of 50th Percentile of Annual Maxima (2-yr 1-hour estimates).

Statistic	**Valley** 50% (85%) upper confidence limit	**Mountain** 50% (85%) upper confidence limit	**Desert** 50% (85%) upper confidence limit
50th-percentile	0.0978 (0.1071)	0.1208 (0.1250)	0.1523 (0. 2143)
85th-percentile	0.2583 (0.2787)	0.3002 (0.3614)	0.2647 (0.3250)
95th-percentile	0.4198 (0.4590)	0.4788 (0.5618)	0.4504 (0.6452)

Table 3. Regression Coefficients for Rainfall Percentile Estimates.

Statistic	**Desert (20 or more years of record)** 50% (85%) upper confidence limit	**Desert (5 or more years of record)** 50% (85%) upper confidence limit
50th-percentile	0.1523 (0. 2143)	0.1223 (0.1860)
85th-percentile	0.2647 (0.3250)	0.2623 (0.3250)
95th-percentile	0.4504 (0.6452)	0.4660 (0.6285)

Table 4. Desert Region Regression Coefficients for Rainfall Percentile Estimates.

Station ID	Station Name	California Stormwater BMP Handbook, Appendix D; P_6	Calculated P_6 without cumulative event records	Calculated P_6 with cumulative event records
47473	Riverside Citrus	0.50	0.53	0.52
49325	Victorville Pump	0.47	0.45	0.46

Table 5. P_6 Comparative Analysis

Statistic	**Valley** 50% (85%) upper confidence limit	**Mountain** 50% (85%) upper confidence limit	**Desert** 50% (85%) upper confidence limit
P_6	1.3169 (1.4807)	1.6209 (1.9090)	0.9658 (1.2371)

Table 6. Regression Coefficients for P_6.

Drawdown	C = 0.25	C = 0.50	C = 0.75	C = 1.00
24 hours	0.185	0.372	0.578	0.743
48 hours	0.231	0.461	0.692	0.923

Table 7. Maximized Detention Volume, based on Published $P_6 = 0.47$

Drawdown	C = 0.25	C = 0.50	C = 0.75	C = 1.00
24 hours	0.182	0.364	0.546	0.723
48 hours	0.226	0.451	0.677	0.903

Table 8. Maximized Detention Volume, based on this study's Calculated $P_6 = 0.46$

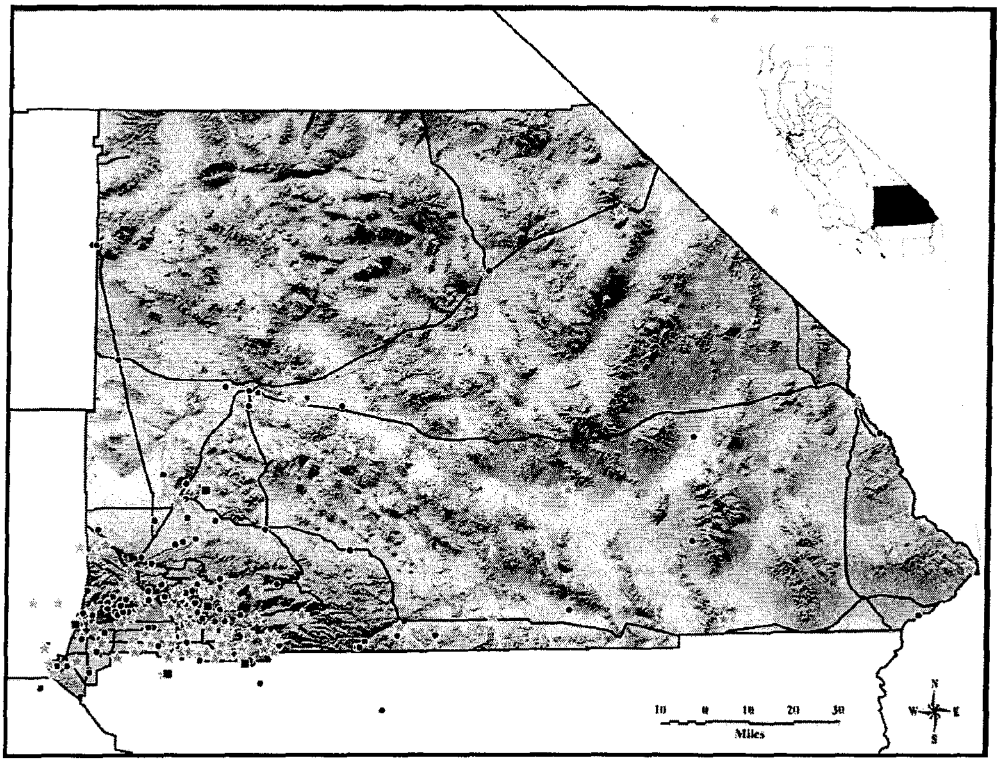

Figure 1. Locations of hourly stations: • = station with less than 15 years of data; ■ = station with between 15 and 20 years of data; ★ = station with greater than 20 years of data.

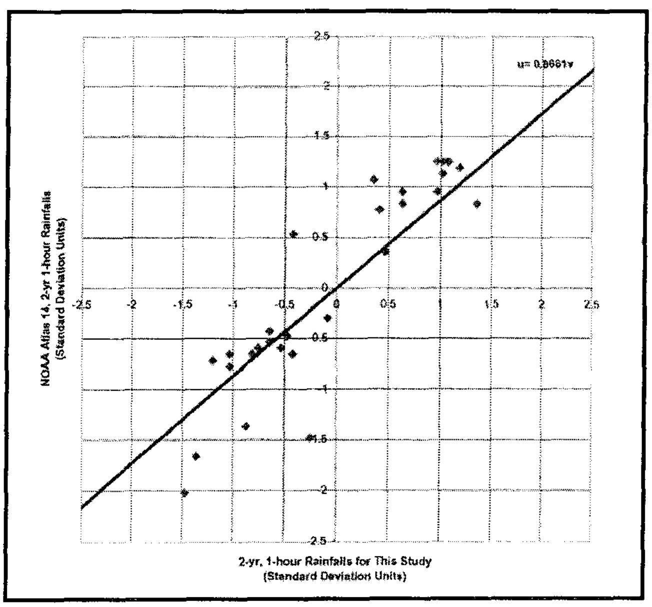

Figure 2. Comparison of 2-yr, 1-hour rainfalls using standard deviation units.

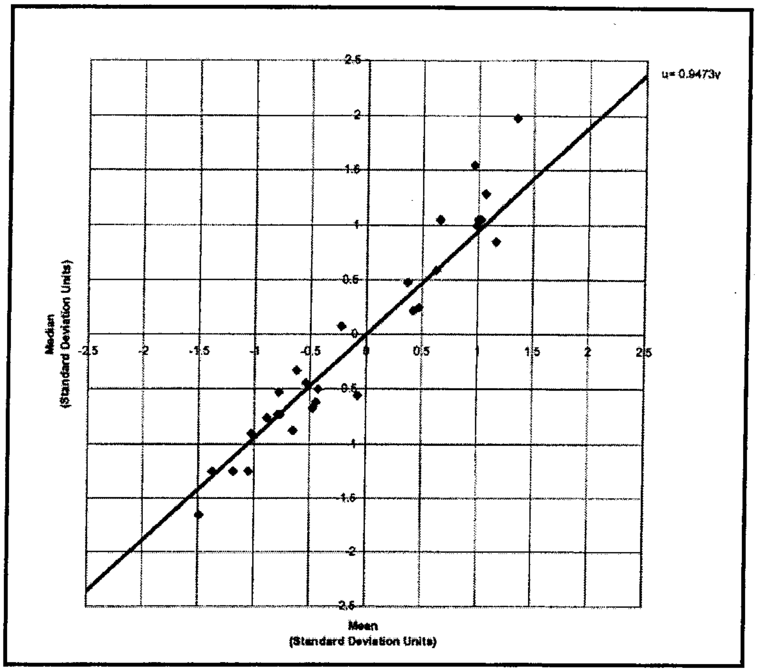

Figure 3. Comparison of mean vs. median 2-yr, 1-hour rainfalls (this study) using standard deviation units.

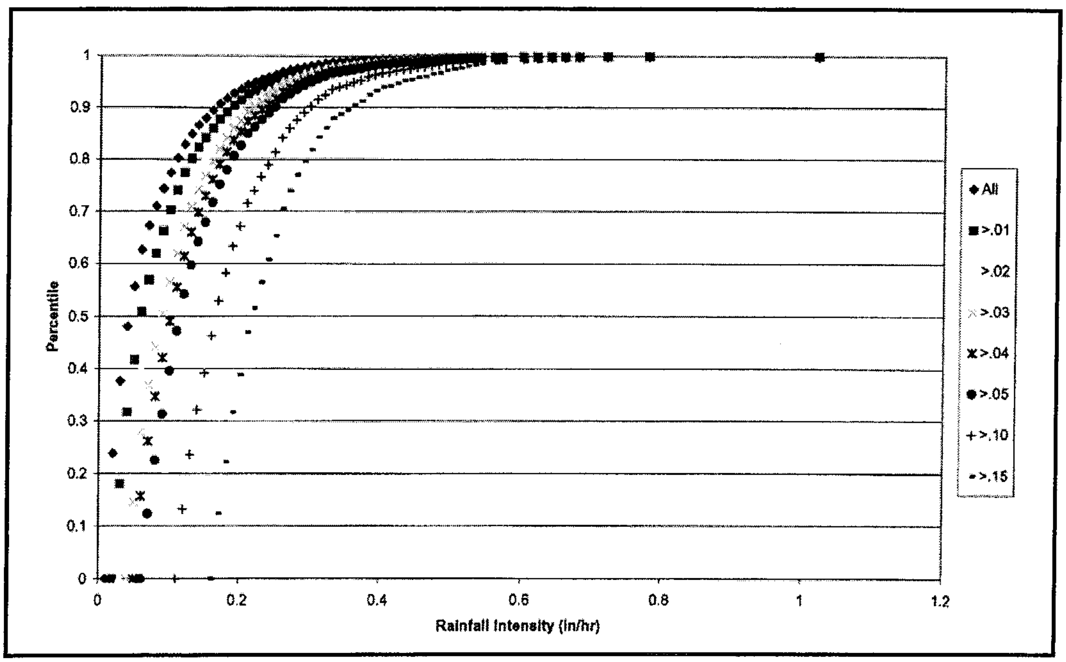

Figure 4. Rainfall threshold analysis NCDC 45212 - Lytle Creek Foothill.

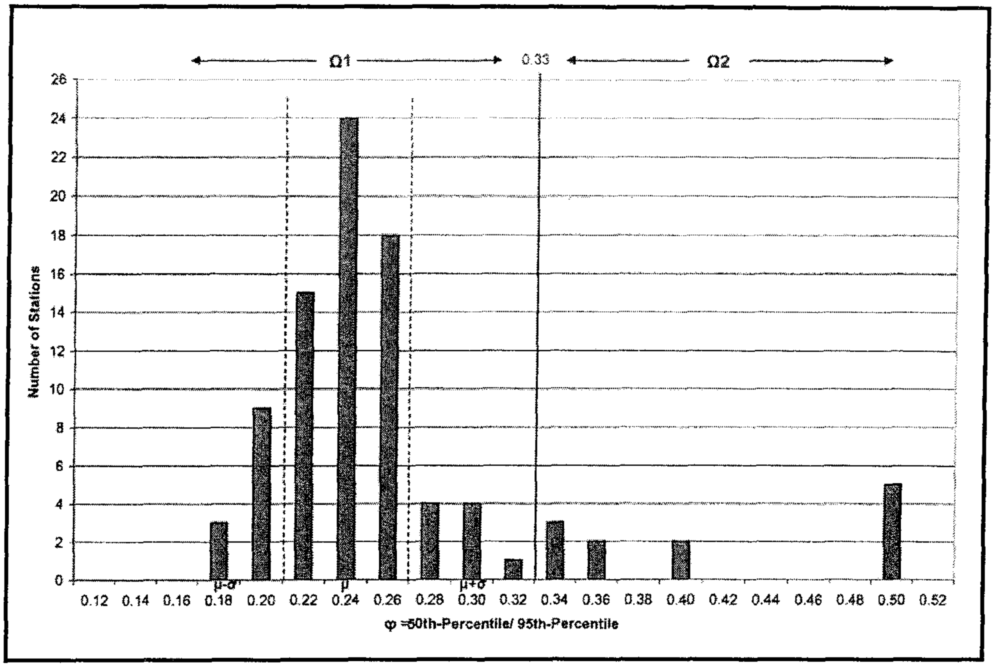

Figure 5. Definition of two ranges (Ω1, Ω2) in values of normalized 50th-percentile.

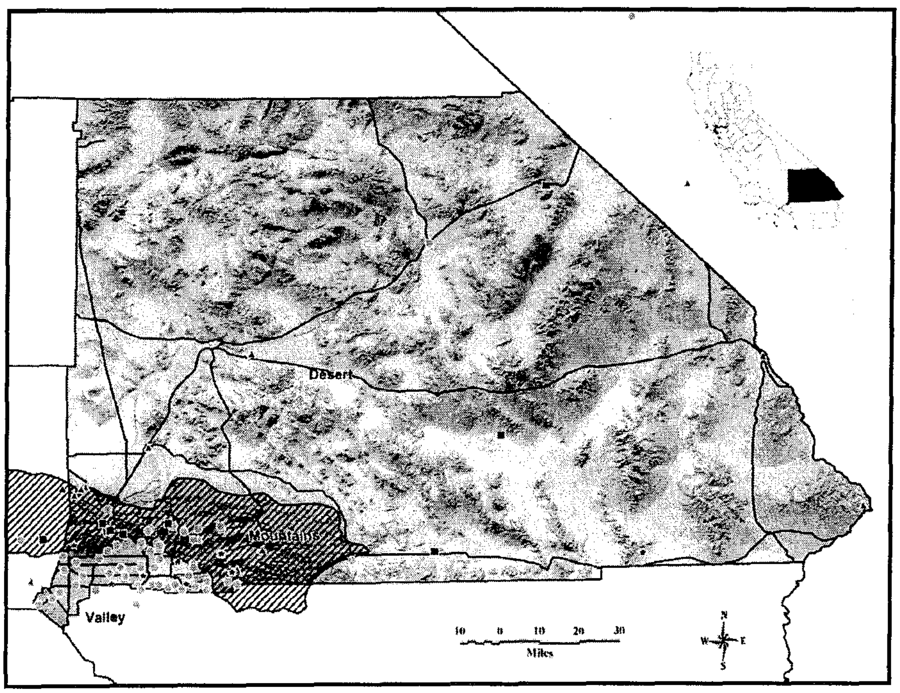

Figure 6. Location of stations analyzed for 50th-percentile / 95th-percentile: ■ = $0 < \xi \mu\text{-}\sigma$; ● = $\mu\text{-}\sigma \leq \xi < \mu+\sigma$; ★= $\mu+\sigma \leq \xi < 0.33$; ▲ = $\xi \geq 0.33$

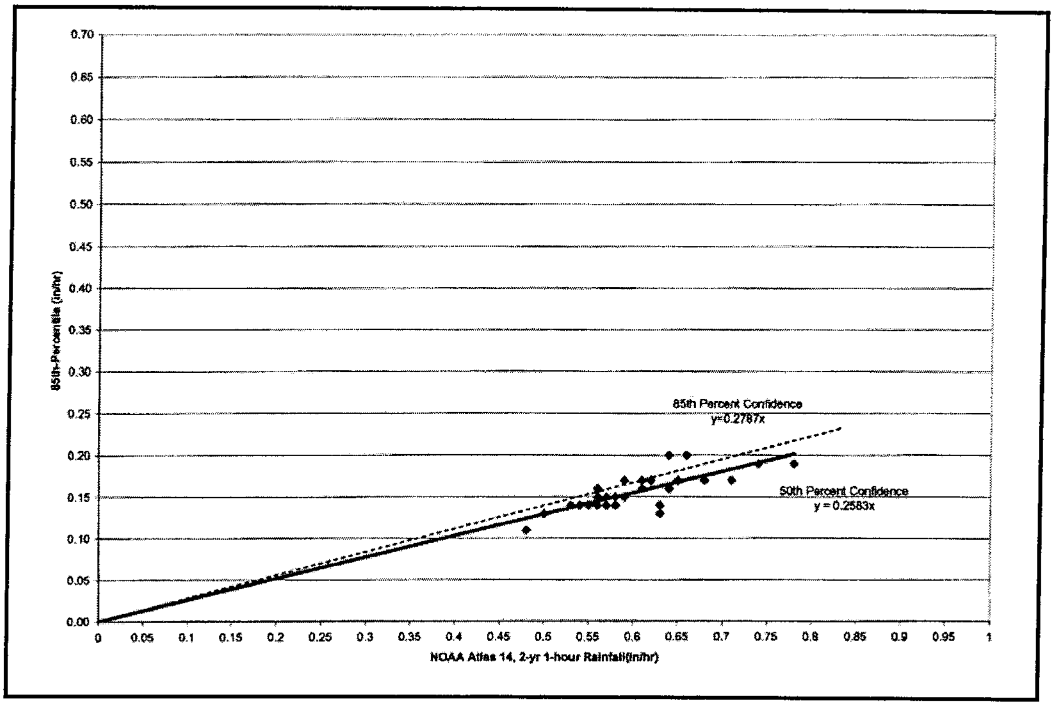

Figure 7. 85th-Percentile vs. NOAA Atlas 14, 2-yr, 1-hour rainfalls - Valley Region.

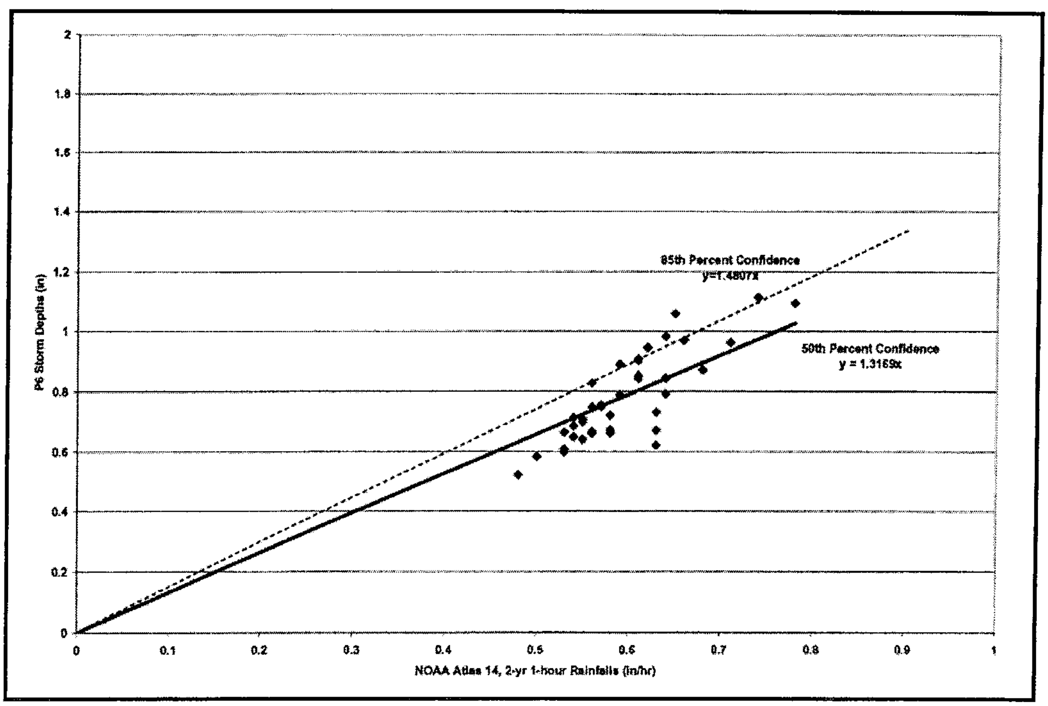

Figure 8. P6 vs. NOAA Atlas 14, 2-yr, 1-hour rainfalls - Valley Region.

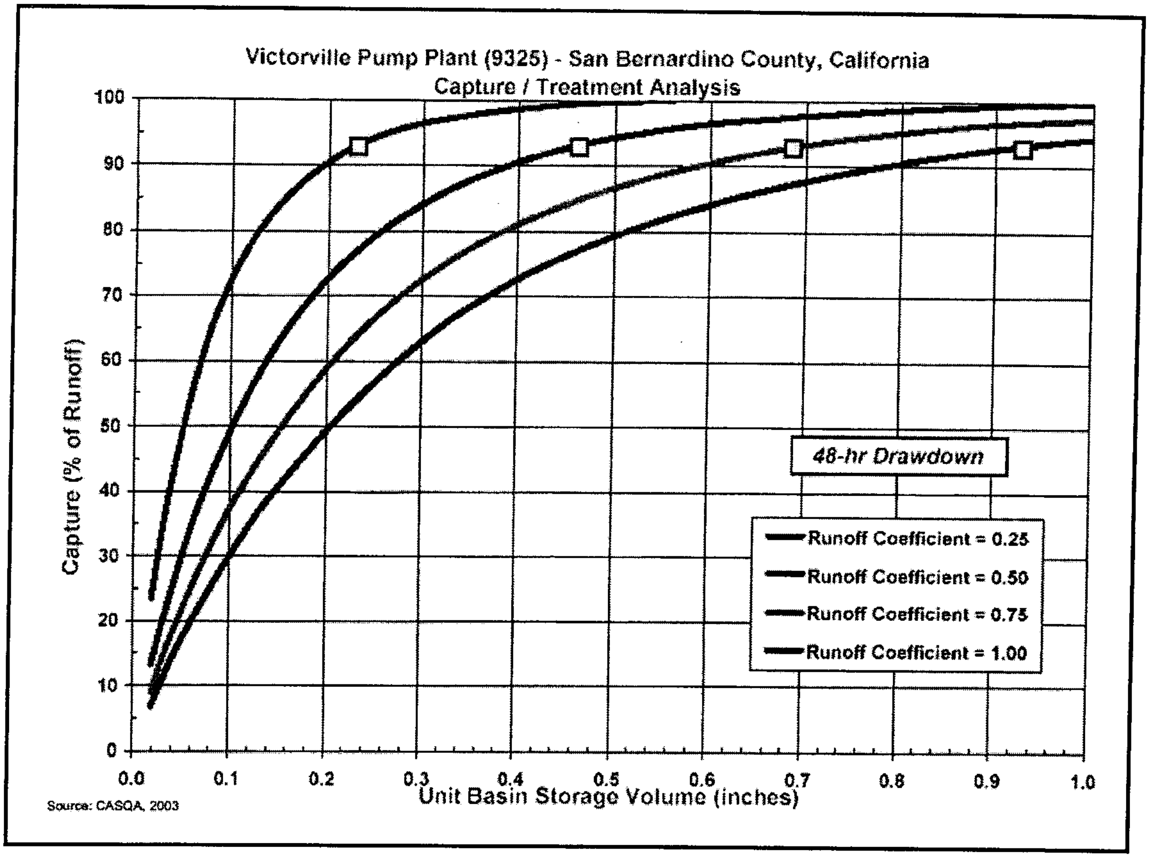

Figure 9. Victorville Pump Plant (9325) - San Bernardino County, California capture/treatment analysis: ▪ = P_6 method calculations.