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SPONSORED PROJECT INITIATION

Date: April 2,1976

Project Title: ~~Research - Initiation~~ - Precipitation Frequency in Mountainous Terrain

Project No: E - 20 - 681

Project Director: Dr. Bruce H. Bradford

Sponsor: National Science Foundation

Agreement Period: From 4/1/76 Until 3/31/78
18 month budget period plus 6 months for submission of required reports,etc.

Type Agreement: Grant No. ENG 76- 09438

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Reports Required:

Annual Letter Technical, Final Report

Sponsor Contact Person (s):

Technical Matters

Contractual Matters
(thru OCA)

Mr. Gaylord L. Ellis
Grants Officer
National Science Foundation
Washington, D. C. 20550
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SPONSORED PROJECT TERMINATION

Date: 11/22/78

Project Title: ~~Research Initiation~~ - Precipitation Frequency in Mountainous Terrain

Project No: E-20-681

Project Director: Dr. B. H. Bradford

Sponsor: National Science Foundation

Effective Termination Date: 3/31/78

Clearance of Accounting Charges: 3/31/78

Grant/Contract Closeout Actions Remaining:

- ☐ Final Invoice and Closing Documents
- ☐ Final Fiscal Report
- ☐ Final Report of Inventions
- ☐ Govt. Property Inventory & Related Certificate
- ☐ Classified Material Certificate
- ☒ Other FCTR in accordance with NSF Important Notice No. 68

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CA–4 (3/76)

E-20-681

ANNUAL REPORT

Grant No. ENG 76-09438 entitled

RESEARCH INITIATION- PRECIPITATION FREQUENCY IN MOUNTAINOUS TERRAIN

Bruce H. Bradford, Principal Investigator
School of Civil Engineering
Georgia Institute of Technology
Atlanta, Georgia

Submitted to

National Science Foundation
Engineering Division
Engineering Mechanics Section
Washington, D. C. 20550

Introduction

Many aspects of hydrologic design require the estimation of the intensity of rainfall for a particular location, duration, and frequency of occurrence (or "return period"). Intensity-duration-frequency values have been obtained from long term raingages at locations throughout the U. S. and are published by the National Weather Service. Interpolation of these values to fit the particular project location is satisfactory in flat terrain, but often results in significant errors in mountainous terrain. The purpose of this research project is to investigate the degree to which errors in intensity-duration-frequency values affect the cost and performance of the systems being designed and to investigate possibilities for improving the designer's estimates of these values.

Summary

The precipitation data used for this project is from the USDA Forest Service's Coweeta Hydrologic Laboratory, located in the Nantahala Mountains approximately 62 miles west-southwest of Asheville, North Carolina. From these data the maximum depth of precipitation for each year of record (annual series) was found for durations of 5, 15 and 30 minutes and 1, 3, 6, 12 and 24 hours.

The date of each event appearing in the annual series was also recorded. This was done for each of 7 recording raingages located throughout the mountainous 4000-acre drainage basin.

The weather maps for the date of each event which appeared in any of the annual series were analyzed and the associated synoptic storm type was recorded for each event. This information will be useful in developing methodology for improving estimates of intensity-duration-frequency values.

The annual series were transformed into intensity-duration-frequency values using the same statistical methods employed by the National Weather Service. This allowed direct comparisons of computed intensity-duration-frequency values with estimates obtained from National Weather Service publications, which are normally the best available data for a project site. The significant deviations between the estimated and calculated values are detailed later in this report.

Two major steps remain for completion of the proposed research. One is to illustrate the impact that these variations would have on the cost and performance of a couple of typical designs which utilize intensity-duration-frequency values. The other is to develop regression equations to adjust intensity-duration-frequency values in terms of topographic and climatological features of a project site.

Research Activity

The first step of this research project was to obtain a cooperative agreement with the Forest Service for use of their precipitation data. The precipitation data for the seven recording gages used in this study had been digitized in the form of time-depth pairs of values for each change in the intensity trace and at midnight.

The input data required for computing precipitation frequency values are the maximum events for the entire period of record. For consistency with the procedures of the National Weather Service precipitation frequency values were calculated from the annual series [3]. The annual series consist of the largest event for each water year of record. The annual series for eight (8) durations (5, 15, and 30 minutes and 1, 3, 6, 12 and 24 hours) and seven (7) recording gages (gage numbers 6, 12, 13, 20, 31, 41 and 96) were collected. Thus fifty-six (56) annual series were developed.

The maximum intensities for durations of 5, 15, 30 and 60 minutes had previously been calculated by computer programs developed by Coweeta Hydrologic

Laboratory personnel. These maximums were computed and listed for all storms of total depth greater than 0.25 inches. The annual maximums for these durations and their data of occurrence were collected by hand by scanning through the storm summaries.

A computer program was developed by the writer to compute the annual series for durations of 1, 3, 6, 12, and 24 hours. The program read in each storm from magnetic tapes and listed the gage number, storm number, date of occurrence and maximum 1, 3, 6, 12 and 24 hour intensities of each storm with total depth greater than 0.25 inches. At the same time the maximum intensity and corresponding storm number for each water year was saved for each of these durations. After this was done for the entire period of record for a particular gage, the annual series for each duration was listed.

The next task was to select which gages and which periods of record to use for developing the intensity-duration-frequency curves. This decision was based on a partially subjective evaluation of the trade-offs between number of gages, length of record, and common period of record. For statistical stability long periods of record are desirable. However, for correlating intensity-duration-frequency values with physiographic features, it is desirable to have common periods of record and many gages. By using partial records of the long record stations it was found that the intensity-duration-frequency values tended to stabilize at about 15 years of record. Five of the seven gages had 16 common years of record. This 16-year period of record (1959-1974) and these five gages (gage numbers 6, 13, 31, 41 and 96) were selected for further analysis.

One activity which was completed this year was to classify by storm type each of the data points in the annual series. There are 640 data points in the annual series (16 years x 5 gages x 8 durations). These were produced from about 120 different storms. By referring to the National Weather Service daily weather maps each of these storms was placed into one of the following categories: (1) Low east; (2) low west; (3) cold front; (4) stationary front; (5) air mass; and (6) tropical storm.

These categories carry strong indications of the orographic effects occurring within the watershed and the precipitation generating mechanisms and will be helpful in explaining the variations of the precipitation frequency values within the watershed.

Synoptic low pressure areas near Coweeta generally travel from southwest to northeast. A low passing east of the watershed (Type 1) will be borne by surface winds from the northeast. Coweeta would lie within the cold sector during the passage of a low east storm. A low passing near but west of Coweeta (Type 2) would have an associated warm front and cold front passage. Rain would be born by surface winds from the northeast shifting to the south and southwest. A cold front (Type 3) passes far west and north (i.e., no associated warm front passage) with winds from south to southwest. Stationary fronts (Type 4) usually lie south of Coweeta watershed and resulting winds in the watershed are from the northeast. Air mass showers (Type 5) generally occur when low speed surface winds are from the south, but the associated erratic mesoscale winds are usually of greater importance. Tropical storms (Type 6) are far less frequent than the other types but appeared several times in these annual series.

Another task which was completed in the first year of this project was to compute the intensity-duration-frequency values for the five gages. Calculation of these values was based on the Extreme Value Type I distribution. When applied to hydrologic analysis this is usually referred to as the Gumbel method. The Gumbel method was chosen for consistency with the National Weather Service procedures [3]. The Gumbel distribution is given by [1]:

$$T = \frac{1}{1 - e^{-e^{-Y}}} \qquad \text{or} \qquad Y = -\ln\,[-\ln(1 - \frac{1}{T}]$$

where T = the return period (or recurrence interval) in years and

Y = the reduced variate

The depth or intensity of precipitation (X) corresponding to the "T-year" event is expressed as a function of the reduced variate as follows:

$$X = \overline{X} + \frac{Y - Y_n}{\sigma_n}\ \sigma_x$$

where $\overline{X} = \sum_{i=1}^{n} X_i/n$ = method of moments estimate of the population mean

$\sigma_x = \sqrt{\dfrac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{n-1}}$ = method of moments estimate of the population standard deviation

X_i = individual values in the annual series i = 1, . . ., n

n = record length (number of years of record)

Y_n and σ_n are the mean and standard deviation of the annual series reduced variates, based on the Weibull plotting positions. They are a function of record length (not the values of X_i) and can be calculated as follows:

$$t_m = \frac{n+1}{m} \qquad m = 1, \ldots, n$$

$$y_m = -\ln[-\ln(1-1/t_m)] \qquad m = 1, \ldots, n$$

$$Y_n = \sum_{m=1}^{n} y_m/n$$

$$\sigma_n = \sqrt{\sum_{m=1}^{n} (y_m - Y_n)^2/n}$$

where t_m = annual series return periods (yrs) based on the Weibull plotting positions

y_m = annual series reduced variates

m = 1,...,n the rank of X_m (i.e., X_1 = largest value in annual series and X_n = smallest value)

A computer program was developed to perform these calculations. The program first rearranges each annual series in order of decreasing magnitude. For a particular duration the annual series is listed for each gage. Accompanying the annual series for each gage (and a particular duration) is the gage number, n, $\overline{X}$, and σ_x. Beside each individual value of that annual series (X_m) is the associated Weibull return period (t_m), the date of occurrence and the storm type. The arrangement in this form gives a quick comparison between gages and a synopsis of the seasonal distribution and dominant storm types for a particular duration.

Gumbel values are computed for six return periods (2, 5, 10, 25, 50 and 100 years). These are first listed as depths of precipitation for each gage (and a particular duration). The Gumbel values for a particular gage are then listed as intensity versus duration and return period.

Research Results

Although the research results are not yet finalized, preliminary tables and figures have been prepared. These will be presented and discussed in this section of the report.

Table 1 is a listing of the annual series for gage 31. This is actually the input data to the intensity-duration-frequency program except that depths rather than intensities are listed and the values have been rearranged into descending order. It is interesting to note that the short duration annual series are primarily from summer storms while the longer duration annual series are more evenly distributed with respect to seasons. Individual storms of particular significance can also be identified from Table 1. For instance, for gage 31 the storm of July 9, 1974 is the storm of record for the durations of 15, 30 and 60 minutes. It also ranks high in the annual series for durations

TABLE 1

Rainfall Duration

5-MIN	15-MIN	30-MIN	60-MIN	3-HRS	6-HRS	12-HRS	24-HRS
.73(08/03/68)	1.23(07/09/74)	1.85(07/09/74)	2.80(07/09/74)	4.29(09/27/64)	5.58(09/27/64)	7.56(09/27/64)	9.84(09/27/64)
.72(07/21/69)	1.06(06/08/66)	1.57(08/14/70)	2.33(09/27/64)	3.57(05/27/73)	4.68(05/27/73)	6.84(05/27/73)	8.40(09/30/65)
.53(08/14/70)	1.04(08/14/70)	1.44(06/08/66)	1.96(07/21/69)	3.03(07/09/74)	4.44(01/21/59)	6.00(09/30/65)	7.68(05/27/73)
.49(08/05/72)	1.00(07/21/69)	1.41(07/21/69)	1.84(08/02/68)	2.70(03/24/75)	4.14(09/30/65)	5.40(02/12/66)	7.44(02/12/66)
.44(07/09/74)	.93(08/03/68)	1.38(09/27/64)	1.77(08/14/70)	2.64(01/21/59)	3.84(02/24/61)	[illegible](10/17/75)	6.48(12/25/74)
.39(07/19/71)	.88(07/20/63)	1.31(08/02/68)	1.63(08/11/60)	2.64(09/30/65)	3.60(03/24/75)	5.04(01/21/59)	5.76(06/03/67)
.37(06/08/66)	.84(09/27/64)	1.16(07/19/71)	1.59(05/27/73)	2.49(06/14/69)	3.48(06/14/69)	5.04(02/24/61)	5.76(03/11/68)
.30(06/26/63)	.75(08/05/72)	1.14(08/11/66)	1.49(06/08/66)	2.46(02/24/61)	3.36(03/06/67)	4.68(06/03/67)	5.76(10/31/69)
.28(09/27/64)	.74(06/02/62)	1.12(01/21/59)	1.42(01/21/59)	2.22(07/30/70)	3.12(04/03/74)	4.20(12/25/74)	5.52(02/24/61)
.27(04/26/65)	.71(04/26/65)	1.08(07/20/63)	1.39(08/03/61)	2.19(06/04/62)	3.06(03/11/68)	3.84(03/11/68)	5.52(10/17/75)
.27(06/02/62)	.71(08/09/73)	1.07(06/02/62)	1.26(07/20/63)	1.98(07/06/60)	2.82(02/12/66)	3.84(12/11/62)	5.28(12/11/62)
.26(08/09/73)	.66(08/11/60)	1.01(08/05/72)	1.23(06/04/62)	1.92(08/02/68)	2.64(06/04/62)	3.60(07/22/70)	5.28(07/22/70)
.22(08/11/60)	.62(07/19/71)	1.01(05/27/73)	1.21(03/15/71)	1.89(06/03/67)	2.58(12/29/70)	3.60(09/28/63)	5.04(01/21/59)
.22(07/26/59)	.61(01/21/59)	.95(07/21/61)	1.12(09/30/65)	1.71(07/20/63)	2.46(09/28/63)	3.48(06/14/69)	5.04(04/28/63)
.20(03/06/67)	.55(07/21/61)	.79(09/30/65)	1.06(08/05/72)	1.68(04/29/66)	2.34(07/06/60)	3.12(09/17/60)	4.08(01/22/71)
.20(07/21/61)	.49(03/06/67)	.73(03/06/67)	1.00(03/06/67)	1.56(07/24/71)	1.98(02/21/71)	3.00(05/13/72)	4.08(05/13/72)
				1.14(03/21/72)	1.86(05/13/72)	2.64(01/21/71)	3.84(09/17/60)

NOTE: Period of record is 1959-1974 for the 5, 15, 30 and 60 minute durations and 1959-1975 for the 3, 6, 12 and 24 hour durations.

Table 1. The annual series for depth of rainfall (in inches) at Gage 31 with date of occurrence (in parentheses) for various durations.

of 5 minutes and 3 hours.

Table 2 illustrates the distribution of storm types for gage 6 (the lowest elevation gage in the watershed) and gage 31 (the highest gage). The table lists the number of particular storm types appearing in each annual series. For instance, for gage 6 the five minute duration annual series was produced from 2 low west, 12 cold front, 1 air mass, and 1 tropical storm. Of the data points in the 8 annual series for gage 6 the predominant storm type was cold front which produced 47 of the total 128 data points.

Except for gage 6 air mass thunderstorms predominate for the short durations. Low west storms (cold and warm front) appear most frequently in the annual series for durations of 6, 12, and 24 hours at all gages.

Figure 1 illustrates the most standard form of the output data. It is the intensity-duration-frequency curve for gage 31. Figure 2 provides the same information in the form of a precipitation frequency curve with depth of precipitation plotted against return period for various durations.

Figures 3 and 4 illustrate the variations among the five gages and the errors that would result from using what is normally the best available data. Reference 3 (TP25) contains about 100 intensity duration-frequency curves for various locations in the United States. Designers often use the intensity-duration-frequency curve from TP25 for a location near the project site. The curves marked as TP25 in Figures 3 and 4 are for Asheville, N. C. Another source of precipitation frequency data is Technical Paper No. 40, Rainfall Frequency Atlas of the United States [2]. TP40 contains isopluvials of rainfall depth drawn on 8 1/2 x 11 inch maps of the conterminous United States. The curves marked as TP40 in Figures 3 and 4 were found from this source by locating Coweeta on these maps.

TABLE 2

Gage	Storm Type	Duration 5 Min	15 Min	30 Min	60 Min	3 Hr	6 Hr	12 Hr	24 Hr	Total
6	Low East	0	0	0	1	0	2	4	1	8
	Low West	2	2	2	1	4	(5)	(5)	(8)	29
	Cold Front	(12)	(8)	5	(6)	4	3	(5)	4	47
	Stationary Front	0	1	2	2	1	1	0	0	7
	Air Mass	1	4	(6)	(6)	(5)	3	1	2	28
	Tropical Storm	1	1	1	0	2	2	1	1	9
31	Low East	0	0	0	0	0	2	2	1	5
	Low West	2	3	3	3	3	(7)	(6)	(8)	35
	Cold Front	5	5	5	(6)	5	3	5	4	38
	Stationary Front	1	1	1	1	1	2	0	0	7
	Air Mass	(7)	(6)	(6)	5	(7)	2	2	2	37
	Tropical Storm	1	1	1	1	0	0	1	1	6

Table 2 Number of storm types in each annual series for gages 6 and 31
(Parentheses indicate the most frequently occurring storm type for each annual series.)

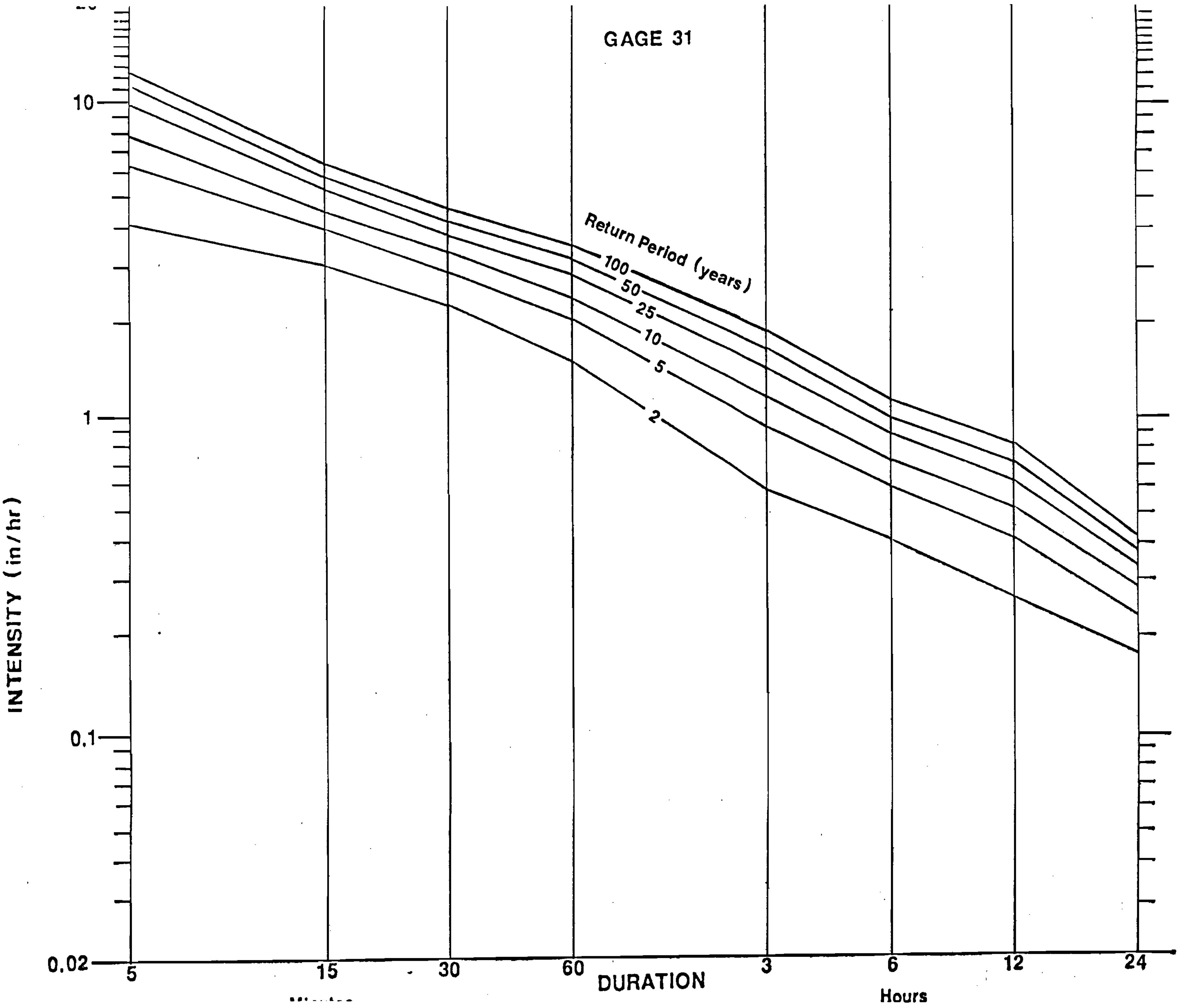

GAGE 31
Return Period (years)
100
50
25
10
5
2
INTENSITY (in/hr)
10
1
0.1
0.02
5
15
30
60
3
6
12
24
DURATION
Hours

FIGURE 2 PRECIPITATION-FREQUENCY CURVE FOR GAGE 31

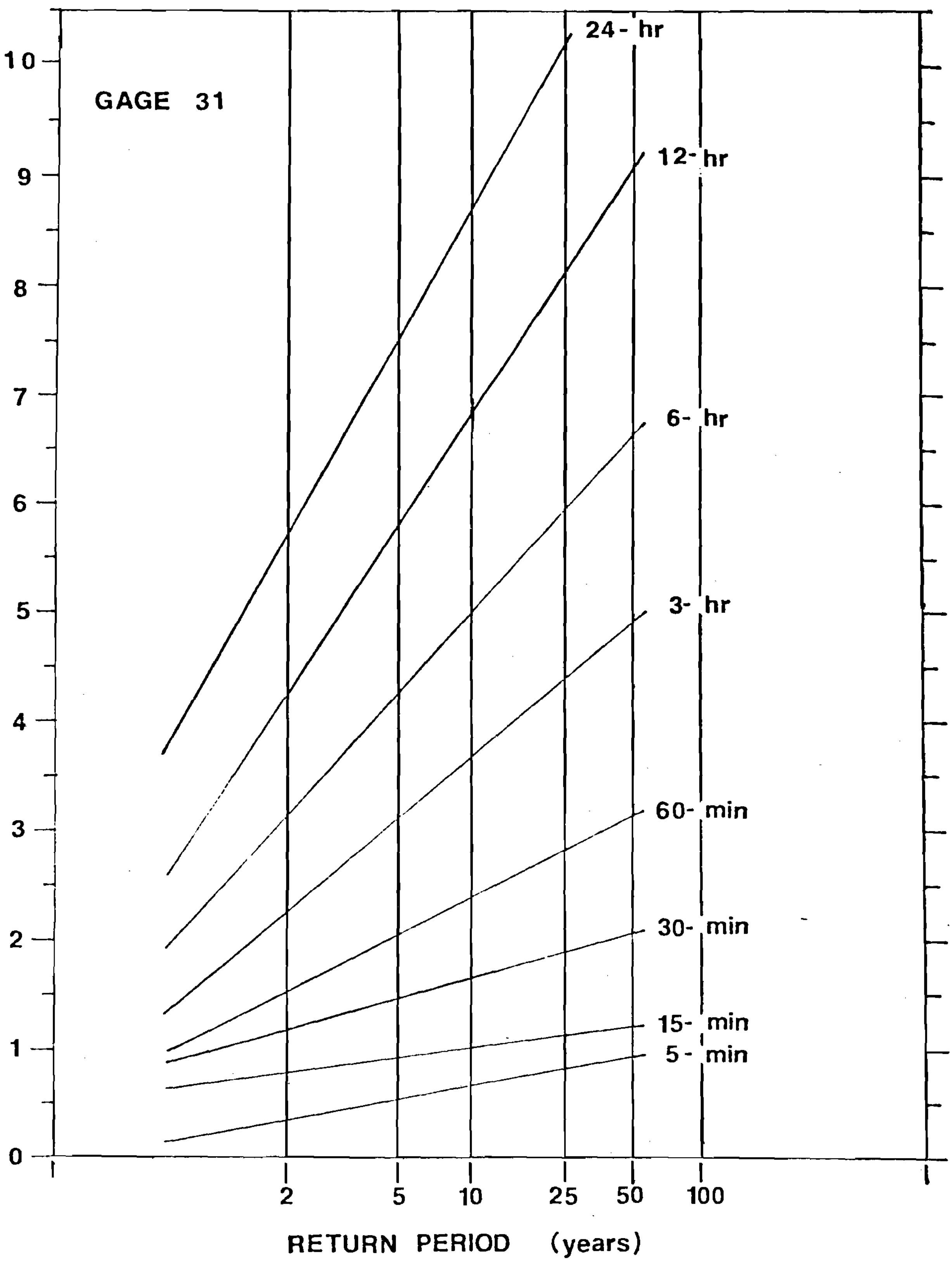


FIGURE 3 INTENSITY-FREQUENCY CURVE

(1 HOUR DURATION)

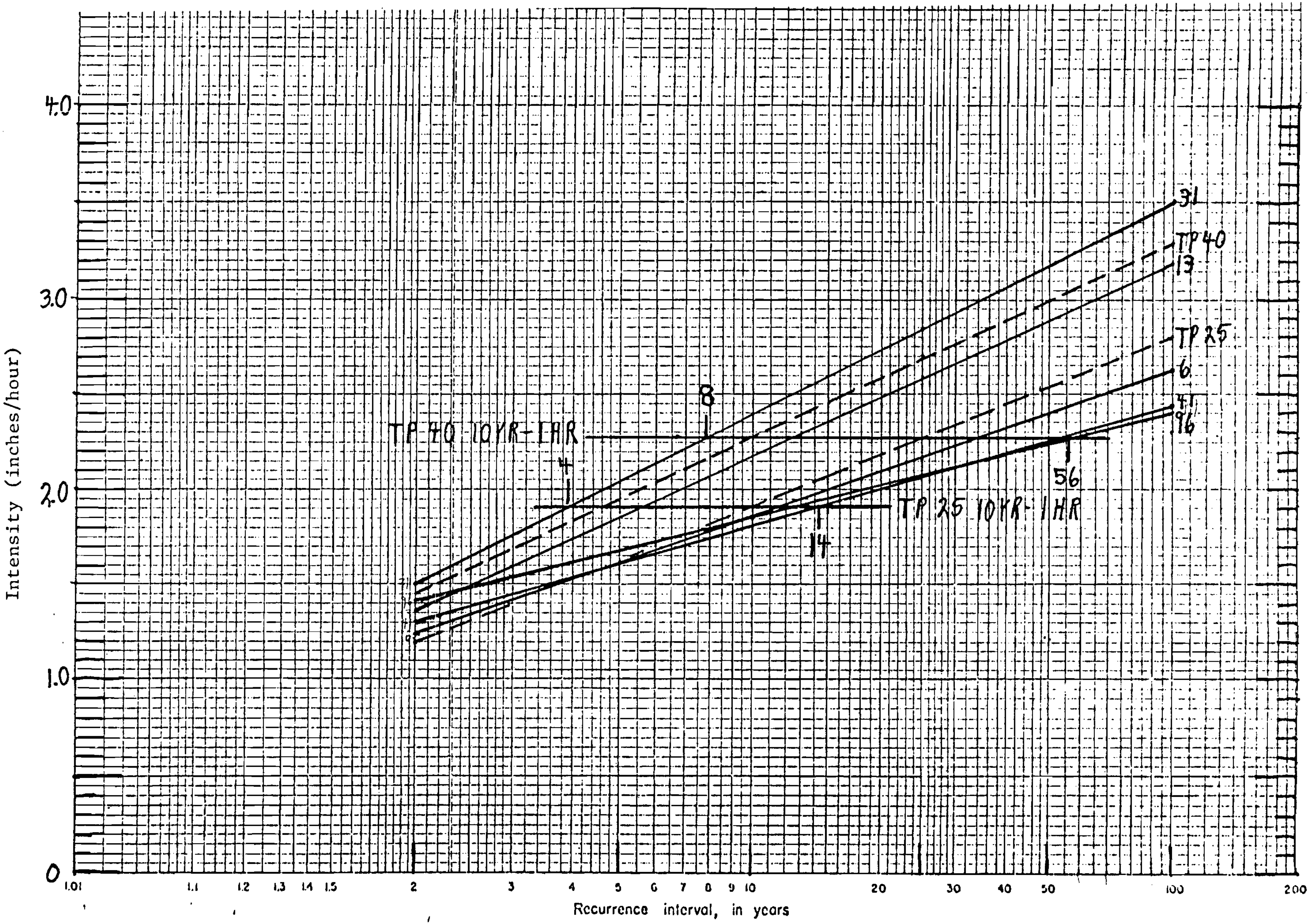
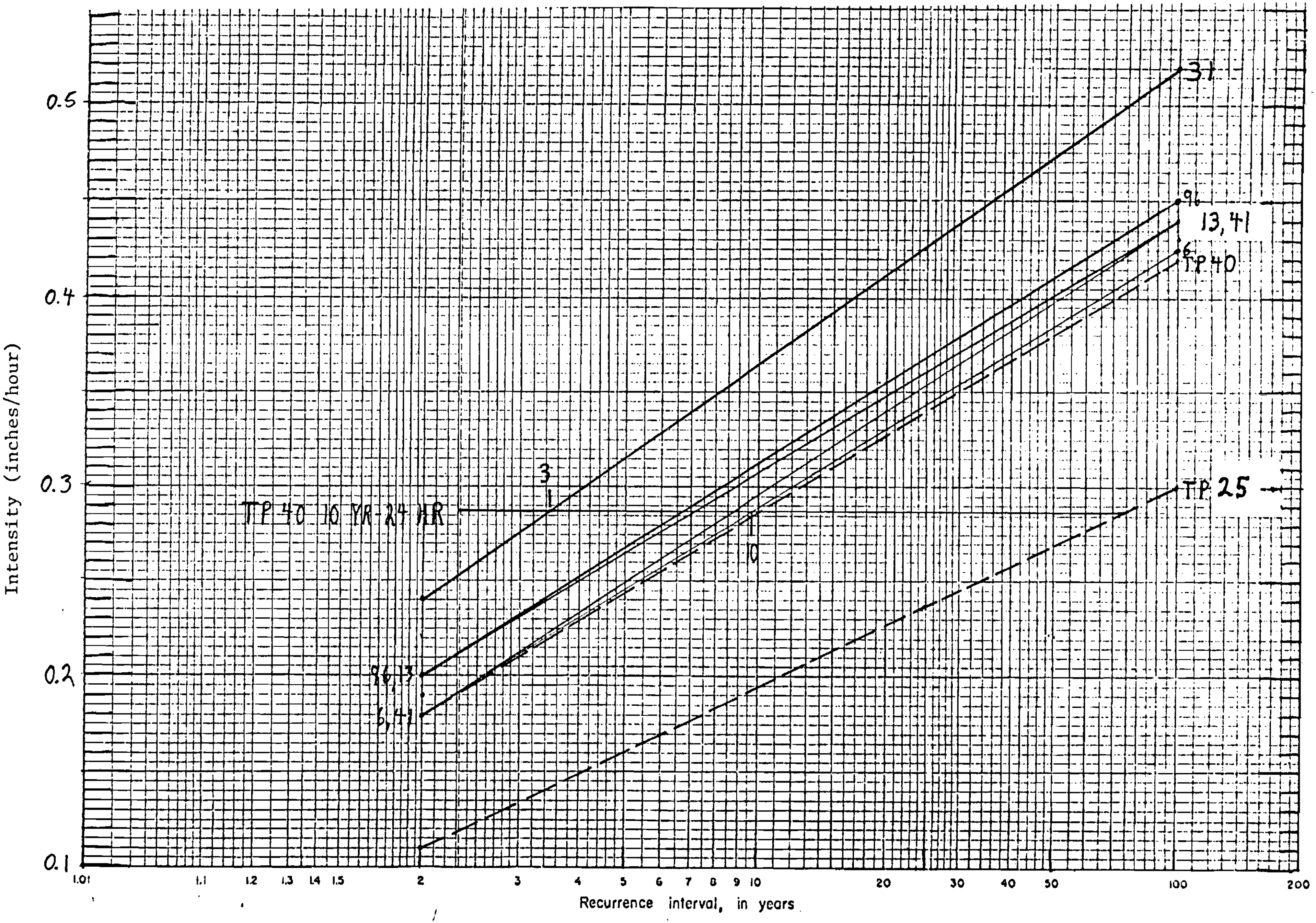


FIGURE 4 INTENSITY-FREQUENCY CURVE

24 HOUR DURATION



Figures 3 and 4 illustrate the extreme uncertainty in selecting precipitation frequency values. For example, the 10-year return period 1-hour duration intensity for Coweeta is about 2.3 inches per hour based on TP40 (see Figure 3). However, this intensity corresponds to calculated return periods of approximately 8, 13, 32, 54 and 56 years for gages 31, 13, 6, 41 and 96, respectively. Similarly, the TP25 10-year 1-hour intensity would represent a calculated return period ranging from 4 to 14 years for the Coweeta gages.

Figure 4 presents 24-hour duration intensity frequency curves. TP40 matches the lowest elevation gage (gage 6) quite well but significantly underestimates gage 31. For example, the TP40 10-year 24-hour intensity corresponds to a calculated 3-year return period for gage 31. TP25 severely underestimates the 24-hour intensity frequency values for all of the Coweeta gages.

Research Accomplishment

Different users of the outputs of this research would have different viewpoints as to its most significant accomplishments. The central thrust of this project is: (1) to demonstrate the uncertainty associated with the selection of precipitation frequency estimates in mountainous terrain; and (2) to examine the consequences that this uncertainty has on many commonly accepted hydrologic design procedures. However, the resulting reduction and classification of the Coweeta precipitation data provide information of value to many other aspects of engineering practice as well. This enhancement of the Coweeta data will be discussed first and the specific implications on hydrologic design will follow.

In 1934, personnel of the Coweeta Hydrologic Laboratory began installing an intensive raingage network. In the writer's opinion, a significant accomplishment of this research is the reduction classification and interpretation of data from this network.

The first of these accomplishments is a record of the maximum 1, 3, 6, 12 and 24 hour intensities for each storm of total depth greater than 0.25 inches. This was developed for each of the seven digitized recording gage records. This is viewed as a significant extension of the work of Coweeta Hydrologic Lab personnel who have developed similar records for durations of 5, 15, 30 and 60 minutes. One valuable study which could be performed from this information is to analyze the relative merits of using partial duration series rather than the annual series for developing precipitation frequency values. It would also serve as an independent check on the National Weather Service empirical factors for converting from annual series to partial duration.

The data of occurrence and time at which each maximum intensity began is also included. This information could be used to see if maximum intensities for the shorter durations are usually nested within the longer durations as is commonly assumed when developing "design storms" for hydrologic design. Also, seasonal trends for significant storms of record could be identified from the records developed for this research project.

The annual series provide a concise overview of significant storms for the Coweeta watershed, their date of occurrence and the storm type. The intensity-duration-frequency curve for a gage is developed from its annual series for the various durations, and hydrologic design (either in the form of a single value or a design storm) is in turn based on the intensity-duration-frequency curve. These research results, therefore, provide an insight into the actual basis of hydrologic design. Storm type trends, variations in values for different gages, and the persistence of individual storms to appear in the annual series for different durations and different gages can all be identified from these annual series. Another valuable study which could be performed using the results of this research is to fit the annual series to other probability distributions and to compare the quality of fit of the Gumbel and other probability distributions.

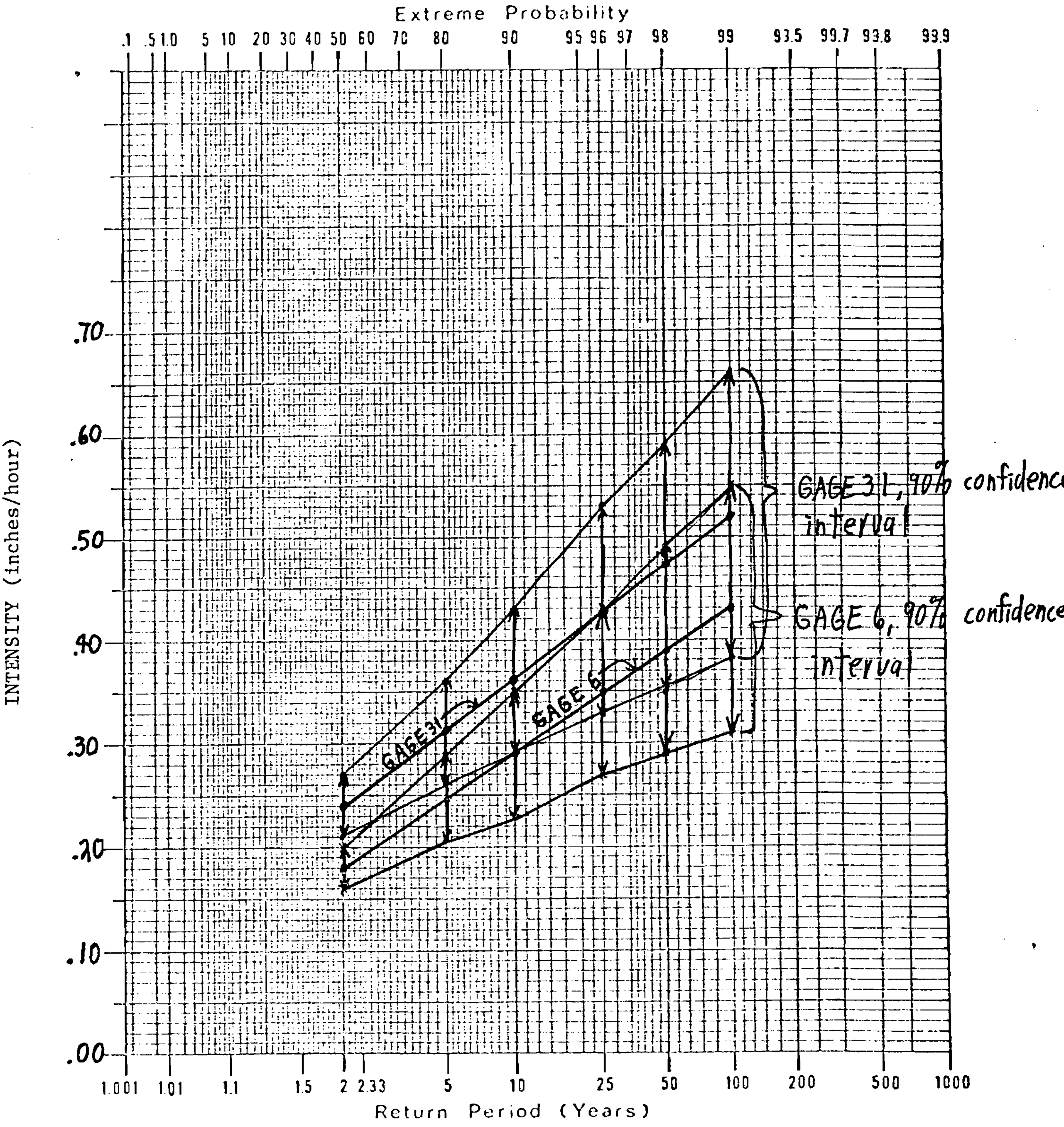
The foregoing paragraphs have described research accomplishments which relate primarily to the Coweeta precipitation data, per se. However, in the writer's opinion the most significant accomplishment of the research project is to demonstrate that the selection of intensity-duration-frequency values from normally available data is an extremely weak basis for hydrologic design especially for sites located in mountainous terrain. This is due to the extreme uncertainty associated with these intensity-duration-frequency values.

There are two primary sources of this uncertainty. The first is the statistical uncertainty in fitting a finite sample to an assumed probability distribution. This uncertainty is dependent primarily on the length of record and, of course, is true for flat as well as mountainous terrain. The second uncertainty results from the spatial variations in intensity-duration-frequency values and is particularly significant in mountainous terrain.

The design objective in selecting a particular return period is to arrive at the point where marginal cost equals marginal benefits. However, the designer only has a short sample from which to estimate the actual relationship between magnitude (in this case precipitation intensities) and return period. State-of-the-art hydrologic design does not consider this uncertainty, and failure to do so virtually eliminates the possibility of achieving the original design objective.

Figure 5 illustrates the combined effects of statistical uncertainty and physiographic variations within Coweeta watershed. It is a plot of 24 hour duration intensities versus return period for gages 6 and 31 calculated from 16 year records by the Gumbel method. Included in Figure 5 are the 90% confidence bands for the two curves. The combined effects are staggering. For

FIGURE 5 INTENSITY-FREQUENCY CURVE AND 90% CONFIDENCE LIMITS
(24 HOUR DURATION)



example, the lower 90% confidence band for the 24 hour, 100 year intensity at gage 6 is 0.31 inches/hour, while the upper band for gage 31 is 0.66 inches/hour. Thus, one has very little idea of the true 100 year, 24 hour intensity when both physiographic and statistical variability are considered.

Personnel Supported

The following two individuals have been supported in part by this research project.

Bruce H. Bradford, Assistant Professor
School of Civil Engineering
Georgia Institute of Technology

William J. March, Graduate Research Assistant
School of Civil Engineering
Georgia Institute of Technology

Mr. March holds a bachelors and masters degree in meteorology and did all of the storm typing reported on herein. Both Mr. March and Dr. Bradford participated in all other phases of the project.

Technical Papers

A technical paper entitled,"Precipitation Data for Two Appalachian Mountain Sites," is presently in preparation. The paper will be submitted to a publication series of the U. S. Department of Agriculture Forest Service and will be authored by Lloyd W. Swift and G. Bryant Cunningham of Coweeta Hydrologic Laboratory and Bruce H. Bradford and William J. March of Georgia Institute of Technology. The writer plans to submit at least one paper to a refereed journal such as Water Resources Research.

Acknowledgements

The writer would like to express his appreciation to the Forest Service, U. S. Department of Agriculture for permission to use their precipitation data. The writer is particularly greatful to Dr. Lloyd W. Swift and Mr. G. Bryant Cunningham of Coweeta Hydrologic Laboratory for their kind assistance in obtaining access to these data.

References

1. Linsley, R.H., Jr., M.A. Kohler, and J.L.H. Paulhus, Hydrology for Engineers. New York: McGraw-Hill Book Company, 1975.

2. "Rainfall Frequency Atlas of the United States," Weather Bureau Technical Paper No. 40, United States Weather Bureau, Washington, D.C. 1961.

3. "Rainfall Intensity-Duration-Frequency Curves for Selected Stations in the United States, Alaska, Hawaiian Islands, and Puerto Rico," Weather Bureau Technical Paper No. 25, United States Weather Bureau, Washington, D.C., Dec. 1955.

E-20-681

FINAL REPORT

Grant No. ENG 76-09438 entitled

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PRECIPITATION FREQUENCY IN MOUNTAINOUS TERRAIN

Bruce H. Bradford, Principal Investigator
School of Civil Engineering
Georgia Institute of Technology
Atlanta, Georgia

Submitted to

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NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

SUMMARY OF COMPLETED PROJECT

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4. GRANT NUMBER ENG76-09438	5. BUDGET DUR. (MOS) 18	6. PRINCIPAL INVESTIGATOR(S) Bradford	7. GRANTEE ACCOUNT NUMBER

8. SUMMARY (Attach list of publications to form)

Many commonly applied procedures in the design of hydrologic systems require estimates of precipitation intensity-duration-frequency values for the project site. The intent of these procedures is either to determine the economic optimum return period or to design the system for a prespecified level of performance. Although this would require accurate estimates of the precipitation-frequency values at the site, data on these values is quite sparse and the values are known to vary significantly, particular in mountainous terrain.

The objective of this project was to examine this problem. More specifically, the project involved the following: (1) to closely examine the variations in precipitation-frequency values within a small densely gaged mountain watershed; (2) to compare these values to published data which is the best normally available information for a project site; (3) to evaluate the consequences of failing to account for these variations in the design of hydrologic systems; and (4) to develop methods of improving estimates of precipitation-frequency values.

The precipitation data used for this project is from the USDA Forest Service's Coweeta Hydrologic Laboratory, a 4000 acre watershed located in the Nantahala Mountains in the southwest corner of North Carolina. Intensity-duration-frequency values for eight durations were developed form a common 16 year period for five recording raingages. Regression analysis is used to relate the precipitation-frequency values to the microscale physiographic features at the gage site.

The results of this project clearly show that the resolution of the best normally available precipitation-frequency data is not sufficient to account for the significant variations which occur over short distances in mountainous terrain. The results also demonstrate that significant improvement in precipitation-frequency estimates is possible with the use of regression analysis. Even with improved estimates, however, there is still a great deal of statistical and physiographic uncertainty associated with precipitation-frequency values. This suggests that the present day basis of treating these estimates deterministicly is inadequate and design procedures which explicitly incorporate these uncertainties are needed.

9. SIGNATURE OF PRINCIPAL INVESTIGATOR/ PROJECT DIRECTOR	TYPED OR PRINTED NAME Bruce H Bradford	DATE 10/4/78

NSF Form 98A (5-76)

INTRODUCTION

Drainage and flood control design is frequently based on "design storms" which have specified frequencies of recurrence (i.e. return period). The implied objective is to provide the "optimal" level of protection beyond which the marginal cost of additional protection exceeds the marginal benefit. Errors in estimates of the design storm either result in costly over design or under design, which is equally undesirable. The optimal level of performance will result, only if such design is based on accurate estimates of the precipitation-frequency characteristics of the project site.

Normally, the best available data for these estimates are publications such as Weather Bureau Technical Paper No. 25 [1955] and Hershfield [1961]. More resent sources show greater detail. Miller, et.al. [1973] covers eleven Western U.S. states with isopluvial maps presented at a scale of 1:2,000,000 and Frederick, et.al. [1977] covers the other 37 conterminous states at a scale of about 1:14,000,000 but only for durations from 5 to 60 minutes. The designer usually uses the intensity-duration frequency curve for the location nearest the project site (from Weather Bureau Technical Paper No. 25) or interpolates from the smoothed, small-scale isopluvial maps from publications such as Hershfield [1961]. However, neither approach accounts for the significant variations which would be anticipated over short distances in mountainous terrain.

It is obvious that it would be too expensive both in time and money to carefully gage every potential project site; and the data in the above references cannot be expected to always apply to small basins in regions of rapidly varying microclimates. Nevertheless it is interesting to examine the variations within a small watershed and the order of magnitude of errors which would result from using the best normally available design data.

The annual report for this project covered in detailed the activities of the first year. These included the following: (1) Cooperative agreement with the Forest Service for use of their precipitation data; (2) collection of the 56 Annual Series (largest event for each water year of record); (3) storm typing of each event in these annual series; and (4) computation of the intensity duration-frequency values for each gage. These activities will be reiterated briefly when necessary for continuity. However, the primary purposes of this report are: (1) to look closely at the variations in precipitation frequency within a small, densely gaged mountain watershed; (2) to measure the errors that would occur at this location from using what is normally the best available data; (3) to illustration the cost and performance consequences of these errors in a design example; (4) to correlate the precipitation frequency variations with physiographic features and/or more accurately known precipitation values (such as mean annual precipitation); (5) to test the statistical significance of the variations, errors and models of 1, 2, and 3, respectively; (6) to discuss what these findings indicate with respect to the need and opportunity for obtaining improved precipitation-frequency estimates in mountainous terrain; and finally (7) to suggest the need to explicitly incorporate the uncertainty associated with precipitation-frequency estimates into the design of water resources systems.

DATA AND SITE DESCRIPTION

The precipitation data used for this project are from the Coweeta Hydrologic Laboratory of the U.S. Department of Agriculture Forest Service. The laboratory is located in a mountainous watershed in the southwest corner of North Carolina approximately 62 miles west-southwest of Asheville, North Carolina. The 4000 acre watershed faces northeast and is in the Nantahala range of the Blue Ridge Mountains. Topography is quite steep with elevations ranging from 2220 to 5223 ft. over a horizontal distance of 3 miles.

Digitized precipitation records from seven recording gages were processed in this study. Elevations at the gage sites range from 2249 feet at Gage 6 (located on the valley floor) to 4475 feet at Gage 31 (located at Mooney Gap on a major ridgeline). The gage number, mean annual precipitation, elevation, record length and period of record for each gage are shown in Table 1. Fig. 1 shows the Coweeta watershed and the location of these gages.

CALCULATION OF INTENSITY-DURATION-FREQUENCY VALUES

Maximum 5, 15, 30 and 60 minute intensities for all storms of total depth greater than 0.25 inches were available from the computer printouts of computer programs written by Coweeta Hydrologic Lab personnel. The annual maximum intensity (i.e. annual series) for each gage and each of these durations was selected from these printouts. A computer program was then written to read the precipitation records for each gage; calculate the maximum 3, 6, 12 and 24 hour intensity for each storm of total depth greater then 0.25 inches; and select the annual maximum for each of these durations. In this way 56 annual series were collected (i.e. 7 gages times 8 durations).

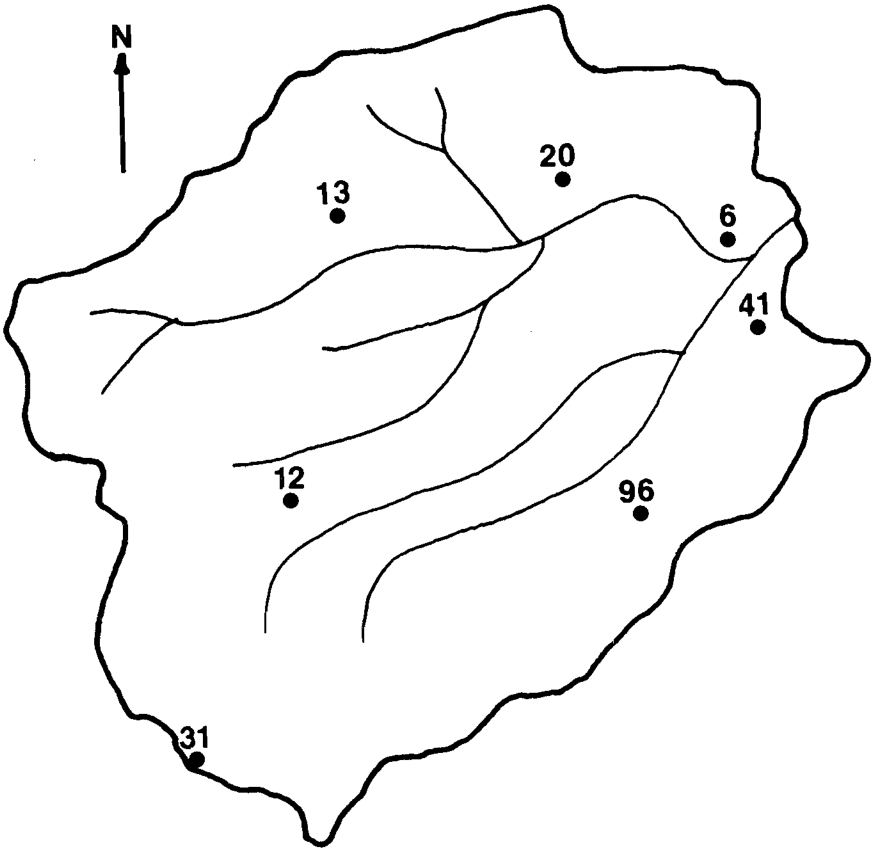

Figure 1. Recording Gage Location - Coweeta Watershed

TABLE 1

RECORDING GAGE INFORMATION

Gage Number	Elevation (ft.)	Mean Annual Precipitation (in.)	Record Length (yrs)	Period of Record
6	2249	73.32	39	1936-1974
12	3250	*	29	1942-1958, 1963-1974
13	3150	78.51	31	1944-1974
20	2425	*	8	1967-1974
31	4475	96.68	17	1959-1975
41	2500	73.96	17	1958-1974
96	2900	82.00	32	1944-1975

*Mean annual precipitation was not calculated for gages which were not used in the regression analysis.

The decision of which gages and which periods of record to use was based on a partially subjective evaluation of the trade-offs between the desire to use many gages, long records and a common period of record. Of course, for statistical reliability long records are desirable. However, for correlating intensity-duration-frequency values with physiographic features, it is desirable to have many gages (i.e. more degrees of freedom) encompassing a wide range of physiographic features. It was also found that it was necessary to use common periods of record in order to develop significant regression models. This left, essentially, four choices: (1) 8 years (1967-1974) and seven gages; (2) 12 years (1963-1974) and six gages; (3) 16 years (1959-1974) and 5 gages; and (4) 31 years (1944-1974) and 3 gages.

It was felt that a 12 year record was too short and that 3 gages were insufficient. Therefore, 16 years of record (1959-1975) and 5 gages (No's. 6, 13, 31, 41 and 96) were selected.

The annual series were fit to the extreme value Type I (Gumbel) distribution [Linsley, et al. 1975]. The Gumbel method was chosen for consistency with the procedures of the National Weather Service [Hershfield, 1961].

INTENSITY-DURATION-FREQUENCY RESULTS

Annual series intensity-duration-frequency values are listed in Table 2. The values have been grouped by duration in order to evaluate variations among the gages. The gages are listed in order of increasing mean annual precipitation. Values selected from what is the best normally available data for a project site are also presented. These values were interpolated from isopluvial maps for the appropriate duration and return period by locating (as closely as possible) the Coweeta watershed. Values for durations of 60 minutes and less were selected from Frederick, et al. [1977]. The 3, 6, 12 and 24 hour values were selected from Hershfield [1961]. The best normally available data values have been converted from their published form (partial-duration series) to annual series using the factors recommended by NWS [Hershfield, 1961]. The 24 hour duration values are plotted on extreme value paper in Figure 2. Appendix A contains plots similar to Figure 2 for each duration. The intensity-duration frequency curve for each of the 5 gages is also in Appendix A.

The intensity duration frequency information will be discussed in two parts. First, variations in the values calculated at the Coweeta gages will be pre-

Table 2 INTENSITY-DURATION-FREQUENCY CHARACTERISTICS OF COWEETA WATERSHED

5-Minute Intensities (in/hr)

Location	Return Period (yrs)					
	2	5	10	25	50	100
Gage 6	3.72	5.74	7.09	8.79	10.04	11.29
Gage 41	4.46	5.95	6.95	8.20	9.13	10.05
Gage 13	4.32	5.92	6.98	8.33	9.32	10.31
Gage 96	5.11	7.16	8.53	10.25	11.52	12.79
Gage 31	4.13	6.41	7.92	9.83	11.24	12.65
Best Normally Available Data	4.80	6.12	7.00	8.10	8.91	9.72

15-Minute Intensities (in/hr)

Location	Return Period (yrs)					
	2	5	10	25	50	100
Gage 6	2.49	3.37	3.95	4.69	5.24	5.78
Gage 41	2.76	3.49	3.98	4.60	5.05	5.51
Gage 13	2.87	3.56	4.02	4.60	5.03	5.45
Gage 96	3.14	4.08	4.71	5.50	6.08	6.66
Gage 31	3.08	3.99	4.59	5.36	5.92	6.48
Best Normally Available Data	3.20	4.27	4.99	5.88	6.54	7.20

30-Minute Intensities (in/hr)

Location	Return Period (yrs)					
	2	5	10	25	50	100
Gage 6	1.86	2.39	2.75	3.19	3.52	3.85
Gage 41	1.96	2.43	2.75	3.15	3.45	3.74
Gage 13	2.05	2.74	3.20	3.77	4.20	4.63
Gage 96	2.20	2.78	3.17	3.66	4.02	4.38
Gage 31	2.29	2.93	3.35	3.89	4.28	4.68
Best Normally Available Data	2.54	3.53	4.20	5.03	5.64	6.25

60-Minute Intensities (in/hr)

Location	Return Period (yrs)					
	2	5	10	25	50	100
Gage 6	1.24	1.61	1.85	2.16	2.39	2.62
Gage 41	1.30	1.60	1.80	2.06	2.25	2.44
Gage 13	1.36	1.85	2.17	2.59	2.89	3.19
Gage 96	1.41	1.67	1.85	2.07	2.24	2.40
Gage 31	1.50	2.03	2.39	2.84	3.17	3.50
Best Normally Avaliable Data	1.76	2.50	2.97	3.60	4.00	4.50

Table 2--cont'd.

3-Hour Intensities (in/hr)

Location	Return Period (yrs) 2	5	10	25	50	100
Gage 6	.63	.83	.97	1.14	1.27	1.40
Gage 41	.66	.88	1.02	1.20	1.34	1.47
Gage 13	.65	.93	1.11	1.34	1.51	1.68
Gage 96	.66	.88	1.02	1.20	1.33	1.46
Gage 31	.74	1.03	1.22	1.47	1.65	1.83
Best Normally Available Data	.73	.99	1.15	1.36	1.51	1.67

6-Hour Intensities (in/hr)

Location	Return Period (yrs) 2	5	10	25	50	100
Gage 6	.43	.56	.65	.76	.84	.92
Gage 41	.45	.58	.66	.77	.85	.93
Gage 13	.45	.63	.74	.89	1.00	1.11
Gage 96	.45	.60	.70	.83	.92	1.02
Gage 31	.52	.71	.84	1.00	1.11	1.23
Best Normally Available Data	.45	.61	.72	.87	.97	1.07

12-Hour Intensities (in/hr)

Location	Return Period (yrs) 2	5	10	25	50	100
Gage 6	.30	.41	.48	.57	.64	.70
Gage 41	.31	.42	.49	.58	.65	.71
Gage 13	.31	.43	.51	.61	.69	.76
Gage 96	.31	.42	.49	.58	.65	.71
Gage 31	.36	.49	.57	.68	.76	.84
Best Normally Available Data	.26	.36	.43	.52	.58	.64

24-Hour Intensities (in/hr)

Location	Return Period (yrs) 2	5	10	25	50	100
Gage 6	.18	.25	.29	.35	.39	.43
Gage 41	.18	.25	.30	.35	.39	.44
Gage 13	.20	.26	.31	.36	.40	.44
Gage 96	.20	.26	.31	.37	.41	.45
Gage 31	.24	.31	.36	.43	.47	.52
Best Normally Available Data	.15	.21	.25	.30	.34	.38

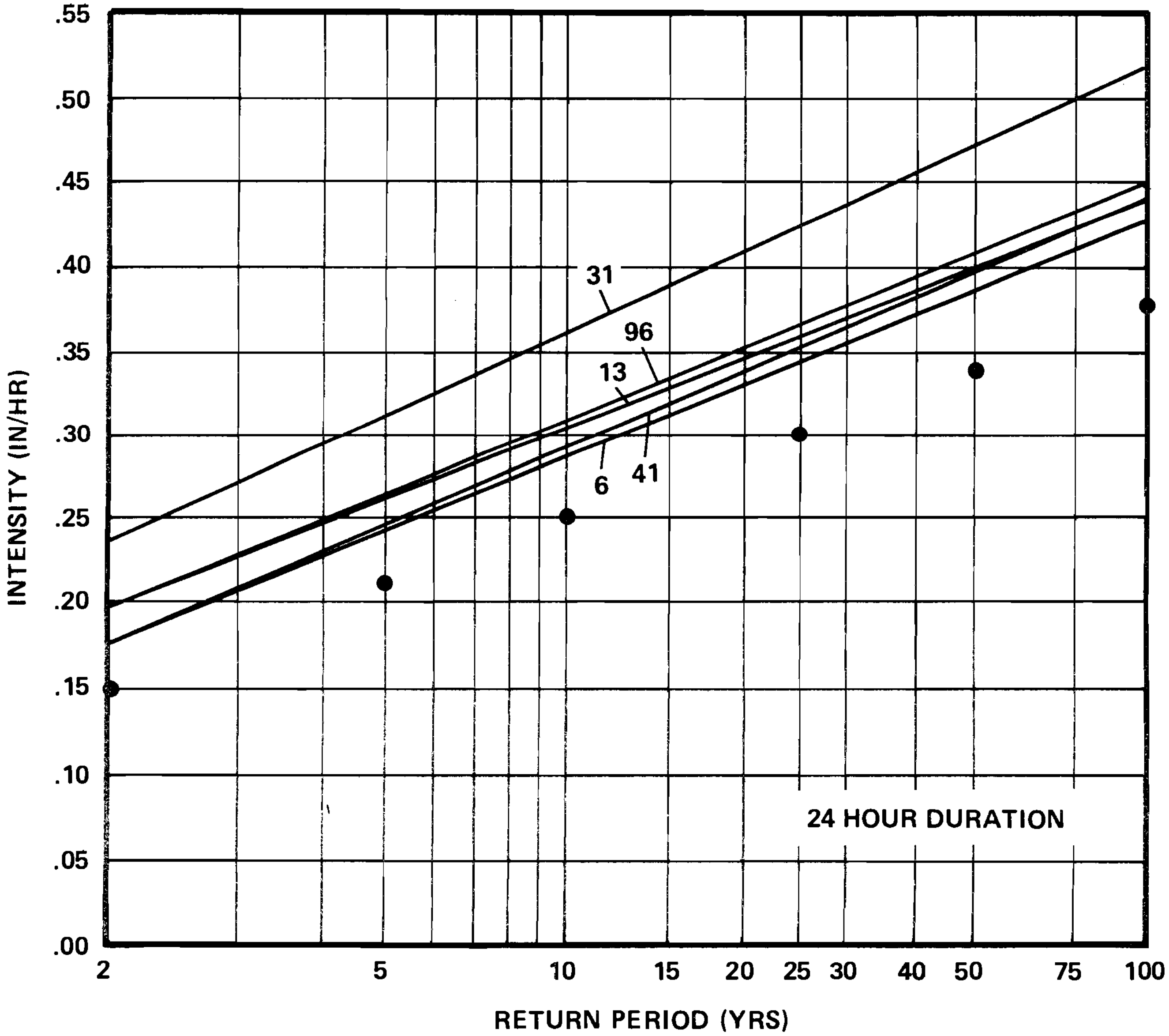

Figure 2. Precipitation-Frequency Curves, 24-Hour Duration

sented; then these values will be compared to the best normally available values. In both cases it will also be necessary to evaluate the statistical significance of these variations since the Coweeta values reported herein are based on short and, therefore, statistically unreliable records.

The measures of statistical significance will attempt to establish the confidence with which one can attribute precipitation-frequency variations to physiographic differences rather than statistical errors of estimation. These measures will be based on work by Kaczmarek [1957] who developed the probability distribution of estimates calculated by the Gumbel method. These distributions are function of the moments of the annual series, record length, and return period.

Precipitation-Frequency Variations at Coweeta

Table 2 shows the significant variations in precipitation-frequency values among the Coweeta gages, although none of the 5 gages are more than 3 miles apart. On the average the highest value (for a particular duration and frequency) exceeds the smallest value by about 25%. For the 3, 6, 12 and 24 hour durations Gage 6 (the lowest gage) has the lowest values and Gage 31 (the highest gage) has the highest values. The trends are somewhat more erratic for the shorter durations particularly for high return periods. Gage 6 still has the lowest 2-year return period intensity for all durations and Gage 31 has the highest 2-year intensity for all durations except 5 minutes and 15 minutes. Table 3 summarizes the precipitation-frequency ranges for the 2-year and 100-year return periods.

Of course the estimates of the more frequent events are much more reliable than the estimates of the rare events. Therefore, one would

TABLE 3. SUMMARY--COWEETA PRECIPITATION FREQUENCY VARIATIONS

2-YEAR VALUES

	Duration							
	5 min	15 min	30 min	60 min	3 hr	6 hr	12 hr	24 hr
Lowest Intensity (in/hr)	3.72(6)	2.49(6)	1.86(6)	1.24(6)	0.63(6)	0.43(6)	0.30(6)	0.18(6)
Highest Intensity (in/hr)	5.11(96)	3.14(96)	2.29(31)	1.50(31)	0.74(31)	0.52(31)	0.36(31)	0.24(31)
Ratio: Highest to Lowest Intensity	1.37	1.26	1.23	1.21	1.17	1.21	1.20	1.33

100-YEAR VALUES

	Duration							
	5 min	15 min	30 min	60 min	3 hr	6 hr	12 hr	24 hr
Lowest Intensity (in/hr)	10.05(41)	5.45(13)	3.74(41)	2.40(96)	1.40(6)	0.92(6)	0.70(6)	0.43(6)
Highest Intensity (in/hr)	12.79(96)	6.66(96)	4.68(31)	3.50(31)	1.83(31)	1.23(31)	0.84(31)	0.52(31)
Ratio: Highest to Lowest Intensity	1.27	1.22	1.25	1.46	1.29	1.34	1.20	1.21

NOTE: Gage numbers of the reported intensities are noted in parentheses.

be fairly confident that the reported differences in the 2-year values are due to the physiographic differences between the particular gage locations whereas the differences in the 100-year values might be attributed to uncertainty in estimating these values.

To quantify this conventional hypothesis testing was used [Benjamin and Cornell, 1970]. The distribution of the estimator (i.e., the observed intensity-duration-frequency value) was developed in accordance with Kaczmarek [1975]. The null hypothesis (H_o) chosen was that the actual values (for a particular return period and duration) at any two gages were equal. Rejection of the null hypothesis, therefore, would indicate a significant difference in the observed values while acceptance would indicate that the observed difference is not significant when one recognizes the inherently probabilistic nature of precipitation intensities. The "operating rule" was defined as follows:

accept H_o if the difference in the two observed values $(x_{T,D} - y_{T,D})$ lies within the interval $0 \pm C$

where: $x_{T,D}$ is the observed T year D duration value at one gage

$y_{T,D}$ is the observed T year D duration value at another gage

The value of C is calculated such that:

$$P[-C \leq X_{T,D} - Y_{T,D} \leq + C | H_o] = 1 - \alpha$$

where: $X_{T,D}$ is the (random variable) estimator of the actual T year D duration value at one gage

$Y_{T,D}$ is the (random variable) estimator of the actual T year D duration value at another gage

and α is the significance level.

In a test of this form the probability of rejecting H_o when it is true is α. Therefore, rejection of H_o at a low value of α provides a strong indication that the observed differences were due to physiographic difference at the gage sites.

A test of this form was performed for all return period-duration combinations and all possible gage combinations (i.e., 6 return periods x 8 durations x $\frac{5!}{3!2!}$ gage combinations = 480 tests). Each test found the lowest value of α at which H_o could be rejected.

Table 4 summarizes these results for the 2 and 100 year return periods. The comparisons in Table 4 are for the gage having the highest observed value vs. the gage having the lowest observed value. As expected, there are stronger indications of significant differences for the 2 year values than for the 100 year values. For example, at the 10% significance level the null hypothesis is rejected for all 2 year values except for the 3 hour duration and accepted for all 100 year values except for the 60 minute duration. For return periods between 2 and 100 years there is a rather orderly increase in the value of α required to reject the null hypothesis. For example, for the twenty-four hour duration values of 14, 21, 30 and 39 percent are required for the 5, 10, 25 and 50 year return periods, respectively.

Comparison to Best Normally-Available Data

Table 5 compares the highest and lowest intensities at Coweeta to the best normally available precipitation-frequency data.

As seen in Table 5 the best normally available precipitation-frequency data overestimates the Coweeta intensities for the 15, 30 and 60-minute durations and underestimates Coweeta for the 12 and 24-

TABLE 4

SUMMAR--SIGNIFICANCE TESTS ON OBSERVED DIFFERENCES IN INTENSITY-DURATION-FREQUENCY VALUES WITHIN COWEETA WATERSHED

2 YEAR RETURN PERIOD

	Duration							
	5 min	15 min	30 min	60 min	3 hr	6 hr	12 hr	24 hr
RATIO: Highest to Lowest Observed Intensities	1.37	1.26	1.23	1.21	1.17	1.21	1.20	1.33
Lowest α for rejection of H_o (%)	2	2	1	6	14	6	9	0

100 YEAR RETURN PERIOD

	Duration							
	5 min	15 min	30 min	60 min	3 hr	6 hr	12 hr	24 hr
RATIO: Highest to Lowest Observed Intensities	1.27	1.22	1.25	1.46	1.29	1.34	1.20	1.21
Lowest α for rejection of H_o (%)	32	34	28	9	26	21	44	41

NOTE: Low α implies a significant difference in observed values.

TABLE 5

HIGHEST AND LOWEST COWEETA INTENSITIES AS A FRACTION OF BEST NORMALLY AVAILABLE DATA VALUES

Return Period (YRS)	Ratio	Duration							
		5 min	15 min	30 min	60 min	3 hr	6 hr	12 hr	24 hr
2	Highest	1.06(96)	.98(96)	.90(31)	.85(31)	1.01(31)	1.16(31)	1.38(31)	1.60(31)
	Lowest	.78(6)	.78(6)	.73(6)	.70(6)	.86(6)	.96(6)	1.15(6)	1.20(6)
5	Highest	1.17(96)	.96(96)	.83(31)	.81(31)	1.04(31)	1.16(31)	1.36(31)	1.48(31)
	Lowest	.94(6)	.79(6)	.68(6)	.64(41)	.84(6)	.92(6)	1.14(6)	1.19(6)
10	Highest	1.22(96)	.94(96)	.80(31)	.80(31)	1.06(31)	1.17(31)	1.33(31)	1.33(31)
	Lowest	.99(41)	.79(6)	.65(6)	.61(41)	.84(6)	.90(6)	1.12(6)	1.16(6)
25	Highest	1.27(96)	.94(96)	.77(31)	.79(31)	1.08(31)	1.15(31)	1.31(31)	1.43(31)
	Lowest	1.01(41)	.78(13)	.63(41)	.57(41)	.84(6)	.87(6)	1.10(6)	1.17(6)
50	Highest	1.29(96)	.93(96)	.76(31)	.79(31)	1.09(31)	1.14(31)	1.31(31)	1.38(31)
	Lowest	1.02(41)	.77(13)	.61(41)	.56(96)	.84(6)	.87(6)	1.10(6)	1.15(6)
100	Highest	1.32(96)	.92(96)	.75(31)	.78(31)	1.10(31)	1.15(31)	1.31(31)	1.37(31)
	Lowest	1.03(41)	.76(13)	.60(41)	.53(96)	.84(6)	.86(6)	1.09(6)	1.13(6)

NOTE: Gage numbers with the highest and lowest intensities are shown in parentheses.

hour durations. The 5-minute Coweeta values bracket the best normally available values for the 2, 5, and 10 year return periods, but the best normally available data values underestimate all the Coweeta gages for the 25, 50, and 100-year values. The 3-hour and 6-hour Coweeta values bracket the corresponding best data values for all return periods.

The level of confidence associated with these differences should also be evaluated. In this test the null hypothesis is that the actual value at a Coweeta gage is equal to the corresponding best available data value. The primary difference from the previous test is that the best normally available data value $Y_{T,D}$ is not a random variable, it is a single valued, published intensity. This test was performed for all return period-duration combinations and each gage (i.e., 6 return periods x 8 durations x 5 gages = 240 tests). Again the lowest value of α at which H_o could be rejected was found.

Table 6 lists this value of α for gages 6 and 31 for the 2 and 100 year return periods. It also indicates whether the observed Coweeta intensity was higher or lower (H or L) than the best normally available data value. The differences in the 2 year values generally have greater statistical significance than the differences in the 100 year values. For example, note that for gage 6 2-year values the null hypothesis is rejected at the 10% level for all but one duration and accepted for gage 6 100-year values for all but two durations. Again there is usually an orderly increase in the value of α required to reject the null hypothesis. For example, for the twenty-four hour duration at gage 6 values of 13, 27, 32 and 41 percent are required for the 5, 10, 25, and 50 year return periods, respectively.

TABLE 6

SUMMARY--SIGNIFICANCE TESTS ON DIFFERENCES BETWEEN BEST NORMALLY AVAILABLE AND OBSERVED COWEETA VALUES

2 YEAR RETURN PERIOD

	Duration							
Gage Number	5 min	15 min	30 min	60 min	3 hr	6 hr	12 hr	24 hr
6	1L	0L	0L	0L	2L	46L	8H	3H
31	16L	54L	6L	2L	87H	8H	0H	0H

100 YEAR RETURN PERIOD

	Duration							
Gage Number	5 min	15 min	30 min	60 min	3 hr	6 hr	12 hr	24 hr
6	46H	14L	0L	0L	23L	28L	61H	48H
31	23H	47L	2L	9L	61H	45H	15H	9H

NOTE: Table lists the lowest value of α for rejection of null hypothesis (%). A low α implies a significant difference in observed Coweeta and best normally available values.

H indicates the observed Coweeta intensity is higher than the best data value.
L indicated the observed Coweeta intensity is lower than the best data value.

An interesting and important comparison is to look at the intended return period when selecting values from the best normally available data versus the actual return period based on the Coweeta gage records. This would reflect the desired performance versus the resulting performance of hydrologic designs which are based on intensity-duration-frequency values. For example, the best normally available 25-year, 24-hour intensity for Coweeta is 0.30 in/hr. By referring to Figure 2 one notes that this intensity corresponds to approximately a 12-year value for Gage 6 and a 4-year value for Gage 31.

Table 7 shows the range of Coweeta return periods which would result from choosing intensities from the best normally available data. A return period greater than the desired indicates over design at above optimum cost. A return period less than the desired indicates under design and less than optimum performance.

It is clear from Table 7 that in most instances the actual performance of a system would be quite different than the desired performance.

Design Example

Probably the most common use of precipitation-frequency data is in the design of storm drainage systems but the rational method. Grigg and O'Hearn [1976] developed relationships between drainage cost, return period and level of urbanization for planning type estimates of storm drainage systems. Their development revealed that costs (C) were proportional to pipe diameter (D) to the 1.663 power, D was proportional to flowrate (Q) to the .375 power, and Q was proportional to rainfall intensity (I) to the first power. Thus, C is proportional to I to the 1.663 x .375 = .624 power.

TABLE 7

RANGE OF RETURN PERIODS BASED ON OBSERVED DATA VS. DESIRED RETURN PERIOD WHEN DESIGN IS BASED ON BEST NORMALLY AVAILABLE DATA

Desired Return	Duration							
Period (yrs)	5 min	15 min	30 min	60 min	3 hr	6 hr	12 hr	24 hr
2	2-3	2-4	3-7	3-8	2-3	1.5-2	1.2-1.5	1.1-1.5
5	3-6	6-15	13-60	13-150	4-10	3-8	2-3	1.5-3
10	5-10	14-48	42->200	34->900	8-26	5-20	3-6	2-6
25	8-23	40-200	180->1000	120->1000	17-80	12-65	6-15	4-12
50	12-42	90->500	>400->1000	>300->1000	30-200	22-150	10-30	7-23
100	19-80	200->1000	>1000->1000	>1000->1000	50->900	40->300	18-55	13-44

NOTE: Only lower bounds are indicated on extrapolation to return periods greater than 200 years.

In the use of the rational method the storm duration is assumed to equal the time of concentration. Grigg and O'hearn presented a case study of a drainage system in Englewood Colorado. Time of concentrations in the system varied from 15 minutes to 40 minutes. This is an average (geometric mean) time of concentration of 24.5 minutes. The cost for a 5 year return period and 40% imperviousness was $1394/acre.

The comparison to be made here is to compare the desired cost and performance of this system if it were located at Gage 31 to the actual cost and performance that would result from utilizing the best normally available precipitation-frequency information. A similar comparison will be made for the system assuming it to be located at Gage 6. In both cases the desired return period is 5 years.

The following precipitation-frequency information is needed to make this comparison:

Englewood, Colo. 24.5 min 5 year intensity = 2.3in/hr

Gage 6 24.5 min 5 year intensity = 2.75in/hr

Gage 31 24.5 min 5 year intensity = 3.36in/hr

Best Available Data 24.5 min 5 year intensity = 4.0in/hr

Gage 6 Return Period (for duration = 24.5 min, intensity = 4.0 in/hr) = 55 years

Gage 31 Return Period (for duration = 24.5 min, intensity = 4.0in/hr) = 15 years

Since cost varies with the .624 power of intensity the system cost based on the best available data for Coweeta could be estimated as follows:

$$C = a\ I^{.624}$$

Englewood $C = \$1394/\text{acre}$ for $I = 2.3\text{in/hr}$. Therefore $a = 1394/2.3^{.624} = 829.0$

Coweeta (best available data) $C = 829.0\ (4)^{.624} = \$1969/\text{acre}$

However, the desired cost for a microclimate like Gage 6 would be:

Gage 6 $C = 829.0\ (2.75)^{.624} = \$1558/\text{acre}$

and for Gage 31 $C = 829\ (3.36)^{.624} = \$1776/\text{acre}$

These results are summarized in the following table:

	Desired Cost	Actual Cost	$\frac{\text{Actual Cost}}{\text{Desired Cost}}$	Desired Performance	Actual Performance
Gage 6	\$1558/acre	\$1969/acre	1.26	5 year	55 year
Gage 31	\$1766/acre	\$1969/acre	1.11	5 year	15 year

Regression Analysis

One possibility for obtaining better estimates of precipitation-frequency values is to determine empirical relationships between these values and more readily available parameters which affect precipitation-frequency values. This technique was used extensively by Miller, et al. [1973] to estimate precipitation-frequency values in the western United States. Their findings indicated that parameters such as elevation, slope, aspect, exposure, roughness and mean annual precipitation explained a significant amount of the variations in precipitation-frequency values. Of course, mean annual precipitation at a project site is not a measurable physiographic feature like the others. However, it can be estimated with much greater resolution and accuracy than can precipitation frequency values, since it can be measured without the use of recording gages.

The first three variables to be investigated were elevation, slope and aspect. Separate regression equations were developed for each combination of the 8 durations and the 2 and 100 year return periods. Regression equations for the other return periods were not necessary, since the Gumbel distribution requires only two points to define the entire precipitation-frequency curve.

Of these three parameters, elevation was usually the best single predictor of intensity for a given duration and return period. Generally, the 2-year intensities can be predicted more accurately than the 100-year intensities, and the long duration intensities can be predicted more accurately than the short duration intensities. Table 8 lists which parameter was the best single predictor, the correlation coefficient and the coefficient of determination. The coefficient of determination is the ratio of explained variations to total variations. As seen in Table 8 between 85 and 98 percent of the variations in the 2-year intensities are explained for durations greater than or equal to 1 hour. Similarly between 71 and 94 percent of the variations in the 100-year intensities are explained for durations greater than or equal to 1 hour.

The information shown in Table 8 is for single linear regression equations of the form $y=a_o + a_1 x_1$ where y is the dependent variable (i.e. intensity for a particular duration and return period) and x_1 is

TABLE 8

RESULTS OF CORRELATING PRECIPITATION-FREQUENCY VALUES WITH ELEVATION, SLOPE AND ASPECT

	2 YEAR RETURN PERIOD			100 YEAR RETURN PERIOD		
Duration	Most Significant Variable	Correlation Coefficient	Coefficient of Determination	Most Significant Variable	Correlation Coefficient	Correlation of Determination
5-Min	Slope	.60	.36	Elevation	.51	.26
15-Min	Slope	.93	.86	Elevation	.50	.25
30-Min	Slope	.89	.79	Elevation	.81	.66
60-Min	Elevation	.92	.85	Elevation	.84	.71
3-Hrs	Elevation	.94	.88	Elevation	.94	.88
6-Hrs	Elevation	.96	.92	Elevation	.97	.94
12-Hrs	Elevation	.96	.92	Elevation	.97	.94
24-Hrs	Elevation	.99	.98	Elevation	.95	.90

the most significant independent variable (i.e. elevation in 13 of the 16 cases). Addition of the second most significant variable did not substantially improve the correlations. Also, log-linear regression equations of the form $\log y = \log c_o + c_1 \log x_1$ (or equivalently, $y = c_o x_1^{c_1}$) were developed. However, in most cases they did not fit the data as well as the linear equations.

The next predictor investigated was mean annual precipitation (MAP). Overall the quality of predictions using MAP and elevation was about equal. This is to be expected since the correlation coefficient between the two was 0.969.

Hypothesis tests were also used to test the significance associated with the correlation of precipitation frequency with elevation or MAP. The null hypothesis is that the true correlation coefficient between intensity-durations-frequency values and the independent variable (i.e. elevation or MAP) is zero. Table 9 lists the lowest value of α at which the null hypothesis could be rejected for the 2 year and 100 year return periods. Rejection of the null hypothesis at a low value of α implies a statistically significant correlation between intensity-duration-frequency values and the independent variable. The significance is much stronger for larger durations. For example, with MAP the null hypothesis is rejected for the 2 year values at the 10% significance level for durations of 30 minutes and greater.

Mean annual precipitation should be a particularly useful parameter for correlations over large areas, since it is directly related to the precipitation process. To illustrate this a correlation of the 2-year, 24 hours intensity with normal annual precipitation was made using the seven cities of: Atlanta, GA; Indianapolis, IND; Charlotte, N.C.;

TABLE 9

SIGNIFICANCE LEVEL (α) FOR ELEVATION AND MEAN ANNUAL PRECIPITATION

2 YEAR RETURN PERIOD

DURATION	ELEVATION SIGNIFICANCE LEVEL (%)	MEAN ANNUAL PRECIPITATION SIGNIFICANCE LEVEL (%)
5 min	100	90
15 min	20	16
30 min	16	4
60 min	3	2
3 hrs	2	1
6 hrs	1	1
12 hrs	1	1
24 hrs	0	0

100 YEAR RETURN PERIOD

DURATION	ELEVATION SIGNIFICANCE LEVEL (%)	MEAN ANNUAL PRECIPITATION SIGNIFICANCE LEVEL (%)
5 min	38	19
15 min	40	20
30 min	10	14
60 min	7	16
3 hrs	2	8
6 hrs	0	4
12 hrs	0	4
24 hrs	1	0

Raleigh, N.C.; Pittsburgh, PA; Chattanooga, TN; and Nashville, TN. The correlation coefficient was 0.84 with the following equation:

$$y=-.001 + .0031\,x \qquad \text{(Eq. 1)}$$

where: y=2 year, 24 year intensity in inches per hour and

x=normal annual precipitation (1941-1970) in inches.

This is fairly close to the corresponding equation developed for Coweeta:

$$y=-.006 + .0026\,x \qquad \text{(eq. 2)}$$

It is interesting to note that the use of Equation 1 to estimate the Coweeta 2 year, 24 hour intensities would yield improved designs over the best normally available data (average error ≃ 20% vs. average error ≃ 30%). Equations 1 overestimates the observed Coweeta 2 year, 24 hours intensities by about 0.04 in/hr. This is probably due to the fact that Coweeta is sheltered from the prevailing winds. Exposure was not helpful in explaining the microscale variations within Coweeta but would probably be significant for correlations over larger areas.

SUMMARY AND CONCLUSIONS

The foregoing sections of this paper have presented a rather detailed analysis of the precipitation-frequency characteristics of one small, mountain watershed. The most salient findings are as follows:

(1) Precipitation-frequency values estimated from precipitation records using standard statistical methods will normally vary significantly over short distances in mountainous terrain.

(2) Although there is a great deal of statistical uncertainty associated with these estimates, the variations can, for the most part, be attributed to physiographic differences at the various gaging points.

(3) The resolution of the best normally available precipitation-frequency data is not sufficient to account for these micro-scale variations in precipitation-frequency values.

(4) Often the best normally available precipitation-frequency data does not even provide a good estimate of the average precipitation-frequency values for a small, mountainous watershed.

(5) Often, the cost and performance of systems designed using the best normally available data would be quite different than the "optimum"cost and performance.

(6) The variations in precipitation-frequency values over short distances in mountainous terrain are strongly correlated with elevation and mean annual precipitation.

Perhaps one general conclusion can be made from these observations: there is a low probability that an engineer can achieve the desired level of performance when the project site is in mountainous terrain and his design is based on the best normally available precipitation-frequency data. It is necessary, therefore, to establish a methodology for obtaining better estimates of precipitation-frequency values and/or establish a better basis for hydrologic design.

The writers' believe that significant improvement in precipitation-frequency estimates is possible with the use of regression analysis. This belief is based on the successful use of this technique by Miller, et al. [1973], as well as the significant correlation of precipitation-frequency with elevation and mean annual precipitation at the Coweeta gages, which serves as a confirmation of the technique for small watersheds in mountainous terrain.

Even with improved estimates, however, there will still be a great deal of uncertainty associated with these values. In mountainous terrain the primary uncertainty is probably due to phsiographic differences. There is also a great deal of statistical uncertainty associated with these values which, of course, is not restricted to areas of rapid physiographic variability. However, present design procedures make no attempt to take these uncertainties into account. In orther words, the optimim return period is chosen as if the intensity corresponding to that return period is precisely known. A more rational basis would be to treat the estimate of the particular precipitation-frequency value as a random variable, study the moments and distribution of this estimator, and choose the design level which would minimize the "expected costs" of over design or under design. Recent research has established guidelines for this type of an approach [Tang and Yen, 1972; and Slack, et al., 1975]. It is believed that this paper demonstrates the need to apply such as approach to hydrologic designs which are based on estimates of precipitation-frequency values.

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Georgia Institute of Technology

William J. March, Graduate Research Assistant
School of Civil Engineering
Georgia Institute of Technology

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LITERATURE CITED

Benjamin, J. R. and C. A. Cornell, Probability, Statistics, and Decision for Civil Engineers, McGraw-Hill Book Co., pp 403-419.

Frederick, R. A., V. A. Myers, and E. P. Auciello, 1977. Five-to-60-Minute Precipitation Frequency for the Eastern and Central United States, NOAA Technical Memorandum NWS HYDRO-35, National Oceanic and Atmospheric Administration, Silver Spring, MD.

Grigg, N. S. and O'Hearn, J. P., "Development of Storm Drainage Cost Functions," Journal of the Hydraulics Division, ASCE, Vol. 102, No. HY4, Proc. Paper 12069, April, 1976, pp. 515-526.

Hershfield, D. M., 1961. Rainfall Frequency Atlas of the United States for Durations from 30 Minutes to 24 Hours and Return Periods from 1 to 100 Years, Weather Bureau Technical Paper No. 40, Washington, D.C.

Kaczmarek, A., 1957. Efficiency of the Estimation of Floods with a Given Return Period, International Association of Scientific Hydrology, General Assembly of Toronto, Volume III, pp. 144-159.

Linsley, R. K., M. A. Kohler, and J. L. H. Paulhus, 1975. Hydrology for Engineers, 2nd ed., McGraw-Hill Book Co., pp. 345-349.

Miller, J. F., R. K. Frederick, and R. J. Tracey, 1973. Precipitation Frequency Atlas of the Western United States, NOAA Atlas 2, National Oceanic and Atmospheric Administration, Silver Springs, MD.

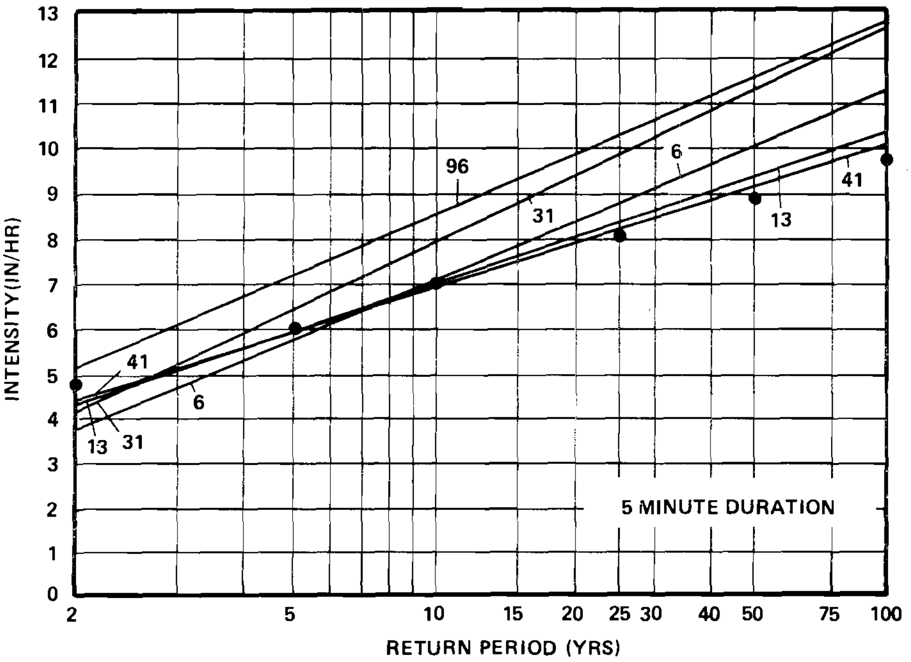
Slack, J. R., J. R. Wallis, and N. C. Matalas, 1975. On the Value of Information to Flood Frequency Analysis, Vol. 11, No. 5, Water Resources Research, pp. 629 - 647.

Tang, W. H. and B. C. Yen, 1972. Hydrologic and Hydraulic Design Under Uncertainty, Proceedings of the International Symposium on Uncertainties in Hydrology and Water Resources Systems, Vol. 2, pp. 868 - 882.

U. S. Weather Bureau, 1955. Rainfall Intensity-Duration-Frequency Curves for Selected Stations in the United States, Alaska, Hawaiian Islands, and Puerto Rico, Weather Bureau Technical Paper No. 25, Washington, D.C.

APPENDIX A

Appendix A contains plots of intensity-duration frequency values calculated for the common sixteen year record for each of the five gages. The first four figures are intensity versus return period plots for each of eight durations. These are presented in this form for comparison between gages. The last five figures (one for each gage) are in the usual published form of intensity-duration-frequency curves.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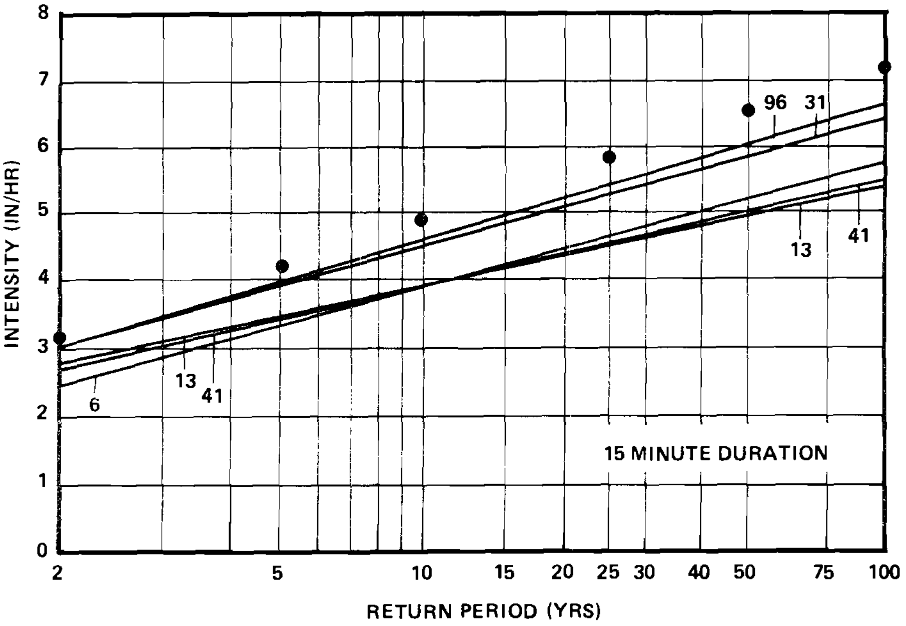
12
11
10
9
8
7
6
5
4
3
2
1
0
2
5
10
15
20
25
30
40
50
75
100
RETURN PERIOD (YRS)
96
31
6
41
13
41
6
13
31
5 MINUTE DURATION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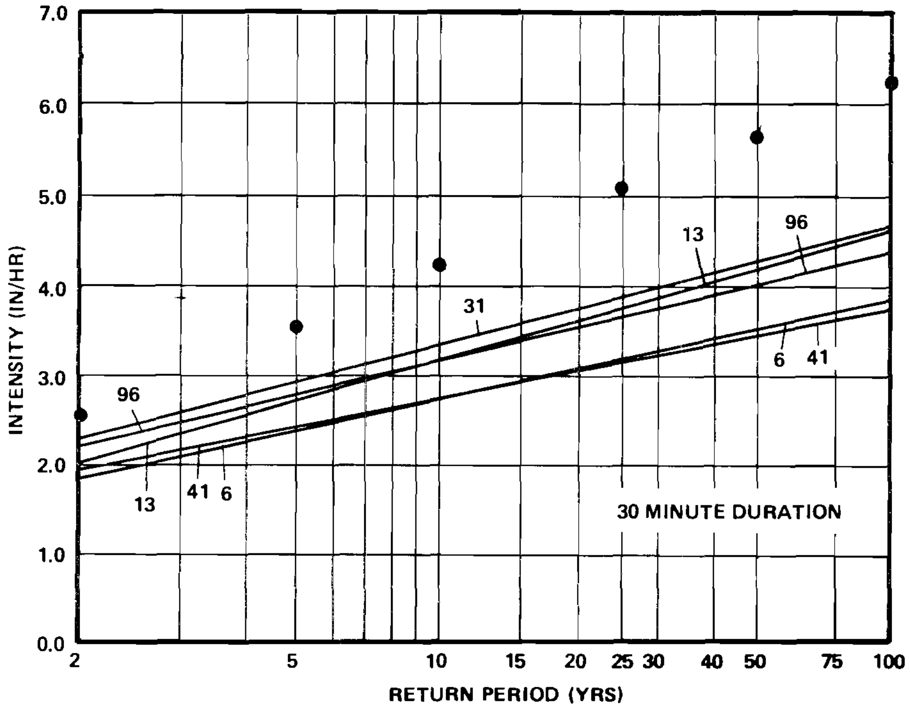
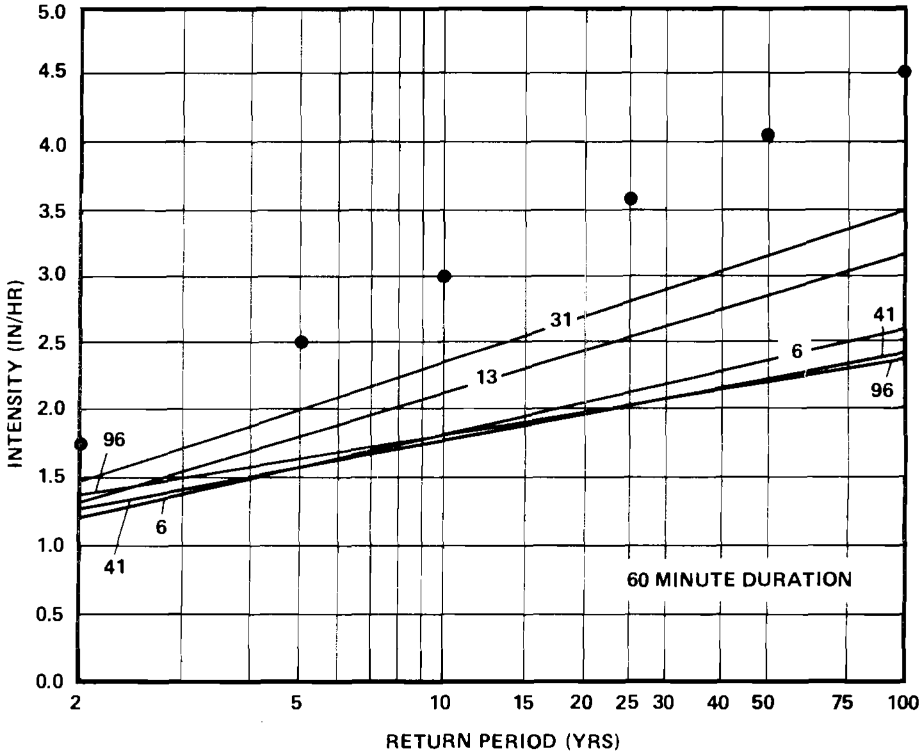
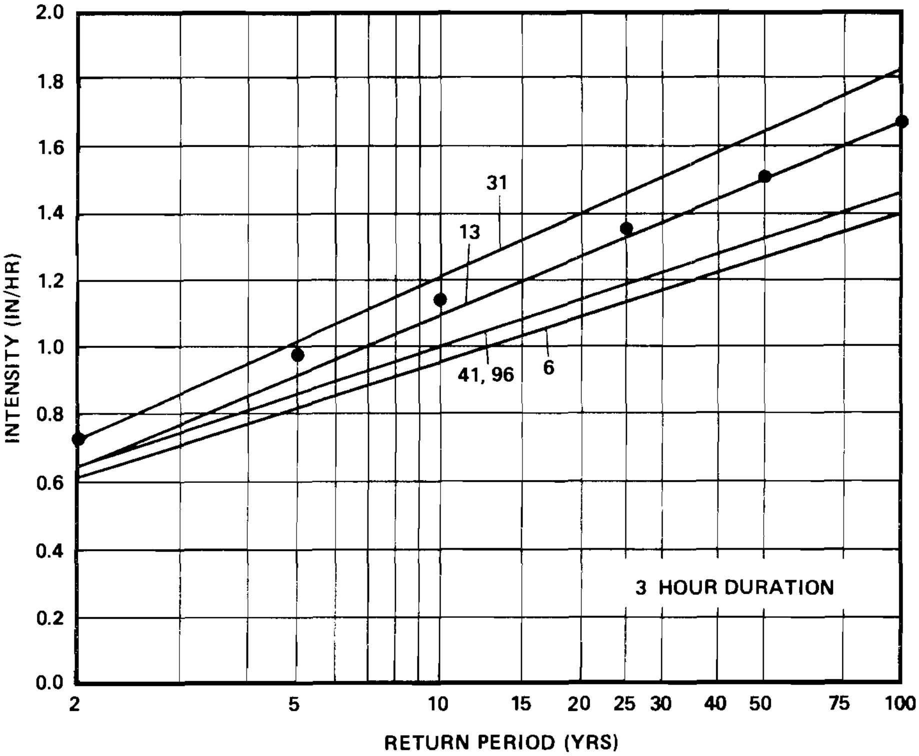
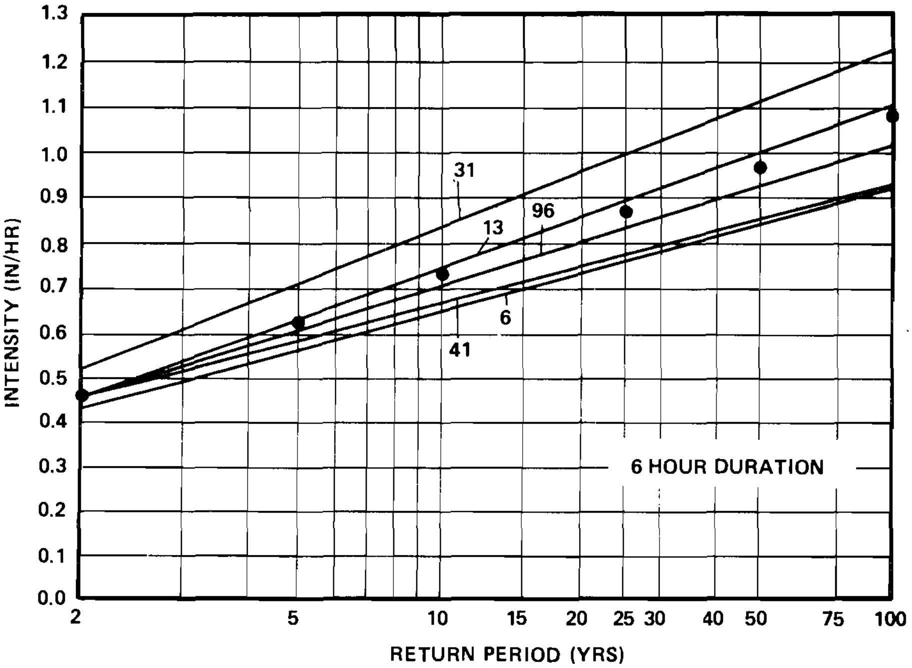
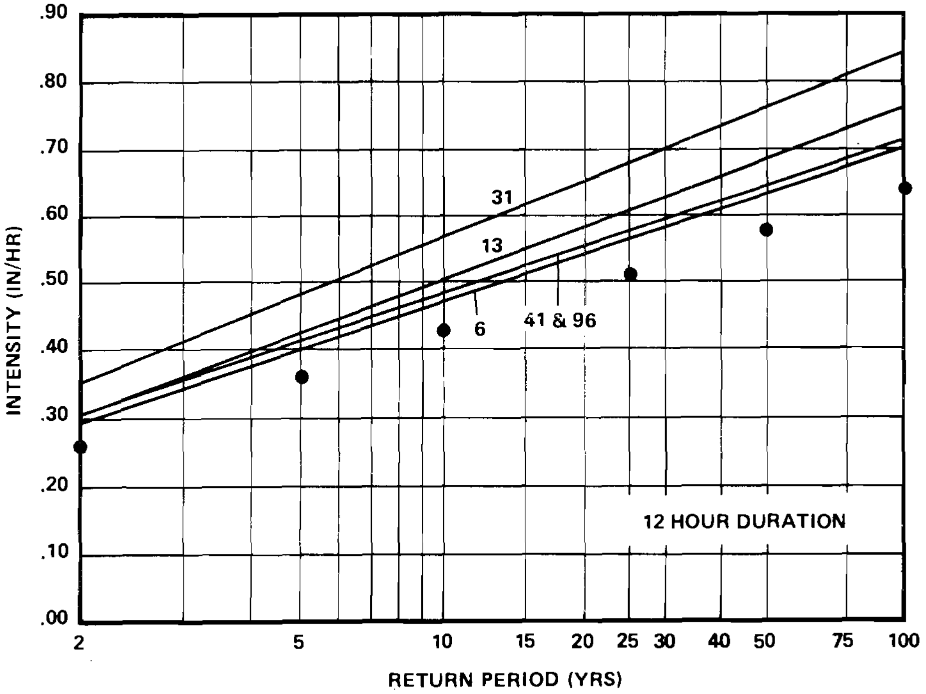
8
7
6
5
4
3
2
1
0
2
5
10
15
20
25
30
40
50
75
100
RETURN PERIOD (YRS)
96
31
13
41
13
41
6
15 MINUTE DURATION


7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
INTENSITY (IN/HR)
2
5
10
15
20
25
30
40
50
75
100
RETURN PERIOD (YRS)
96
13
41
6
31
13
96
6
41
30 MINUTE DURATION

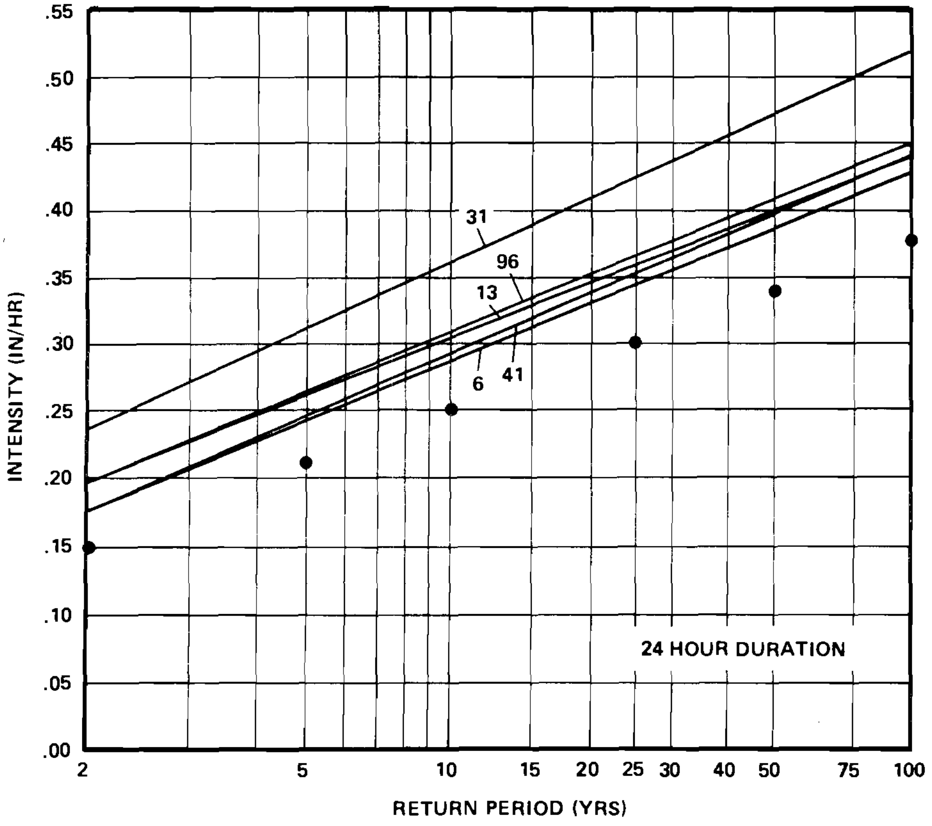

5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
INTENSITY (IN/HR)
2
5
10
15
20
25
30
40
50
75
100
RETURN PERIOD (YRS)
31
13
6
41
96
96
6
41
60 MINUTE DURATION


2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
INTENSITY (IN/HR)
31
13
41, 96
6
3 HOUR DURATION
2
5
10
15
20
25
30
40
50
75
100
RETURN PERIOD (YRS)

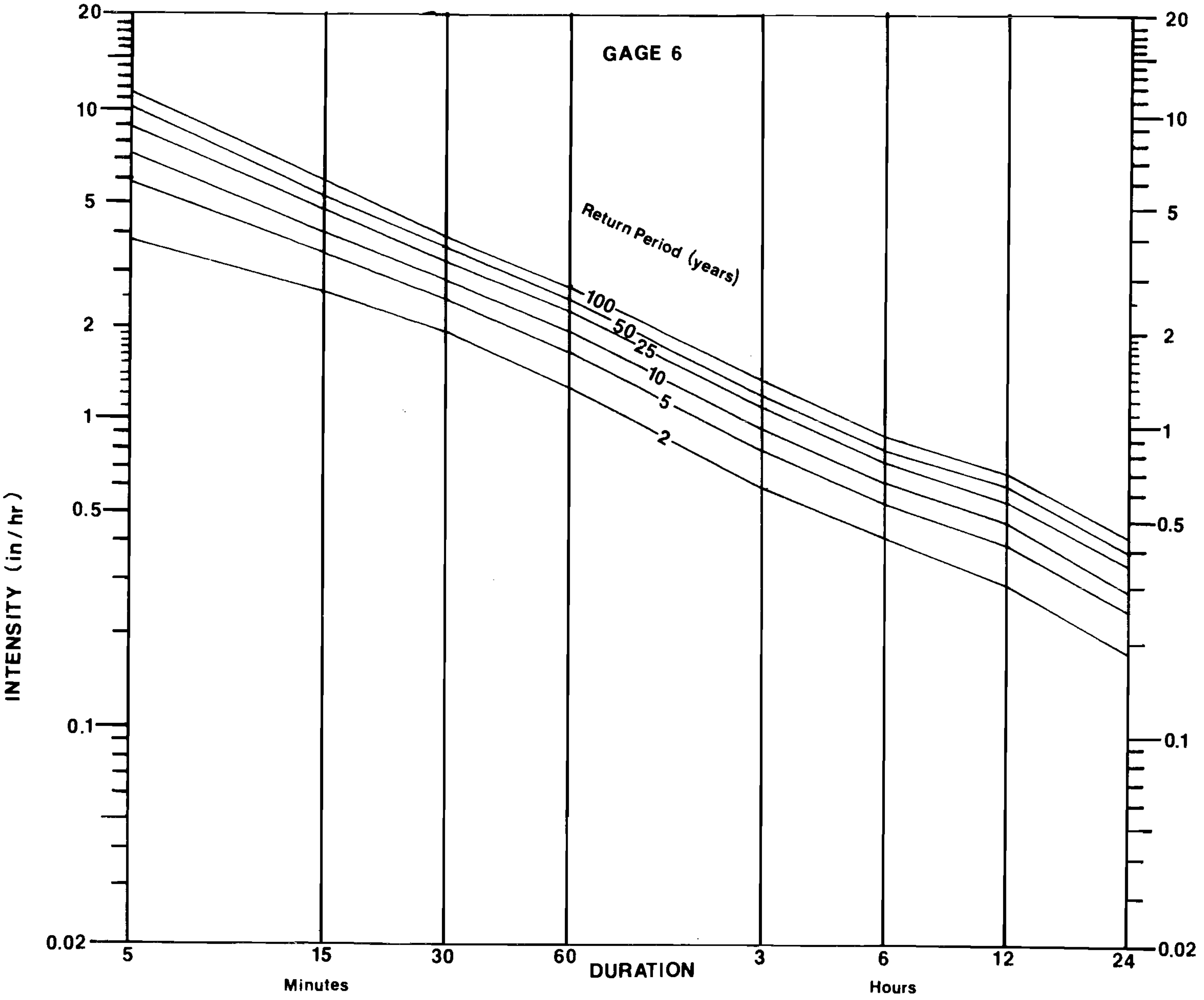

1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
INTENSITY (IN/HR)
31
96
13
6
41
6 HOUR DURATION
2
5
10
15
20
25
30
40
50
75
100
RETURN PERIOD (YRS)

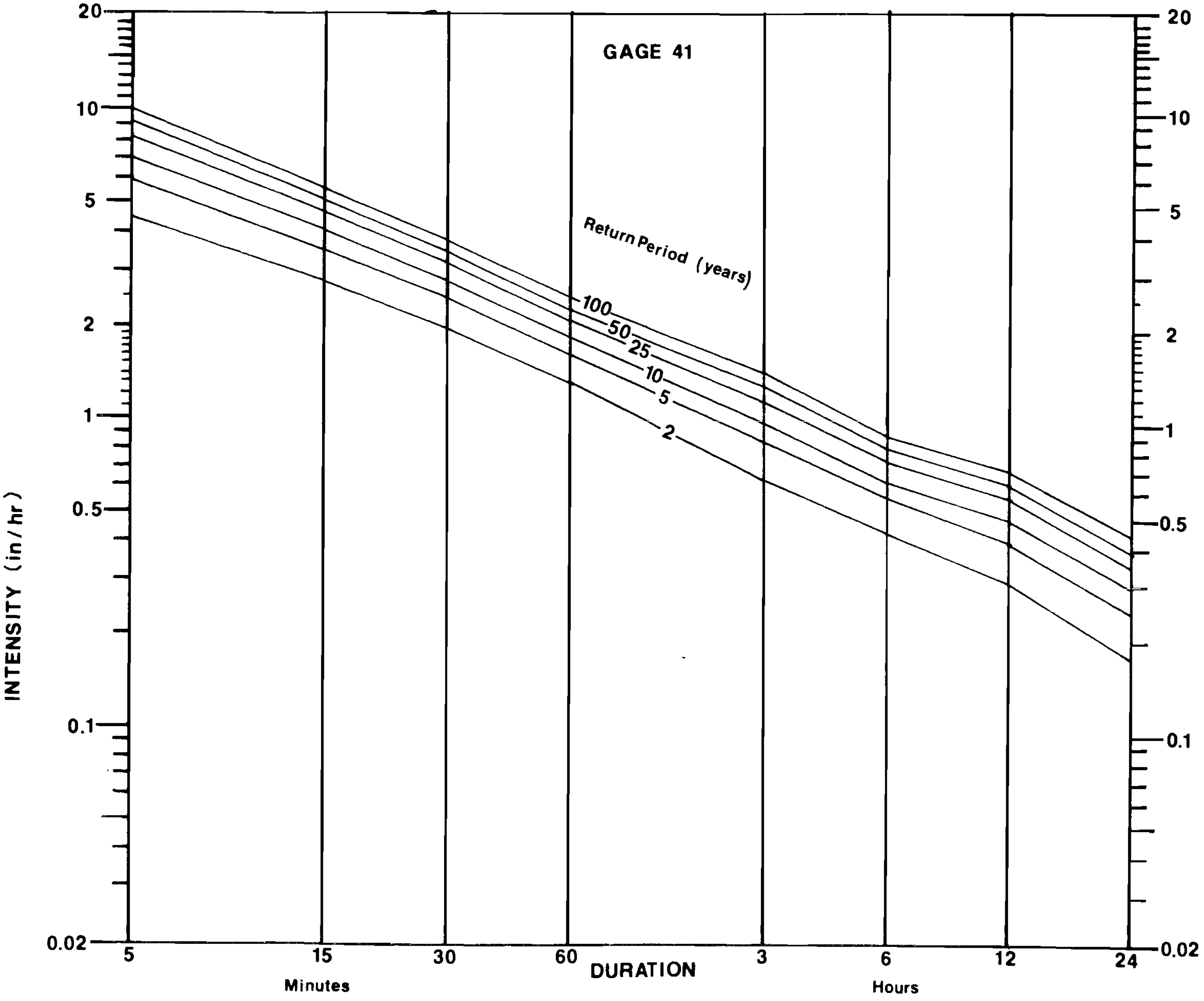


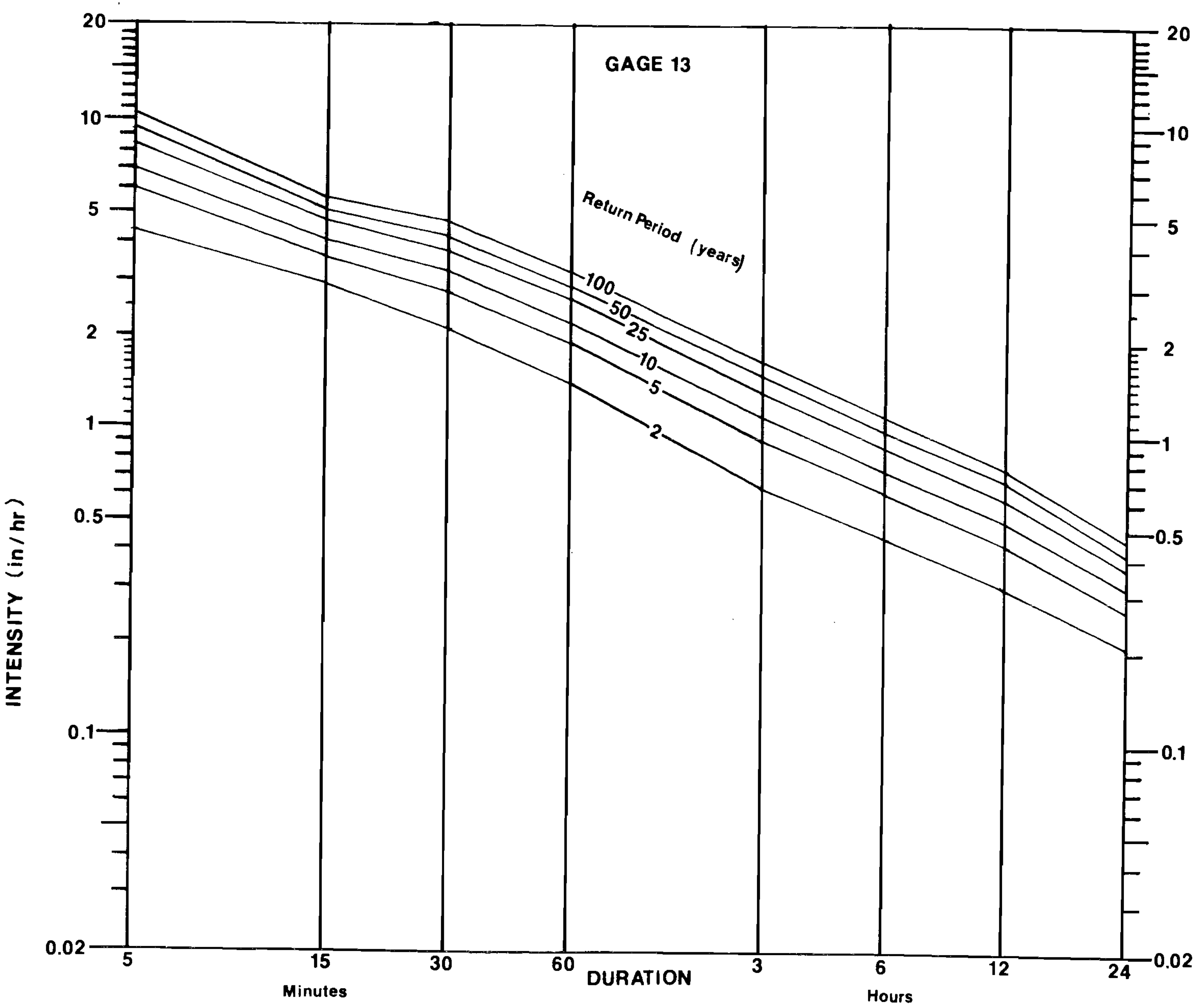
.90
.80
.70
.60
.50
.40
.30
.20
.10
.00
INTENSITY (IN/HR)
31
13
6
41 & 96
12 HOUR DURATION
2
5
10
15
20
25
30
40
50
75
100
RETURN PERIOD (YRS)

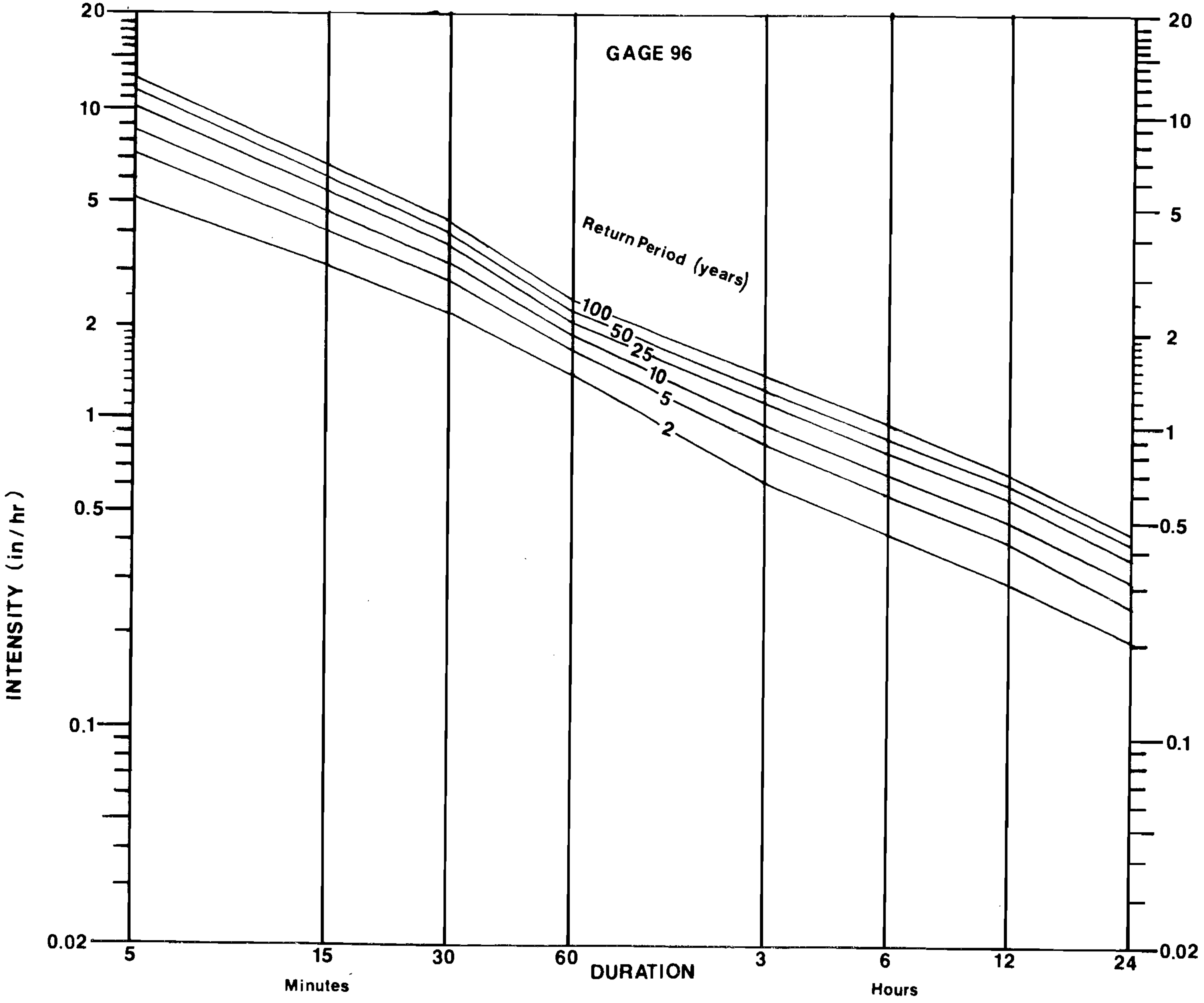


.55
.50
.45
.40
.35
.30
.25
.20
.15
.10
.05
.00
INTENSITY (IN/HR)
31
96
13
6
41
24 HOUR DURATION
2
5
10
15
20
25
30
40
50
75
100
RETURN PERIOD (YRS)


GAGE 6
Return Period (years)
100
50
25
10
5
2
INTENSITY (in/hr)
20
10
5
2
1
0.5
0.1
0.02
DURATION
5
15
30
60
Minutes
3
6
12
24
Hours


GAGE 41
INTENSITY (in/hr)
20
10
5
2
1
0.5
0.1
0.02
Return Period (years)
100
50
25
10
5
2
5
15
30
60
3
6
12
24
Minutes
DURATION
Hours


GAGE 13
Return Period (years)
100
50
25
10
5
2
INTENSITY (in/hr)
20
10
5
2
1
0.5
0.1
0.02
DURATION
5
15
30
60
Minutes
3
6
12
24
Hours


GAGE 96
Return Period (years)
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50
25
10
5
2
INTENSITY (in/hr)
20
10
5
2
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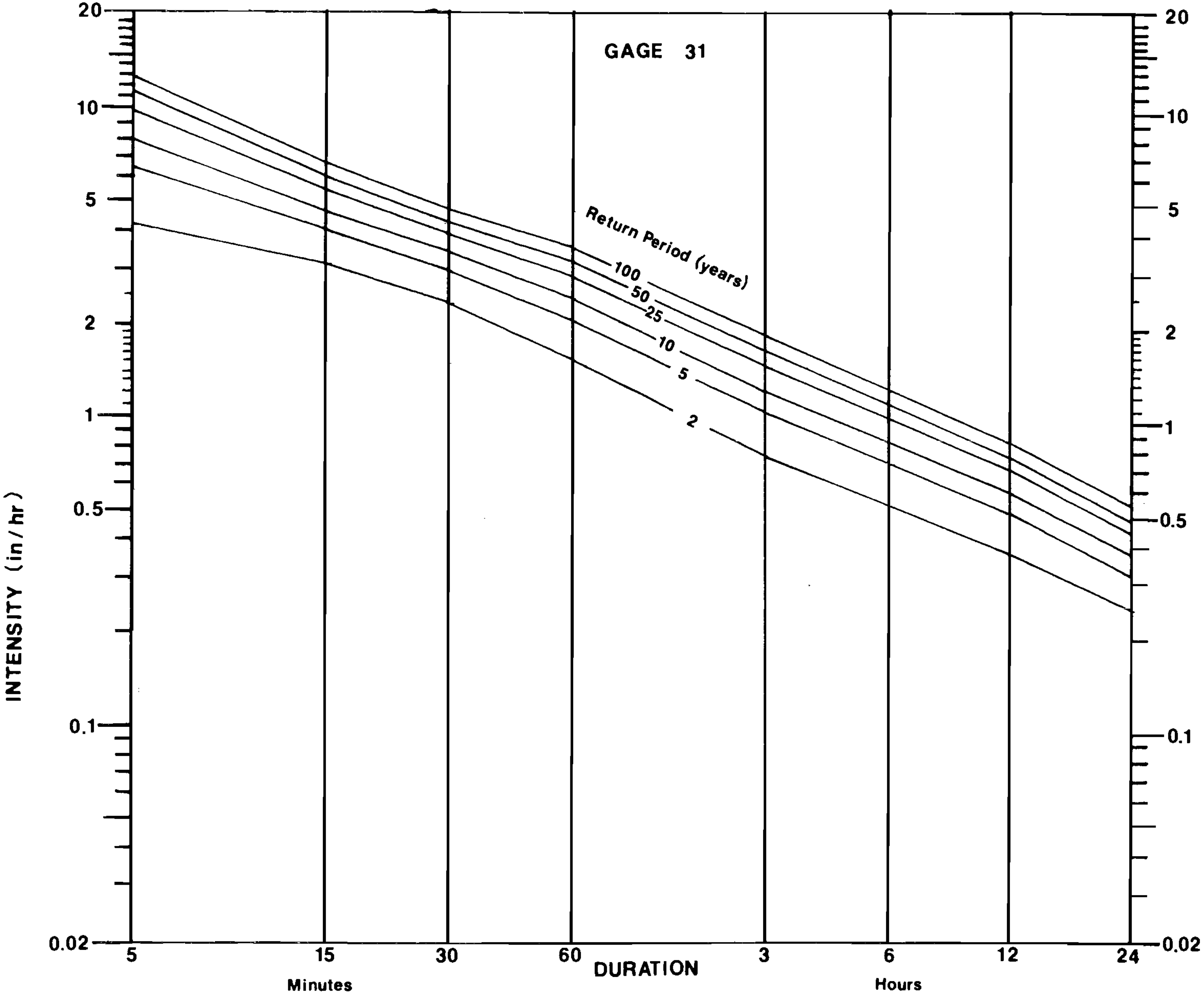
0.1
0.02
5
15
30
60
Minutes
DURATION
3
6
12
24
Hours


GAGE 31
Return Period (years)
100
50
25
10
5
2
INTENSITY (in/hr)
20
10
5
2
1
0.5
0.1
0.02
DURATION
5
15
30
60
Minutes
3
6
12
24
Hours