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1. INTRODUCTION

Often "storms" must be identified in a set of historic data for purposes such as intensity-duration-frequency analysis, rainfall-erosivity factors for erosion estimation, structure design, etc. Many times a storm is identified by assigning a fixed dry time between bursts of rainfall for the entire record. Any dry-period duration less than this assigned duration is included in a storm, and those durations greater than the one assigned separate storms on average. However, it is known that this dry time between storms varies due to a variety of factors. Furthermore, storms identified by using a fixed time between storms do not necessarily produce storm events that are statistically independent.

The minimum dry time between storms (critical dry-period duration,"CD") can be found by using an iterative procedure that determines CD when time-between storm data fit an exponential distribution (Restrepo and Eagleson, 1982, "RE method"). A CD found in this manner accounts for climate and local factors that affect its determination. Site-dependent CD values are needed for the storm generator developed by Bonta (2001), and is the principal reason for this study. Consequently, generalized relationships between CD and other variables with readily available data are needed. One promising source of data are the 4-km^2 values of average monthly and average annual precipitation estimates available from the PRISM model (Daly et al., 1993).

The objectives of this study are to examine the variation of critical duration due to season, climate, region, and elevation of selected rain gauges in arid to humid climates, and to investigate estimation procedures for computing critical duration over large areas and climates of the US. This is an exploratory study using statistical characteristics of data and it does not include storm-physics information.

2. PROCEDURE

2.1 Approach

The approach used was statistical and exploratory. Rain gauges representative of different regions, elevations, climate, and seasonal distributions were subjected to the RE method to determine the CD for each gauge and month, and on annual data sets. Exploratory plots were made of monthly and annual CD versus month to examine seasonal, climate, and regional variations, and against elevations to examine the effect of elevation. Many combinations of variables were examined but are not reported. Attention was given to those variables readily available (e.g., elevation). Monthly values of CD and precipitation were used to examine "seasons". Due to possible biased values in the procedure, November and December values were omitted in this study for monthly values but are included for annual CD values. Only visual comparisons were made.

2.2 Generalized Estimation Equation

Using the results of the exploratory plots above, the data were subjected to linear regression analysis of the logarithms of variables found to be important. Residuals and r^2 values were computed for 10 rain gauges used in the developmental step, expressed as percent errors about the regression line. Monthly CD values were computed for one gauge at each of the three sites using the final regression equation (Table 1). Each of these three gauges were not used in developing the regression equation. The estimated and measured values were compared from these three gauges.

2.3 Data Used

Break-point precipitation data were selected from 13 rain gauges in three USDA-Agricultural Research Service experimental watersheds located in Ohio, Arizona, and Idaho (Table 1). The gauges were selected to represent the range in gauge elevation, and seasonal and annual precipitation at each site. All gauges were used to examine characteristics of the data, ten gauges were used for analysis, and one at each site was used for verification of the estimation procedure. Idaho data were measured at elevations ranging from 1188 m sld to 2147 m sld (Table 1). Ohio gauges were located at elevations about 330 m sld. Arizona gauges were at elevations closer to those of Idaho. Ohio, Idaho, and Arizona gauges represent humid, semiarid, and arid regions, respectively. Standard recording rain gauges were used at the Ohio and Arizona sites, while the dual-gauge system was used at the Idaho site.

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Table 1. Rain Gauge Information

State	Rain-Gauge ID	Gauge Elevation, m sld	Annual Ppt, mm
OH	RG103	365.8	898.7
	RG108	317.0	965.2
	RG115*	349.0	928.4
	RG119	281.9	951.5
AZ	RG4	1274.6	303.5
	RG42	1432.7	317.0
	RG46*	1440.6	341.0
	RG68	1585.7	330.0
ID	057	1188	239.0
	095*	1491	471.9
	116	1459	477.0
	155	1654	712.2
	163	2147	1131.6

* Used for testing eqn 3.

3. RESULTS AND DISCUSSION

3.1 *Effects of Region, Season, Climate, and Elevation*

CD varies with region and month/season (Fig. 1), with CD generally highest for Arizona and smallest for Ohio. Summer months showed a different ranking of CD compared to nonsummer months. May was the month in which CD varied the least by region. CD ranged from 243 min at Ohio to 9104 min at Arizona.

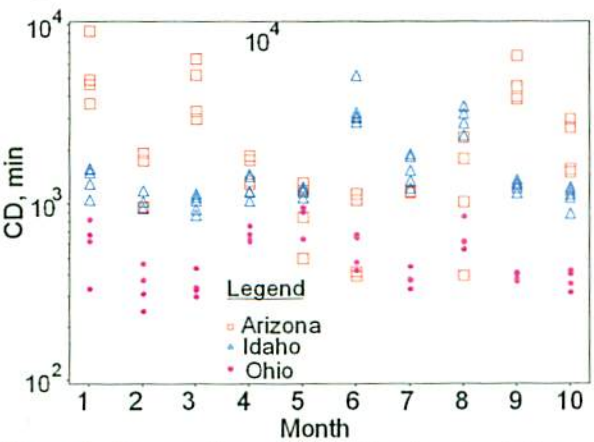

Figure 1. Seasonal (monthly) and regional variation of critical duration (CD).

However, CD at Arizona was as small or smaller than at Ohio during May and August (Fig. 1).

The effect of climate on CD can be seen by the plot of CD vs. average annual precipitation at the three sites (Fig. 2). As found by Restrepo and Eagleson (1982), there is an inverse relationship between these two variables, and their equation visually fits the present data set well (Fig. 2). The best-fit line for this

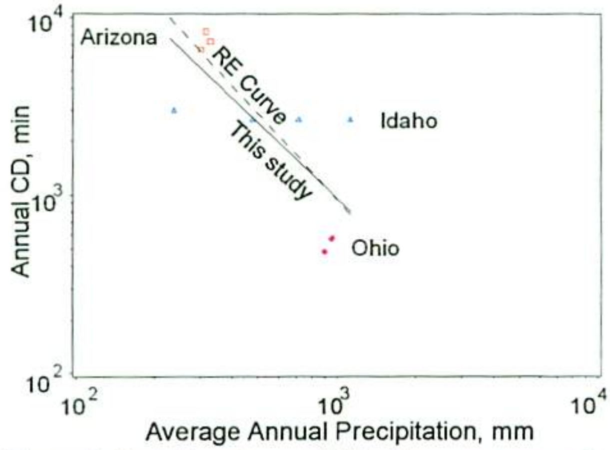

Figure 2. Variation of annual CD with average annual precipitation (RE equation and best-fit line superimposed).

study is also plotted. The two lines are similar in slope and position. However, the data for individual locations can have a positive slope such as at Ohio, and there may not be much variation with large elevation changes such as at Idaho. Arizona data are in accord with the line at all three gauges. It can be concluded that annual values of CD vary inversely with average annual precipitation over large areas, but that the relationship may not hold for an individual site, limiting the utility of this relationship.

Monthly CD values do not follow the same pattern with average monthly precipitation (Fig. 3) as annual values with annual precipitation. Monthly CD varies

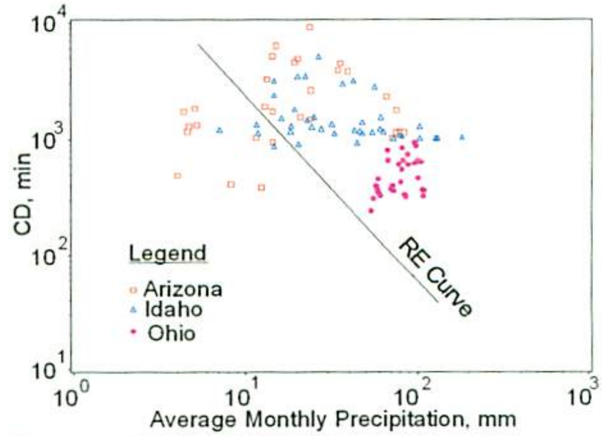

Figure 3. Variation of CD with average monthly precipitation at the three sites.

greatly with average monthly precipitation, and no trend is apparent for all gauges and months at an individual site. The RE equation is also not a good estimator of CD for monthly values across regions as was annual CD using annual precipitation (Fig. 2). This is because the RE equation was developed by lumping several months together, computing an average monthly precipitation, and computing a corresponding average monthly CD. Ohio points were clustered in a small area, and there was also no visual correlation between CD and monthly precipitation for Idaho and Arizona data. Plots of CD vs average monthly precipitation for each month showed results similar to those of annual values in Fig. 2, and some months there was no apparent correlation.

The effects of elevation on CD for the months of June, July, and September typify the wide variation in this factor found at the three sites (Figs. 4-6). These figures show the general trend of variability, and of increasing monthly CD with increasing elevation. Figure 4 shows that Idaho CD values are greater than those of Arizona for similar elevations. Arizona CD values are nearly the same as for Ohio for much greater elevations. The individual Idaho values have a negative slope, opposite that for the entire data set. Figure 5 shows high correlation for CD and elevation for July, with individual Idaho values having a positive slope. Figure 6 shows that in September, Arizona CD values are greater than those at Idaho, opposite those for June (Fig. 4). In September, the Arizona CDs show a negative slope. It appears that over large areas, that

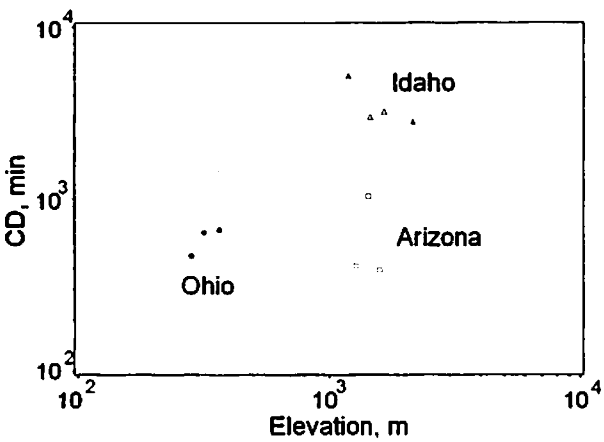

Figure 4. Variation of CD with elevation for June at the three sites.

elevation and CD are correlated to some degree, but that for individual sites and seasons a general relation may not be useful except to characterize CD variation over large areas.

3.2 *Generalized Equation for Critical Duration*

Based on the above results, it appears there is great variation in CD over a region, locally, and seasonally. Also, CD estimation by the RE method is weighted heavily by large times between storms that can greatly

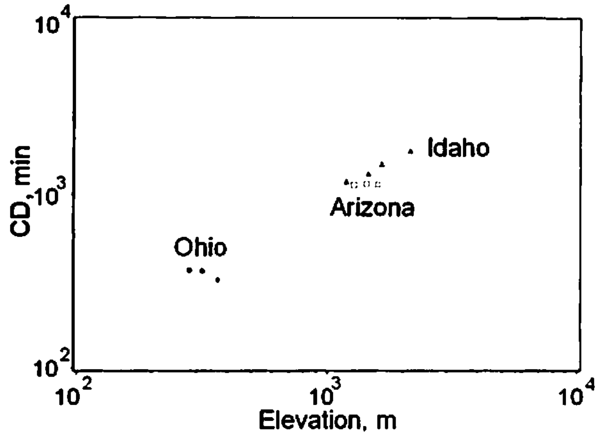

Figure 5. Variation of CD with elevation for July at the three sites.

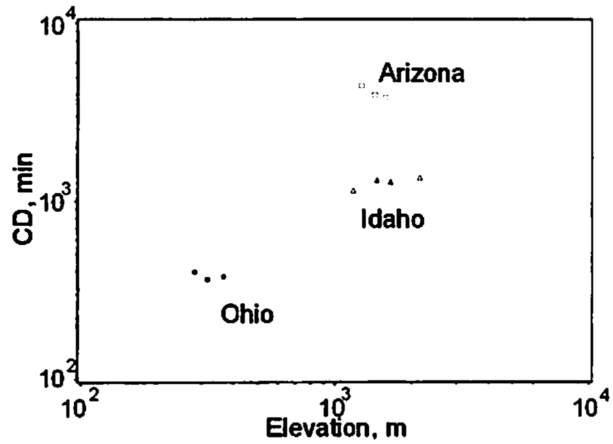

Figure 6. Variation of CD with elevation for September at the three sites.

change CD. Consequently, there can be much variation in CD in the estimation process, and large variation can be expected, especially in dry climates.

Three equations were evaluated for their utility to estimate monthly CD (minutes). The first is a power equation of precipitation only,

$$CD=aP_{mo}^{b} \qquad (1)$$

where P_{mo}=average monthly precipitation in mm, and a and b are parameters. The second equation is,

$$CD=cE^{d} \qquad (2)$$

where E=elevation in meters, and c and d are parameters. The third equation is,

$$CD=eP_{mo}^{f}E^{g}P_{a}^{h} \qquad (3)$$

where P_a=average annual precipitation, and e, f, g, and h are parameters. Season and region are incorporated in equation 3 by P_{mo}, climate and region are considered through P_a, and elevation is considered through E. The form of equation 3 was chosen based on observations in this study. These variables have data that are readily available which are needed for practical applications. Precipitation values have been mapped across the US on a 4-km^2 grid through the use of the PRISM model (Daly et al., 1993) and elevation is readily available. Equation parameters were developed for each month for each equation above.

Results from eqn 1 (Table 2) show that r^2 values range from 0.17 to .97, with most values below 0.76. R^2 values for eqn 2 are worse, ranging from 0 to 0.70. The reason for these results are apparent from the graphs previously shown.

Table 2. Coefficients of determination for best-fit lines to equations 1-3.

	Coefficient of Determination, r^2		
Month	CD=f(Elev), eqn 1	CD=f(P_{mo}), eqn 2	CD=f(P_{mo},E, P_a), eqn 3
1	.40	.52	.85
2	.68	.30	.81
3	.54	.70	.98
4	.66	.58	.92
5	.17	.00	.23
6	.25	.02	.88
7	.97	.52	.98
8	.76	.66	.87
9	.64	.29	.97
10	.81	.41	.86

R^2 values for eqn 3 range from 0.23 for May to 0.98 for March and July. The next smallest r^2 is 0.81 for February, suggesting that this equation performs well for estimating monthly CD values. It can be seen (Fig. 7) that parameters f and h can be either positive or negative. Exponent g on elevation is always positive and falls approximately between 0 and 1.5. Parameters did not change much from April to May, and July to August. Coefficient e varied the greatest of all parameters, ranging from about 0.01 to 1000. The positive and negative parameters in eqn 3 show that CD can be dependent on increasing average monthly precipitation or annual precipitation during some months and on decreasing values during other months.

To test eqn 3, E, P_{mo}, and P_a were entered into the equation for the three rain gages not used in development of parameters (Table 1) and CD values computed. Computed CD values compared favorably with measured values (Fig. 8). The largest disparity in values from the line of equivalence was for the Arizona data. As mentioned previously, CD for arid areas can have large errors of estimation due to long times between storms, and may explain some of the deviations. Differences for Ohio and Idaho were much smaller. Eighty-eight percent of the estimated values in Fig. 8 had errors between -40% and 40% of measured values. The practical impact of large errors in CD needs further examination. However, one example of the insensitivity of CD is in a study by Bonta and Rao (1992). They found that a CD value that was about 2.5 times greater than another one in Ohio did not have an impact on peak-runoff estimation. In that study, CD was determined by two different methods (Bonta and Rao, 1988). The impact of large variations of CD on other variables requires further study, however.

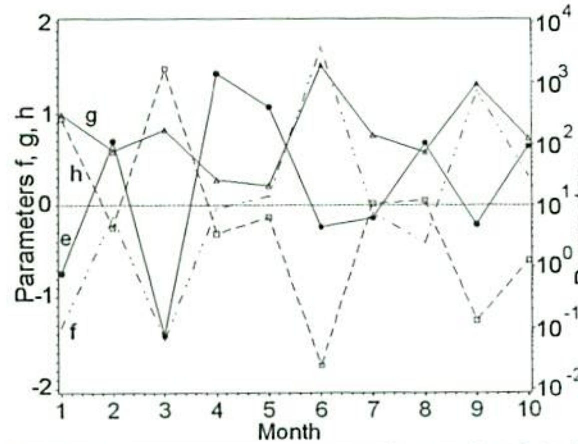

Figure 7. Variation of parameters in equation 3 (e, f, g, and h) with month.

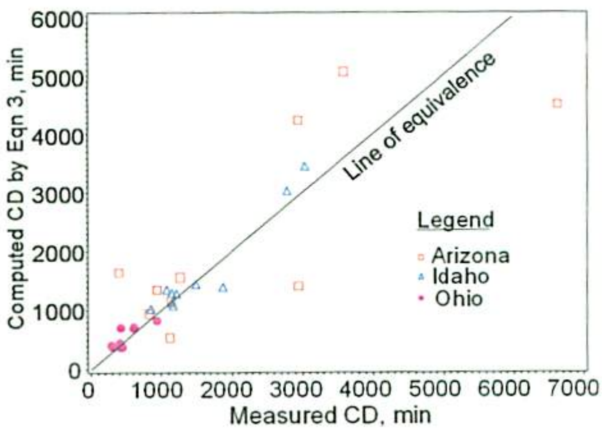

Figure 8. Comparison of measured CD and CD computed by using equation 3 at the three sites for the rain gauges identified in Table 1.

CONCLUSIONS

This exploratory study examined the variation of the critical dry-period duration that separates storms (CD) with region of the US from Ohio to Idaho to Arizona, with season of year (months), and climate. A 3-variable, 4-parameter equation (eqn 3) was developed and tested to estimate monthly values of CD over large areas of the US. The following conclusions can be

Figure 5. Variation of CD with elevation for July at the three sites.

made:

1. CD can be generally characterized by elevation and average annual precipitation, but there can be significant local differences, limiting the practical utility of the relationships for applications such as the storm generator (Bonta, 2001).

2. CD varies with region of the US, season of year (monthly), climate, and elevation.

3. Average monthly precipitation, average annual precipitation, and elevation can explain about 85% of the variability in CD through equation 3.

4. The equation between CD and precipitation developed by Restrepo and Eagleson (1982) appears to fit the annual data well, but it does not fit the monthly CD and average monthly data.

More research is needed to increase the reliability of CD estimation using other variables than those investigated herein, for which the data are readily available. More analyses of data from other regions of the country such as wet and subhumid areas are needed as well. More study is also required on the impacts of errors in estimating CD.

This study has utility for, risk analyses in agriculture, drought studies, stochastic simulation of rainfall events, engineering design, etc.

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