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논 문

격자법을 이용한 면적강우 분석

Areal Rainfall Analysis using Grid Method

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초 록

美國 펜실베이니아 주의 4개 지역에 대해 면적우량을 분석하였다. 강수량이 제일 큰 지점에서 시작하여 이 지점 주위로 직사각형의 블럭을 확장하여 만들었다. 이 직사각형 블럭의 강수량을 구한 후 최대 지점 강수량에 대한 비를 구하였다. 이 강수량 비(Relative storm magnitudes)를 플롯트하여 기존의 커브와 비교하였으며, 각 지역에 대해 여름과 겨울의 강수량비를 각각 구하였다. 또한 등우량선도를 이용한 분석도 시도해 보았다. 이 연구에서 구한 강수량 비를 두 지역에 대한 홍수량을 구하여 홍수빈도 분석 결과와 비교해 보았다.

I. Introduction

Regional rainfall estimates can, in most parts of the United States, be obtained from some type of map, produced as the result of statistical rainfall analysis(e.g. U.S. Weather Bureau Technical Paper 40(TP-40, Hershfield, 1961) and PDT-IDF(Pennsyl- vania Department of Transportation-Intensity Duration Frequency, Aron et al., 1986)). These rainfall estimates are based on records from individual raingages, and therefore, are valid for single points or at best small areas. If an estimate of average rainfall is needed for areas over 10 square miles, the point rainfall estimates taken from maps such as the design rainfall maps from TP-40 and PDT-IDF may be too high.

TP-40 contains a graph with curves for durations varying from 30 minutes to 24 hours as shown in ⟨Fig. 1⟩. These curves make no distinction of regional location or season.

The purpose of this study was to develop a set of relative storm magnitude(R.S.M.) vs. area curves for four regions in Pennsylvania. Separate curves also were developed for summer and winter conditions and compared to TP-40. These curves then can be used to es-

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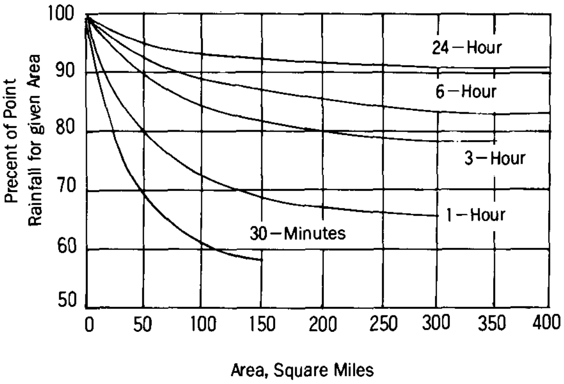
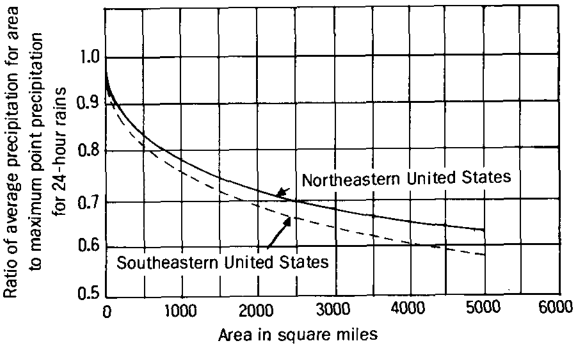
키워드 : Areal rainfall, Relative storm magnitude, Point rainfall, Frequency analysis.



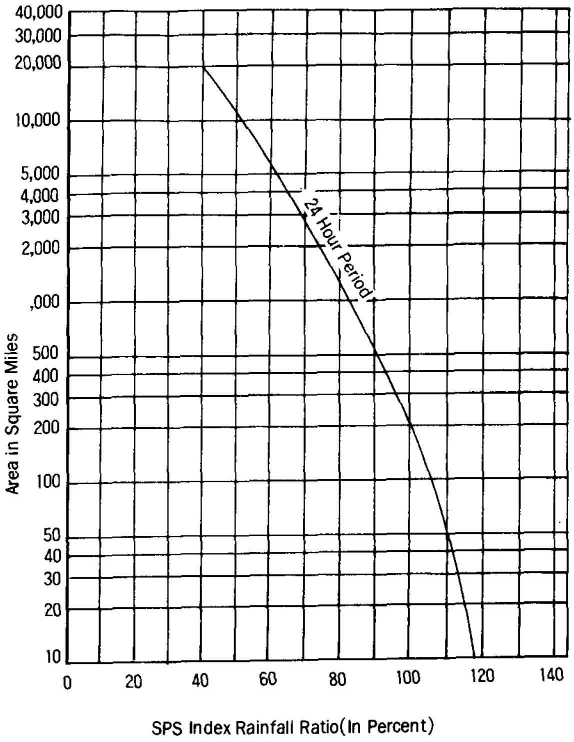
〈Fig. 1〉 TP-40 Relative Storm Magnitude Curves.

timate the average depth of precipitation on basins of various sizes by first determining the magnitude of the design point rainfall within the basin and then multiplying this value by the R.S.M.

Information regarding the spatially-averaged depth of extreme storms for areas of varying size has been collected and published by the Miami Conservancy District and the U.S. Army Corps of Engineers. Fifty-one of the largest rainfall events reported were analyzed to determine the ratio of the average 24-hour precipitation to maximum point precipitation for areas up to 5,000 square miles. The results of this study are presented as two curves, as shown in 〈Fig. 2〉. These relations show a greater spatial attenuation of the 24-hour storms than do the TP-40 curves constuctd for normal storm events.



〈Fig. 2〉 Ratio of average precipitation for area to maximum point precipitation for 24-hour rains



〈Fig. 3〉 SPS Depth-Area-Duration relationships

Another study which transforms point rainfall to spatial rainfall(R.S.M.) is the standard project storm(SPS) depth-area-duration relationship published by the U.S. Army Corps of Engineers, which is shown in 〈Fig. 3〉. In this figure, the SPS index rainfall ratio is expressed as a percentage of the 24-hour storm over an area of 200 square miles.

Ⅱ. Method of Analysis

A truly comprehensive and rigorous statewide spatial storm distribution analysis would require many areas of closely spaced gages. Because of the generally low density of raingages for spatial analyses, the spatial distribution study was performed for four areas which have relatively high density of raingages. The basic steps to determine the relative storm magnitude within each region were the following :

1) Rainfall data were compiled for a represntative number of storm events 〈Table 1〉 and for all the gages within the four chosen regions. The PDT-IDF study provided some data, others were obtained from the National Climatic Data Center bulletin.

〈Table 1〉 Number of Storm events selected

Region	Number of events	Period
1	87	1948~1986
2	106	1948~1986
3	89	1948~1986
4	60	1948~1986

2) Each storm event was scanned for the maximum rain falling over intervals of 1, 2, 3, 6, 12, and 24 hours. Program RAINSORT was written for this task. To increase the rainfall network density, hourly rainfall amounts for the gages which had only daily records were proportionally adjusted, using the distribution of the nearest hourly gage record.

3) For each of the four chosen regions, a rectangular network of 15×15 grid spaces was established spanning the range of all the gages contained within each region.(Area of each grid is about 11. 6 sq. miles)

4) For each event and duration, a representative rainfall was computed for each grid point, and the rainfall at the three nearest gages was weighted in proportion to the square of the inverse distance between the grid point and the gages using the following equation :

$$WT(c, r, d)=\frac{(R_1/d_1^2)+(R_2/d_2^2)+R_3/d_3^2)}{(1/d_1^2)+(1/d_2^2)+(1/d_3^2)} \qquad (1)$$

where WT(c, r, d)=weighted rainfall for each grid(in column c, row r, and duration d)

R_1=Rainfall at the nearest gage, inches

R_2=Rainfall at the second nearest gage, inches

R_3=Rainfall at the third nearest gage, inches

d_1, d_2, d_3=distance from the grid point to the nearest, to the second nearest, and to the third nearest gage respectively, miles

5) The grid point with the largest weighted average rainfall was identified for each event and storm duration, and this grid point was designated as the storm center.

6) The grid points were scanned in the vicinity of the storm center to establish rectangular areas of successively expanding extent, and to average the rainfall amounts of the grid points within each of these areas. Since the storm center rarely coincided with the center of the respective region, two area expansion schemes were used, as described below.

a) Incremental rectangle construction

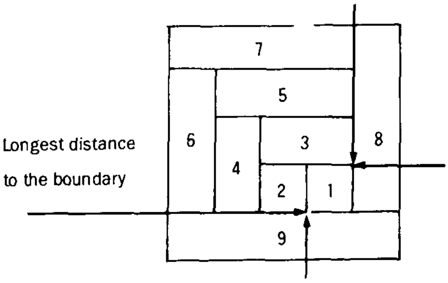
b) Symmetrical expansion with mirror image rainfall projection

The incremental rectangle construction method, illustrated in 〈Fig. 4〉 shows the way to construct rectangles starting at the highest grid(Area 1) and expanding around it until the whole area is covered.

Steps 〈Fig. 4〉

a. Identify grid with highest rain as grid 1.

b. Find the direction of longest distance to the region boundary. In that direction, add a grid to create a rectangle, label as grid 2.



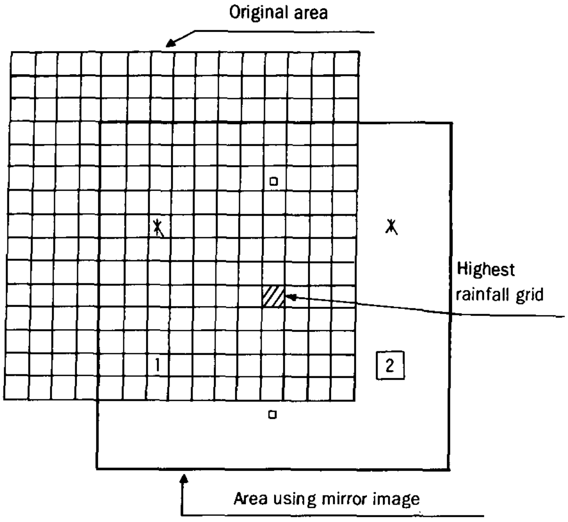
〈Fig. 4〉 Illustration of incremental rectangle construction method

c. Again find the direction of longest distance to the region boundary. In that direction, add as many grids as needed for a new rectangle.

d. Repeat step 3 until the entire region is filled.

The symmetrical expansion with mirror image rainfall projection, illustrated in 〈Fig. 5〉 shows the way to determine the rainfall at each grid using the mirror image.

In case that the grid point of largest rainfall is not in the center of the region, the region boundaries are shifted to place the storm center at the center of the new boundaries. This procedure leaves a space without rainfall records. In order to compute the rainfall amounts for all grid spaces, the records are transferred by mirror image. The rainfall for the grid which has no rainfall record is assumed to be same as that of the opposite side of the highest rainfall grid.



〈Fig. 5〉 Determination of rainfall at each grid using mirror image

For example, in 〈Fig. 5〉 the rainfall for the grid 2 is assumed to be same as that of the grid 1.

7) Curves of relative rainfall were drawn as ratios of average over each expanding area to the rainfall peak at the storm center. These curves represent the average of the rainfall ratios for all events used in the sample.

8) The rainfall events were stratified into categories according to rainfall magnitude and season. To estalish a category of larger storm events, the 39 largest storm events were used because the data extended over a record of 39 years. For seasonal classification, storm events were identified as summer storms for the months from May to October and winter storms from November to April.

9) A comparison was made between the curves for the four regions and the various storm categories, as well as the curves found in previous work cited in chapter 1.

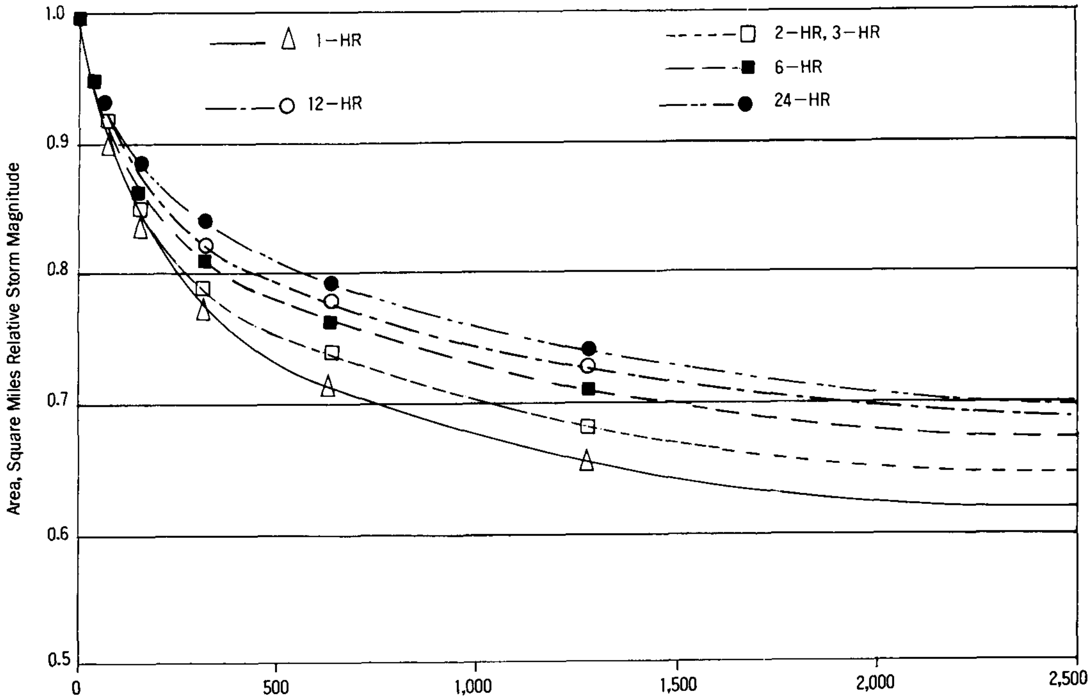
10) The potential sources of error in the applied procedures were discussed, and recommendations were made for improvement in future research wherever applicable.

Ⅲ. Results of the Analysis

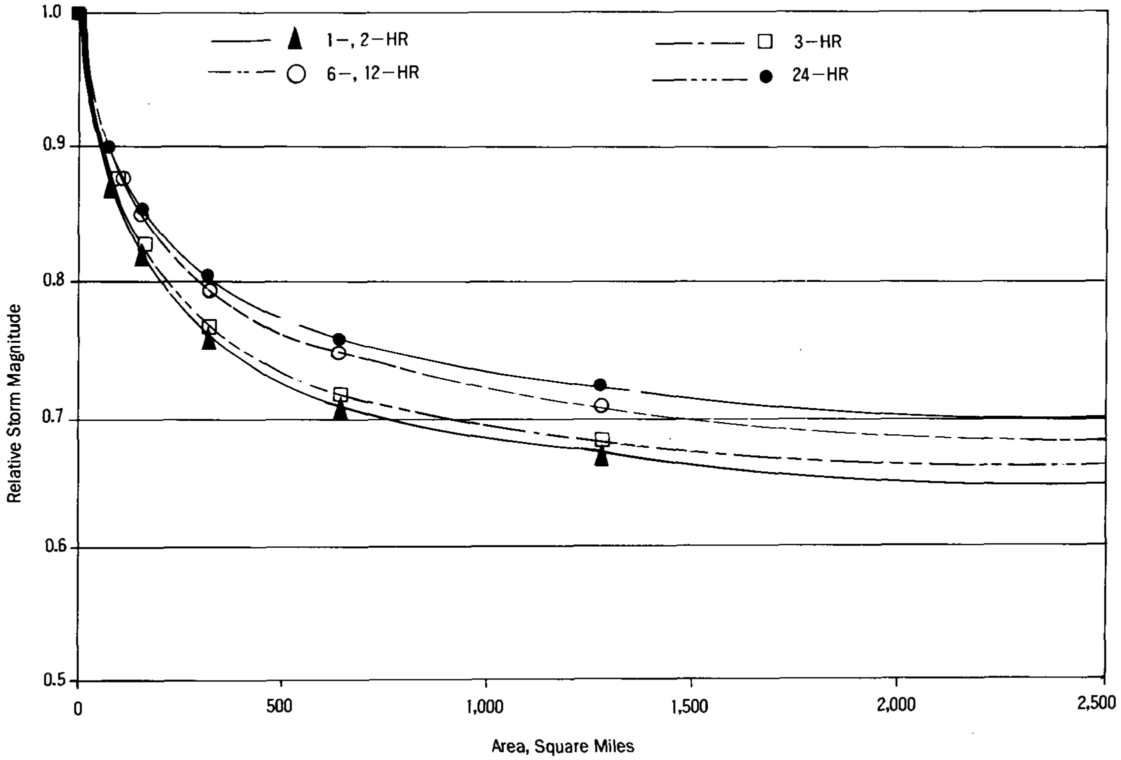
Thirty-nine storm events were used to develop the R.S.M. curves for each region.

The results obtained by the incremental rectangle construction method(a set of R.S.M. curves) are shown in 〈Fig. 6〉 and 〈Fig. 7〉.

The R.S.M. curves in four regions have a



〈Fig. 6〉 R.S.M. curves for Region 1



〈Fig. 7〉 R.S.M. curves for Region 2

similar shape. Although the curves for Region 4 show slightly lower magnitudes than those in the other three regions, the difference of 04 to 0.09 is not great. In the writer's opinion, the small difference is probably due to the fact that Region 4 is mostly of mountainous nature.

The above results are in agreement with Bell(1976, p.58) who noted that, based upon evidence from both the United Kingdom and the United States, relative storm magnitudes appear to vary little with geographical location. From ⟨Fig. 2⟩ it also may be seen that both groups show a similar relationship, thus indicating that areal distribution patterns of individual rainstorms do not vary greatly with location.

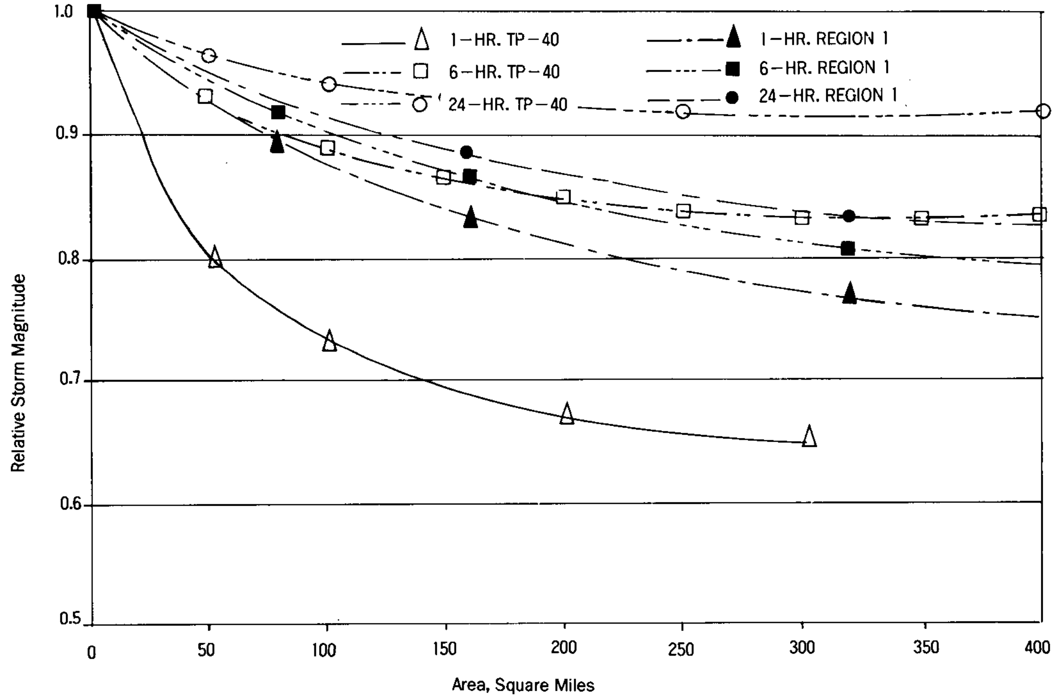
1. Comparison with TP-40 curves

The R.S.M. curves developed by the incremental rectangle construction method were compared with TP-40 curves. ⟨Fig. 8⟩ shows the comparison of TP-40 curves with the R.S.M. curves for Region 1. The 24-hour R.S.M. curves for four regions show lower magnitudes than TP-40. For example, for an area of 400 square miles in Region 1, the R.S.M. is 0.92 according to TP-40 and 0.83 according to the curves developed in this study. The 6-hour curves for Regions 1, 2, and 3 are similar to the TP-40 curve. However, the 6-hour curve for Region 4 is lower than that in TP-40.

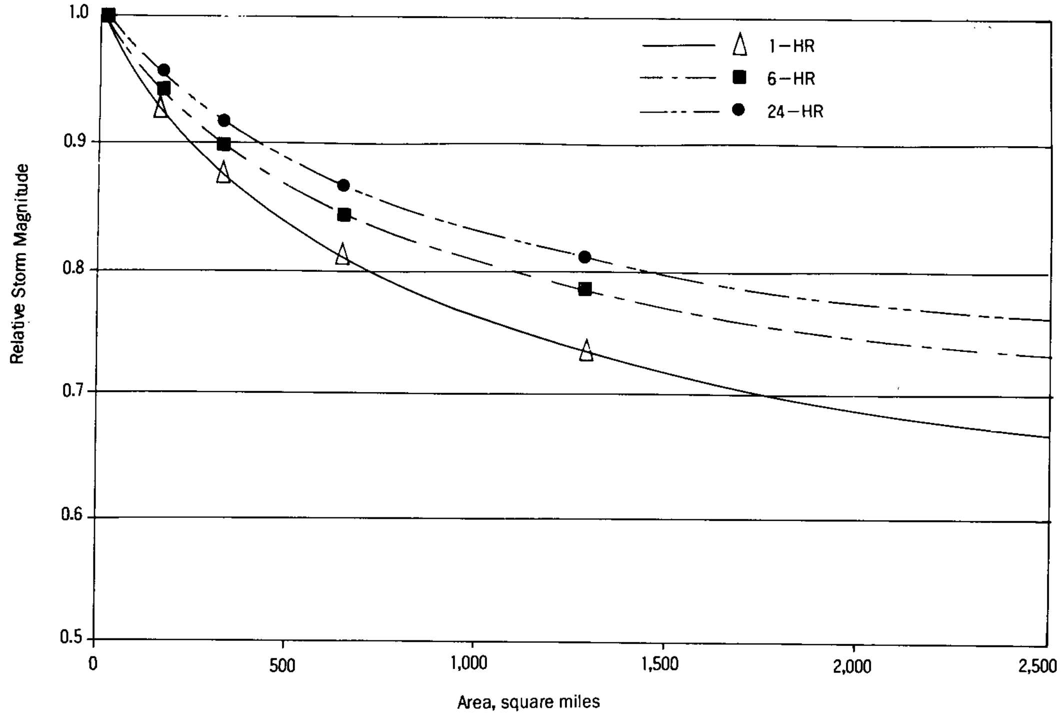
The 1-hour curves for the four regions show higher relative storm magnitudes than TP-40. Therefore, using the 1-hour R.S.M curves developed in this study is more conservative (higher) than using the TP-40 1-hour curve.

2. Area-depth curves using the symmetrical expansion scheme

As a depth-area curve expresses graphically the relation between a progressively



⟨Fig. 8⟩ Comparison of TP-40 curves and R.S.M. for Region 1.



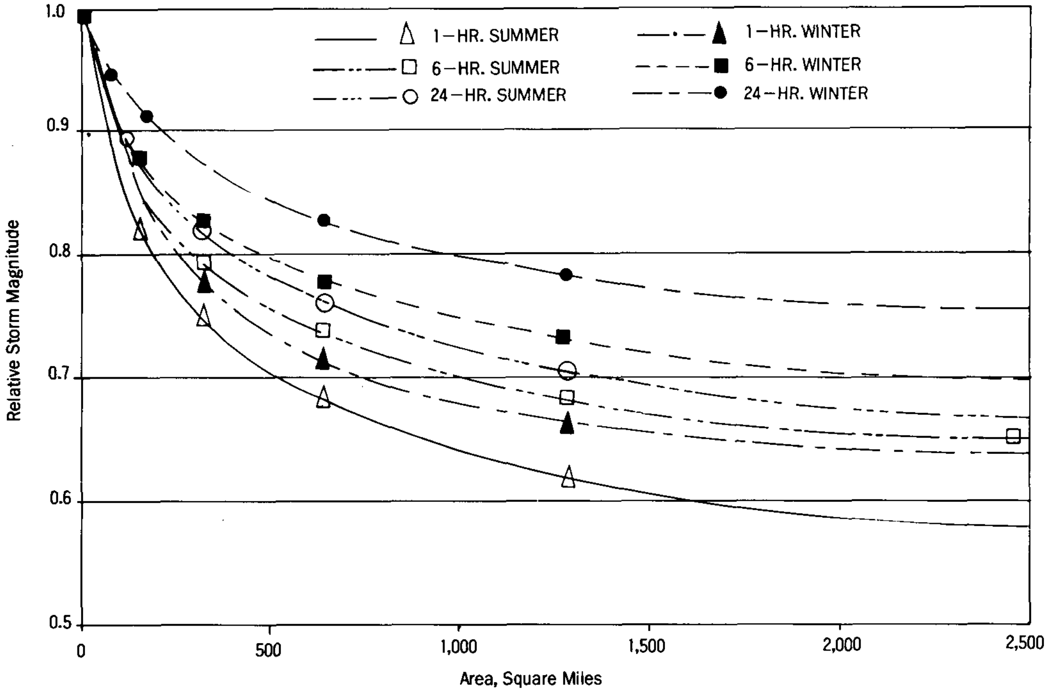
〈Fig. 9〉 R.S.M. curves for Region 1 using mirror image.

decreasing average depth of rainfall over a progressively increasing area from the center, or "eye" of the storm, the areal rainfall and the relative storm magnitudes were calculated by placing the maximum rainfall grid at the center of the region. 〈Fig. 9〉 shows the R.S.M. curves for region 1 developed by using the symmetrical scheme with mirror image rainfall projection. Curves obtained by this method show more conservative magnitudes than those by the incremental rectangle construction method. For areas of 80 to 2,500 sq. miles, the differences in R.S.M. were 0.03 to 0.11 in Region 1 and 2, 0.02 to 0.08 in Region 3, and 0.04 to 0.12 in Region 4. However, since this method assumes the rainfall for the grids which have no rainfall records to be the same as that of the opposite side of the highest rainfall grid, the writer believes that using the curves developed by this scheme is too conservative to use in estimating the average depth of precipitation.

Ⅳ. Variations in Summer and Winter Storms

The R.S.M. curves were developed by averaging the magnitudes of the 39 storm events for areas of 80, 160, 320, 640, 1280, and 2560 square miles. Since many summer storms are thunderstorms with high intensities in small areas and winter storms usually have uniform intensities, it was decided to develop separate curves for these two seasons.

Summer storms were considered to be those occuring from May to October and winter storms were considered to be those occuring from November to April. The monthly distribution of the storm events used in the analysis is shown in 〈Table 2〉. As the majority of



〈Fig. 10〉 Summer/ Winter R.S.M. curves for Region 1.

the storms was summer storms, the number of the winter storms was not adequate to average the relative storm magnitudes. Therefore, 9 to 15 winter storms with high intensities were added to the data from each region to generate a reliable set of winter R.S.M. curves. 〈Table 3〉 shows the monthly distribution of winter storms used in the analysis. 〈Fig. 10〉 show the R.S.M. curves for the region. 1. The 2-, 3-, and 12-hour curves have been omitted because their inclusion would have made the graphs difficult to read.

〈Table 2〉 Monthly distribution of the storm events

Monts	Region 1	Region 2	Region 3	Region 4
Jan.	0	0	1	4
Feb.	1	2	0	1
Mar.	2	5	3	2
Apr.	4	0	2	2
May	6	3	3	2
Jun.	4	6	2	3
Jul.	7	2	5	2
Aug.	4	4	3	6
Sep.	5	4	9	8
Oct.	3	8	3	2
Nov.	2	5	6	2
Dec.	1	0	2	5
Total	39	39	39	39
Total summer	29	27	25	23
Total winter	10	12	14	16

〈Table 3〉 Monthly distribution of winter storms in the augmented data base

Monts	Region 1	Region 2	Region 3	Region 4
Nov.	6	9	8	3
Dec.	4	3	4	7
Jan.	3	1	4	5
Feb.	2	4	2	1
Mar.	4	7	4	3
Apr.	6	1	3	6
Total	25	25	25	25

The results indicate that for all three durations, the relative storm magnitudes of summer storms are lower than those of winter storms. This observation implies that typical summer storm cells are smaller in areal extent than winter storms. The only exception to this rule is found in Region 3, in which the 1 hour summer and winter storm curves are essentially identical.

Because the difference in relative storm magnitudes between summer and winter storms is not great, use of the graphs, presented in Chapter 3, is recommended. These curves are higher, and therefore, more conservative, because of the inclusion of winter storms in the data base.

V. Application Example of the R.S.M. Curves

The R.S.M. curves developed in this study were applied to estimate the flood peak discharges using the hydrologic modeling program HEC-1(U.S. Army Corps of Engineers, 1985) and the flood peak discharges were compared with statistical flood frequency analysis results for the Redbank Creek basin. The site is located 0.3 mile downstream from Leatherwood Creek in Pennsylvania. The PDT-IDF curves were used to generate hourly rainfall distributions. 〈Table 4〉 shows the rainfall amounts used in the HEC-1 analysis.

〈Table 4〉 Watershed area and the rainfall

Basin	Watershed area (sq.mi.)	PDT-IDF Region	24-hour point rainfall	
			10-year	100-year
Redbank Creek	528	2	3.48 in.	5.40 in.

1. The Redbank Creek at St. Charles

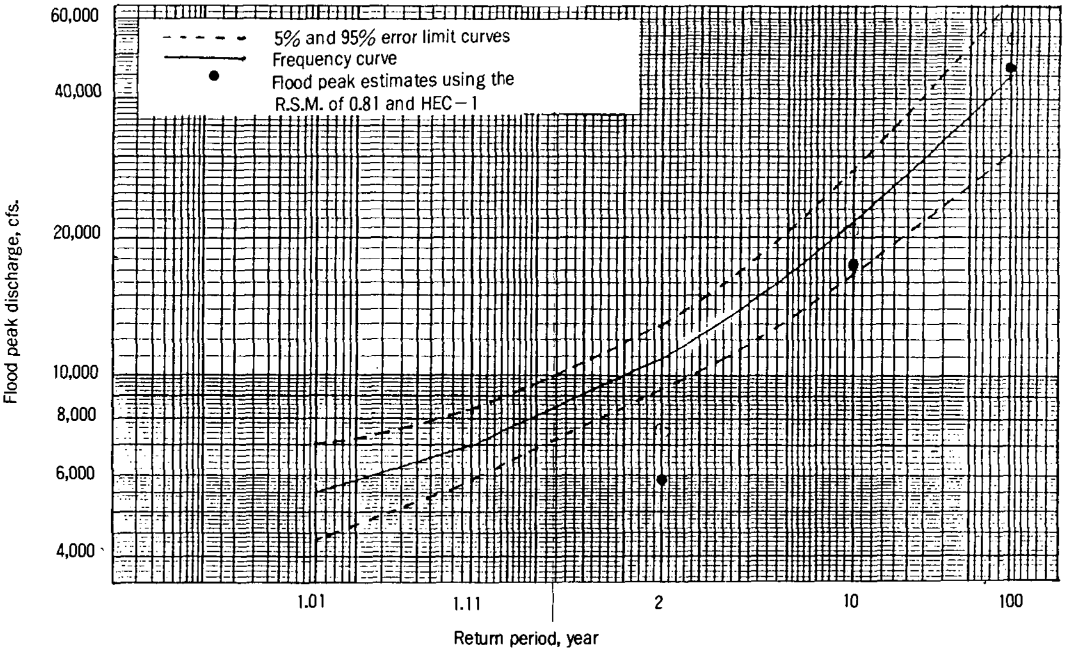
Using the R.S.M. of 0.81 from Fig. 3.1 and HEC-1, flood peak discharges on Redbank Creek at St. Charles were estimated to be 5,880 cfs, 17,590 cfs, and 47,130 cfs respectively for the 2-, 10-, and 100-year return period. A frequency analysis of the 25-year discharge records was performed using the Log-Pearson Type Ⅲ method. 〈Table 5〉 shows the comparison of the results. The optimum R.S.M. values, for which the flood peak estimates and the frequency analysis results were similar, were calculated by a trial and error method and found to be 0.97, 0.88, and 0.79 for the 2-, 10-, and 100-year return period respectively. Considering the reliability of frequency studies and the fact that hydrologic processes are so complex that it is difficult to estimate the accurate flood peak discharge, it might be said that using the R.S.M. leads to reasonable flood peak discharge estimates for 10- and 100-year return period. 〈Fig. 11〉 shows that the 10- and 100-year flood peak estimates using the R.S.M. of 0.81 and HEC-1 fall within the 90 percent reliability band.

〈Table 5〉 Flood peak discharge at St. Charles.

Return period	HEC-1 (R.S.M.=1)	HEC-1 (R.S.M.=0.81)	Flood frequency analysis results
2-year	11,380 cfs	5,880 cfs	10,970 cfs
10-	29,060	17,590	21,550
100-	70,180	47,130	45,000

2. Observations

Bell(1976, p.58) found the statistically significant trend for R.S.M. values to decrease with increasing return period. From the preceding example, the writer also found that



〈Fig. 11〉 Maximum instantaneous annual flows, Redbank creek at St. Charles.

the decreasing R.S.M. values(0.97, 0.88, 0.79 for Redbank Creek) for the increasing return periods(2-, 10-, and 100-year). The writer also found that using higher R.S.M. values than were developed in this study gave similar flood peak estimates to the frequency analysis results for the 2-year return period.

6. Summary, Discussions and Recommendations

The objective of this study was to develop a set of relative storm magnitude curves for Pennsylvania and test the validity of the TP-40 curves. The first step was to choose the areas which have relatively high density of raingages and represent Pennsylvania. Because the program ARDIST utilizes the grid concept to compute the areal rainfall, the four regions which have rectangular shape were chosen to develop the R.S.M. curves.

The next step was to selet the storm events which have high areal rainfall. The PDT-IDF study provided some data, while other data were chosen from the National Climatic Data Center bulletin. A total of 60 to 106 storm events were selected for each region. This data set was used as input for the program RAINSORT which was used to calculate the maximum rainfalling over intervals of 1, 2, 3, 6, 12, and 24 hours.

Output from the maximum rain analysis then was used as input for the program ARDIST which calculated the areal rainfall and the R.S.M. To establish a category of larger events, the 39 largest storm events were used to average the R.S.M. For the variations in summer and winter storms, separate curves also were developed.

The R.S.M. curves developed in this study were applied to estimate the flood peak discharges using HEC-1 and the flood peak discharges were compared with the frequency analysis results for an example basin. From the application example of the R.S.M., the writer found that using higher R.S.M. curves than were developed in this study gave similar flood peak estimates to the frequency analysis results for the 2-year return period.

From the analysis conducted, it appears that TP-40 curves give reasonable results except for 1- and 24- hour duration. The TP-40 24-hour curve is always higher than that developed in this study, while the 1-hour curves developed in this study are higher than those of TP-40 by 0.1 to 0.15 for an area of 40 to 300 square miles.

National Climatic Data Center records were used in this study. However, these data are subject to error because of the difficulty of accurately gaging rain. Gages on hillcrest locations or on rooftop give poor accuracy and it would be better to avoid the data when the wind velocity is high. Therfore, an individual investigation of gages and wind velocity for the wind-swept rain could improve the accuracy of this study.

In this study, only the rainfall data from gages inside each region were used. Including the data from gages outside the region(but close to the region) would improve the accuracy of the result.

The program ARDIST utilized the incremental rectangle construction method which adds grids in the direction of largest distance to the region boundary. Using an alternative incremental rectangle construction method, which adds a grid which has the largest rainfall in the vicinity of the area would improve the accuracy of the result.

For a rigorous check of the validity of R.S.M. curves generated in this study, a representative sample of gaged watersheds of different sizes could be chosen. Using design rainfall amounts from the PDT-IDF manual, and a hydrologic model such as HEC-1, flood simulation runs could be performed over a range of return periods, with and without the R.S.M. factors applied to the rainfall. The simulated flood peaks could then be compared with flood peaks computed from gage data by the Log Pearson Ⅲ technique.

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