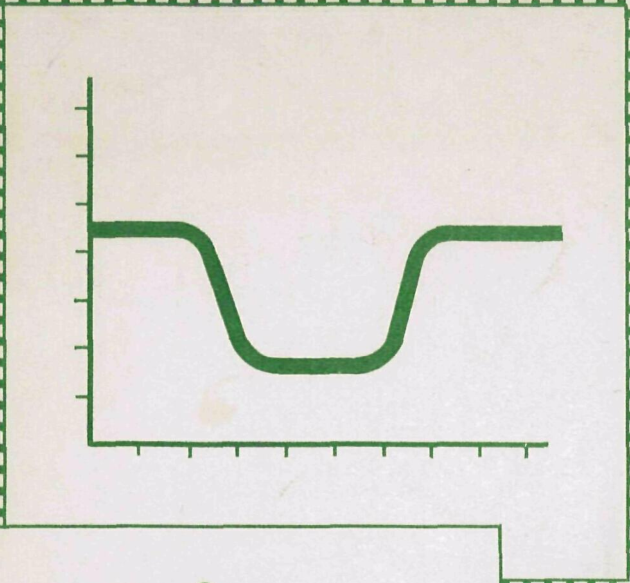
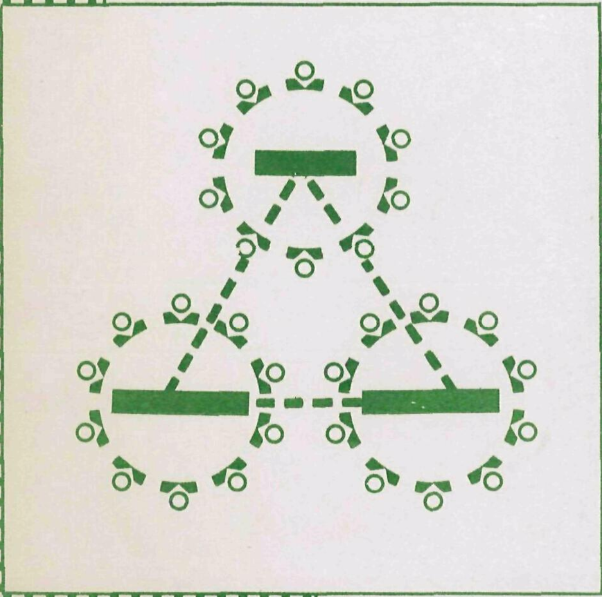
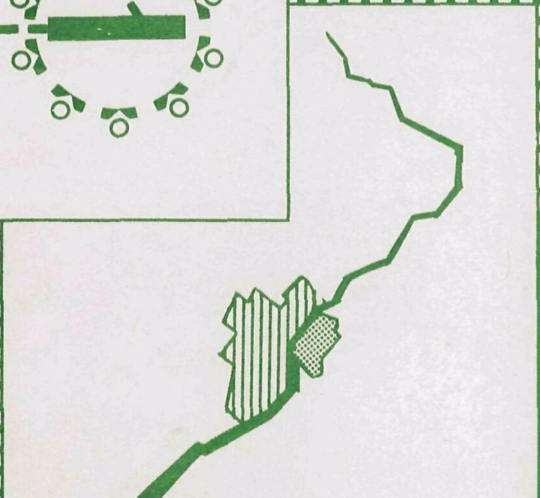
DELAWARE ESTUARY COMPREHENSIVE STUDY







FINAL REPORT

ENVIRONMENTAL PROTECTION AGENCY

DELAWARE ESTUARY COMPREHENSIVE STUDY

FINAL REPORT

CHAPTER I

HYDROLOGY

REGION II
ENVIRONMENTAL PROTECTION AGENCY
Edison, New Jersey

July 1971

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CHAPTER I

SECTION A

ESTUARY AND BASIN PRECIPITATION

Precipitation in the Delaware Estuary area is generally abundant, having an annual average of approximately 42 inches. The average annual precipitation for the entire Delaware River Basin is slightly greater, being about 44 inches.

The record of annual precipitation in the Delaware Estuary area is very nearly a normal (Gaussian) distribution[1]. United States Weather Bureau records[2] show that the average annual precipitation by sub-basins in the Delaware River Basin varies from about 42 to 45 inches. Average precipitation is greatest along the western edge of the basin and in the upper portion of the basin (i.e., New York State).

Although there is a considerable variation in annual precipitation, the variation in monthly precipitation is even more striking. For example, at Philadelphia, the October 1963 recorded value was 0.09 inches as compared to 5.21 inches for October 1943 and an average for the period of record of 2.78 inches. Extreme values are always associated with extreme weather phenomena such as droughts and hurricanes.

Table 1 lists the normal monthly precipitation at Philadelphia, with a range of 2.78 inches in October to 4.63 inches in August. Precipitation is generally greatest during the summer and least during the winter.

The normal snowfall in the study area is approximately 21 inches. Since the average temperature for the winter months is 33°F, much of the winter precipitation occurs as rain rather than snow. The average annual snowfall for the basin varies from about 15 inches in the Bay region to over 70 inches in the headwaters area and the Pocono Mountains.

U. S. Weather Bureau records indicate that approximately 50% of the average annual precipitation occurs between May and September. Summer precipitation over the estuarine area is about 45% of annual. This proportion increases from east to west, with the area west of the Delaware River being almost 50%.

DROUGHT CONDITIONS

The Delaware River Basin has experienced extended periods of subnormal precipitation, commonly referred to as droughts. One definition of a drought is when precipitation is insufficient to meet the needs of estab-

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This section was prepared by Darwin R. Wright, U.S. Environmental Protection Agency, Washington, D.C.

TABLE 1

Precipitation, Total Water Equivalent (in.)

(Climatological Standard Normals, 1931-1960)

(Precipitation During Drought, 1962-1966)

United States Weather Bureau

Philadelphia, Penna.

Month	Drought Period 1962-1966 Total Water Equivalent (in.) 1962	1963	1964	1965	1966	Normal Total	Period of Record 1931-1966 Maximum Monthly (in.)	Maximum Monthly Year	Minimum Monthly (in.)	Minimum Monthly Year
January	2.95	2.31	3.92	2.35	2.82	3.32	6.06	1949	0.45	1955
February	3.51	2.19	2.83	2.18	4.30	2.80	4.64	1958	1.37	1954
March	3.91	3.94	1.94	3.19	0.68	3.80	6.27	1953	0.68	1966
April	3.69	1.13	5.27	2.33	4.35	3.40	6.58	1947	1.13	1963
May	1.85	1.06	0.47	1.23	2.95	3.74	7.41	1948	0.47	1964
June	7.40	2.88	0.21	2.85	0.41	4.05	7.40	1962	0.11	1949
July	2.30	3.13	3.83	3.22	2.35	4.16	7.48	1959	0.64	1957
August	6.58	3.35	0.49	4.05	1.63	4.63	9.70	1955	0.49	1964
September	2.77	6.44	2.42	3.02	8.70	3.46	8.78	1960	0.88	1941
October	0.95	0.09	1.73	2.02	5.12	2.78	5.21	1943	0.09	1963
November	4.60	6.67	1.64	1.05	2.36	3.40	6.67	1963	1.05	1965
December	2.11	1.76	5.13	1.85	4.33	2.94	5.48	1951	0.25	1955
Yr. Total	42.62	34.95	29.88	29.34	40.00	42.48				
Deviation from normal	+0.14	-7.53	-12.60	-13.14	-2.48					

lished human activities[3]. Other definitions are also common, depending on the water user (i.e., farmer, water supply operators, meteorologists, etc.). Many other factors, such as effect on plant life, drying out of soil, and drying up of streams are characteristic of droughts. Consequently, a specific definition is not necessary if the effects are obvious.

The Delaware River Basin Report[3] lists twelve periods of extended subnormal precipitation. The 1930 drought stands out as the most severe, both for duration and for deficiency of precipitation prior to the drought of the 1960's. The beginning of the most recent drought varies, depending on the source quoted, but it is generally agreed that the drought began in 1962 and continued through 1966.

Table 1 lists the U. S. Weather Bureau precipitation records and normals for Philadelphia, Penna. Thirty-five of the forty-eight months of 1962-65 were below normal. During the drought, from September 1962 through December 1965, thirty-two of the forty months were below normal. The total precipitation of 104.60" represents approximately 75% of the normal. The severity of the drought is evidenced by:

1. The total precipitation during 1963-64 was only approximately 70% of the normal.

2. Five minimum monthly totals were recorded.

3. All twelve months of 1965 were below normal.

4. 1965 was the second driest year on record (29.34 inches).

5. 1964 was the third driest year on record (29.88 inches).

6. Precipitation during the period May through November 1964 was about 41% of normal.

7. 1964 was the driest summer (June to August) on record.

8. 1963 had the longest dry spell - October 4 to October 31, 28 days.

9. 1964 had the second driest May and August.

Not only have drought conditions persisted in the lower basin, as is evidenced by the Weather Bureau records from Philadelphia, Pa., but in general, the drought affected the entire basin. In the northern half of the basin the drought caused extremely low streamflow, which in turn resulted in low reservoir storage during 1965.

The Delaware River Basin may expect more severe dry spells for short periods, in addition to extended periods of drought. However, the last drought stands without precedent for its long duration and large precipitation deficiency.

UNITED STATES WEATHER BUREAU STATISTICAL ANALYSIS

In the analysis of stormwater overflows, precipitation records are needed to develop such variables as frequency and duration of combined sewer overflows and rainfall-runoff relationships. As a part of the stormwater overflow study, a rain gage network was installed to provide adequate precipitation records. (See Chapter IV F Stormwater Overflow).

The estuary region does not have a distinct wet or dry season, but there is a pronounced difference in winter and summer precipitation. Summer is characterized by local thundershowers, whereas winter precipitation is generally more widespread and less intense. This variation in precipitation is reflected in the flow and quality of stormwater overflows.

Most precipitation data are usually recorded as daily or even monthly totals. Because of this, little can be concluded concerning stormwater overflows from U. S. Weather Bureau daily precipitation records. In fact, as shown in Table 2 which lists the number of days precipitation was recorded for the period 1961-1965, the differences between drought periods (1963-65) and normal periods (1961-62) are not particularly striking.

TABLE 2

NUMBER OF DAYS PRECIPITATION RECORDED

UNITED STATES WEATHER BUREAU - PHILADELPHIA, PA.

			YEAR		
Month	1961	1962	1963	1964	1965
January	11	7	12	9	8
February	14	12	9	12	10
March	7	12	12	12	10
April	11	14	7	16	11
May	8	13	9	3	9
June	10	10	9	7	11
July	7	10	8	6	7
August	10	9	10	8	14
September	8	5	8	8	4
October	10	7	1	4	6
November	8	8	10	7	9
December	8	12	7	14	7
TOTAL DAY	112	119	102	106	106
TOTAL PREC. (in.)	41.05	42.62	34.95	29.88	29.34

Such records therefore are of little value when attempting to evaluate stormwater overflows. To adequately define and predict stormwater overflows, an analysis of each individual storm is needed. Since the study period for measuring the effects of stormwater overflows was to last only approximately two and one half years, a more general evaluation of "storm phenomena" was desired. Consequently, a contract was let with the U. S. Weather Bureau to furnish a statistical analysis of "storm phenomena" for Philadelphia, Penna.

Precipitation records are available for Philadelphia, Penna., back to 1820, but only data from May 1890 included hourly precipitation values. Consequently, the period from May 1890 through April 1964 was analyzed by the Weather Bureau.

A storm was defined as (1) an hourly precipitation recording of more than a trace, (2) beginning at that hour when the precipitation is a positive number and only a trace or zero for the preceding hour, and (3) ending at any hour with zero or a trace if the preceding hour had positive precipitation. Positive precipitation is defined as an amount greater than zero, or a trace. The duration of a storm is the difference between its ending and starting times. Similarly, the interval between one storm and the next is the starting time of the second minus the ending time of the first.

The analyses furnished by the Weather Bureau included:

1. Bi-variate distribution of rainfall intensity per storm (inches per hour) versus storm duration (hours). This analysis was carried out for each month of the year for the period May 1890 through April 1964 (74 years), resulting in 12 monthly bi-variate distributions.

   For storms that extended from one month to the next, e.g., August 31 thru September 1, the storm was assigned to the month in which the storm lasted the longest. In those cases where the number of hours of storm were equal for both months, the storm was assigned to the month in which it started.

2. A histogram analysis of the interval between successive storms carried out for each month of the year for the period May 1890 through April 1964 (74 years), resulting in 12 histograms.

   For "intervals between storms" that extended from one month to the next, e.g., August 31 to September 1, the interval was assigned to the month in which the interval lasted the longest. If the number of hours of interval were equal for both months, the interval was assigned to the month in which it started.

3. A copy of Official City hourly precipitation data for April 24, 1890, through December 1948, and punched computer cards giving hourly precipitation for Philadelphia Weather Bureau-Airport (36-6889) for the period May 1, 1948 through June 30, 1964.

   Copies of the twelve monthly bi-variate distributions and the twelve monthly histograms are in Appendix 4.

STORM INTENSITY ANALYSES

The marginal probability distributions were computed from the bi-variate distributions. The values were tabulated on the bi-variate distributions in a total column or a total row. Using these values, the monthly storm intensity and storm duration frequency distributions were determined.

Storm intensity was defined as the sum of the hourly precipitation values divided by the number of hours in the storm. Using the monthly intensity marginal distributions, the probability distribution function was plotted on semi-log paper. Figure I-A-1 is a sample plot showing January, July and the entire year. For individual months, the data approached a straight line. Consequently, the lines for January and July represent a visual approximation of a line of best fit to the sets of data. The other months were plotted using the same procedure. An exponential distribution was assumed with the probability distribution function given by:

$$y = 100e^{-\lambda x} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where y = percent of storms with intensity greater than the stated value

x = storm intensity in in./hr.

λ = constant parameter >o (hr./in.)

e = 2.718

Based on the assumption that the data is of the form of equation (1), then $1/\lambda$ equals the mean and $1/\lambda^2$ equals the variance(4). The results of this analysis by months are listed in Table 3.

TABLE 3

STORM INTENSITY

UNITED STATES WEATHER BUREAU - PHILADELPHIA, PA.

May, 1890 - April, 1964

Month	$1/\lambda$ = Mean (in./hr.)	$1/\lambda^2$ = Variance $(in./hr.)^2$
January	0.044	0.0019
February	0.043	0.0018
March	0.044	0.0020
April	0.067	0.0045
May	0.098	0.0095
June	0.121	0.0147
July	0.143	0.0205
August	0.147	0.0205
September	0.112	0.0216
October	0.070	0.0049
November	0.061	0.0037
December	0.051	0.0026

The mean storm intensity varies from 0.044 inches per hour during the winter months to 0.147 inches per hour during the summer months. This is the result of having long duration storms, including snowfall during winter months, while the summer months are characterized by thundershower activity. The variance is also greater during the summer months, which is an indication of the wider range of intensities which result from thundershower activity.

The minimum intensity recorded was 0.01 inches per hour. Most of the storms of this intensity are comprised of hourly precipitation values of 0.01 inches with the storm durations varying from one hour to several hours. Of the 13,183 storms, 30.5% are comprised of a total rainfall of 0.01 inches. From a stormwater overflow point of view, these storms would not produce bypasses to the stream. As expected, maximum storm intensities are recorded during the summer months.

These maximum values should not be confused with actual values as usually reported, because in this case, the storm duration is recorded to the whole hour. For this reason, the maximum storm intensity was recorded in the interval of 1.31 inches/hr. to 1.40 inches/hr. Table 4 lists pertinent maximum storm intensity data.

TABLE 4

MAXIMUM STORM INTENSITIES

UNITED STATES WEATHER BUREAU, PHILADELPHIA, PA.

May, 1890 - April, 1964

Month	Maximum Storm Intensity (in./hr.)
January	.26 - .30
February	.26 - .30
March	.36 - .40
April	.51 - .55
May	1.01 - 1.10
June	1.21 - 1.30
July	1.21 - 1.30
August	1.31 - 1.40
September	1.01 - 1.10
October	.81 - .85
November	.76 - .80
December	.56 - .60

STORM DURATION ANALYSES

Storm duration was defined as the number of consecutive hours during which at least 0.01 inches of precipitation was recorded. Using the monthly duration marginal distributions, the probability distribution function was plotted on semi-log paper. Figure I-A-2 is a plot showing January, July, and the entire year. For the individual months, the data approached a straight line. A visual approximation of a line of best fit to each set of monthly data was drawn. Using equation (1), the λ's were determined and the mean and variance computed. Table 5 lists the results of this analysis.

TABLE 5

STORM DURATION

UNITED STATES WEATHER BUREAU, PHILADELPHIA, PA.

May, 1890 - April, 1964

Month	$1/\lambda$ = Mean (hr.)	$1/\lambda^2$ = Variance (hr.)^2
January	5.04	26.46
February	5.17	26.74
March	4.28	18.28
April	3.65	13.30
May	2.89	8.34
June	2.73	7.46
July	2.08	4.34
August	2.78	7.72
September	3.39	11.47
October	3.47	12.06
November	4.34	18.87
December	4.91	24.10

The mean storm duration ranges from 2.08 hours in July to 5.17 hours in February. This again is an indication of longer duration storms during the winter months and shower activity during the summer months. Obviously, this storm duration analysis corresponds very closely with the storm intensity analysis. That is, summer storms usually have a short duration - high intensity, while winter storms are of a long duration - low intensity. The variance shows the same trend as the storm intensity variance, indicating a wide range of storm durations.

The minimum storm duration was one hour and the maximum storm duration interval was 45 to 46 hours. It should be noted that storm duration does not indicate that precipitation was recorded continuously, but that according to the Weather Bureau data, some precipitation was recorded during the preceding hour for each hour of the storm. Also, what may appear to be a continuous day of rain to the layman, may in fact, be a number of storms because during some hours less than 0.01 inches of rain may have been recorded.

The storm of one hour duration may represent two different types of storms. The first type of storm is the one with a total precipitation of 0.01 inches. The second type is the thundershower, which prevails during the summer months and usually last less than one hour. The percent of one hour duration 0.01 inches total rainfall storms varies from 77% of the total one hour storms for January to 40% of the total one hour storms for July. The thundershower activity is evident when considering the percent of one hour duration storms with an intensity greater than 0.11 -

0.15 in./hr. interval. The range of these storms is from zero percent in January to 12.4 percent in July. The one hour duration storms of varying intensity account for 38% of the total. The one hour duration 0.01 inches total rainfall storms account for 58% of the total one hour duration storms.

The maximum storm durations are recorded during the winter months. Table 6 lists the maximum storm duration and the percent of storms with a duration greater than twelve hours. While July has a maximum storm duration of 19 hours, only 0.4% of the storms are greater than a 12 hour duration. December, which has a maximum storm duration of 45-46 hours, has 7.8% of its storms greater than twelve hour duration.

TABLE 6

STORM DURATION

UNITED STATES WEATHER BUREAU, PHILADELPHIA, PENNA.

May, 1890 - April, 1964

Month	Maximum Storm Duration Interval (Hours)	% Storms Greater Than 12 Hours
January	33-34	9.0
February	39-40	9.4
March	41-42	5.5
April	35-36	3.9
May	39-40	1.6
June	21-22	1.4
July	19	0.4
August	29-30	1.5
September	27-28	2.2
October	23-24	2.6
November	35-36	5.6
December	45-46	7.8

ANALYSIS OF INTERVAL BETWEEN STORMS

The quality of combined sewer overflows has been found to be highly variable, especially when measured by such parameters as BOD or solids. One of the reasons for this variability may be the result of conditions which prevail in the sewer between periods of overflow. Prolonged periods of dry weather may result in the deposition of solids, which are later flushed out if sufficient storm flow results.

Prolonged periods of dry weather may also result in higher concentrations of pollutional materials being deposited on the surface, which enter the combined system from surface runoff. Studies have shown that a large percentage of suspended solids in urban runoff could be attributed to dustfall.(1)

Consequently, the "interval between storms" may be a significant factor in the quality variability of combined sewer stormwater overflows. The Weather Bureau analysis showed that 56% of the "intervals between storms" were less than 21 hours, with 42% less than 7 hours, and 20% equal to or less than one hour. The 56% of the storm intervals (<21 hours) represent a different effect on overflow quality than the remaining 44% that affect the quality of overflows. This difference is especially obvious during thundershower activity. For example, if a thundershower of high intensity is followed closely by another thundershower of high intensity, the second overflow will probably have a lower concentration of total solids, since both the surface and sewer have been flushed by the first thundershower. The surface and sewer deposition does not have enough time to build-up significant amounts in twenty hours or less.

The monthly histograms of the "interval between storms" are contained in Appendix 4 - Stormwater Overflow Sampling and Analysis Program. The number of storms of each interval is tabulated on the histograms. It should be noted on these histograms that the size of the histogram cells is not equal. The cell size for the range from one to twenty-four hours is either one, two, or four hours. From one to six days, every 12 hours and from six to fifteen days, every 24 hours. Then every five days, (i.e., 15, 20, 25, 30) up to a maximum of 7200 hours or 30 days.

It was necessary to break down the small intervals because of the definition of a storm and consequently the storm interval. Intervals between storms of one to six hours are the result of intermittent periods without precipitation during what would appear to be, for example, a complete day of rain. The minimum and maximum "interval between storms" are one hour and 601/720 hours, respectively.

The twelve histograms are all of the same general shape. For the year, 80.5% of the "intervals between storms" are equal to or greater than one hour; 42.0% are ≥ 21/24 hours (1 day); 8.5% are ≥ 133/144 hours (6 days); 0.4% are ≥ 337/360 hours (15 days).

Since the "interval between storms" histograms did not appear to have an exponential distribution, various analyses were tried. The month of October was chosen for this analysis since it had recorded the greatest "interval between storms" and also during October 1963 the longest dry spell on record was experienced. Figure I-A-3 is a plot of interval between storms (hr.) and the frequency of occurrence. The nine curves represent the omission of selected storm intervals. With all intervals included, the data is an S-shaped curve (A). However, with the intervals equal to or less than 21-24 hours omitted, the data approach a straight line. Considering the data in light of stormwater overflows, intervals less than or equal to 21-24 hours are not as important as the longer intervals.

Also, since the data greater than 24 hours appeared to approach a straight line, it could be analyzed using the same procedure as storm intensity and storm duration.

Using the monthly histograms, the probability density function was determined and plotted on semi-log paper. Figure I-A-4 is a plot showing these for January and October. For the twelve individual months, a visual approximation of a line of best fit for each set of monthly data was drawn. Using equation (1), the λ's were determined and the mean and variance computed. Table 7 lists the results of this analysis.

TABLE 7

"INTERVAL BETWEEN STORMS"
(INTERVALS GREATER THAN TWENTY HOURS)

UNITED STATES WEATHER BUREAU - PHILADELPHIA, PENNA.

May, 1890 - April, 1964

Month	$1/\lambda$ = Mean (Days)	$1/\lambda^2$ = Variance (Days)^2
January	3.15	9.91
February	2.93	8.59
March	2.74	7.48
April	3.34	11.18
May	3.04	9.24
June	3.13	9.77
July	3.17	10.05
August	3.34	11.18
September	4.69	22.00
October	5.17	26.71
November	4.26	18.11
December	3.36	11.32

For "intervals between storms" greater than 21 hours (21-24 interval), the Weather Bureau analysis showed that the mean for October was the longest, with 5.17 days and the mean for March was the shortest, with 2.74 days. The longest "interval between storms" was recorded in the 601-720 hour interval during September (1 occurrence) and October (2 occurrences). October had the largest number of "intervals between storms" greater than 360 hours (15 days) with 16 occurrences (13 occurrences were in the 361-480 hour interval). Table 8 lists the maximum "interval between storms" and the percent of "interval between storms" greater than 144 and 288 hours.

TABLE 8

"INTERVAL BETWEEN STORMS"
(INTERVALS GREATER THAN TWENTY HOURS)

UNITED STATES WEATHER BUREAU - PHILADELPHIA, PENNA.

May, 1890 - April, 1964

Month	Maximum "Interval Between Storms" Interval, hours	% "Interval Between Storms" Greater than 144 hours	288 hours
January	361-480	17.1	1.6
February	481-600	14.6	1.5
March	337-480	12.9	0.9
April	481-600	16.0	2.3
May	337-360	16.5	1.7
June	481-600	17.4	1.3
July	361-480	16.2	1.1
August	481-600	18.0	1.3
September	601-720	29.2	7.3
October	601-720	32.7	9.6
November	481-600	26.3	5.1
December	361-480	20.5	2.5

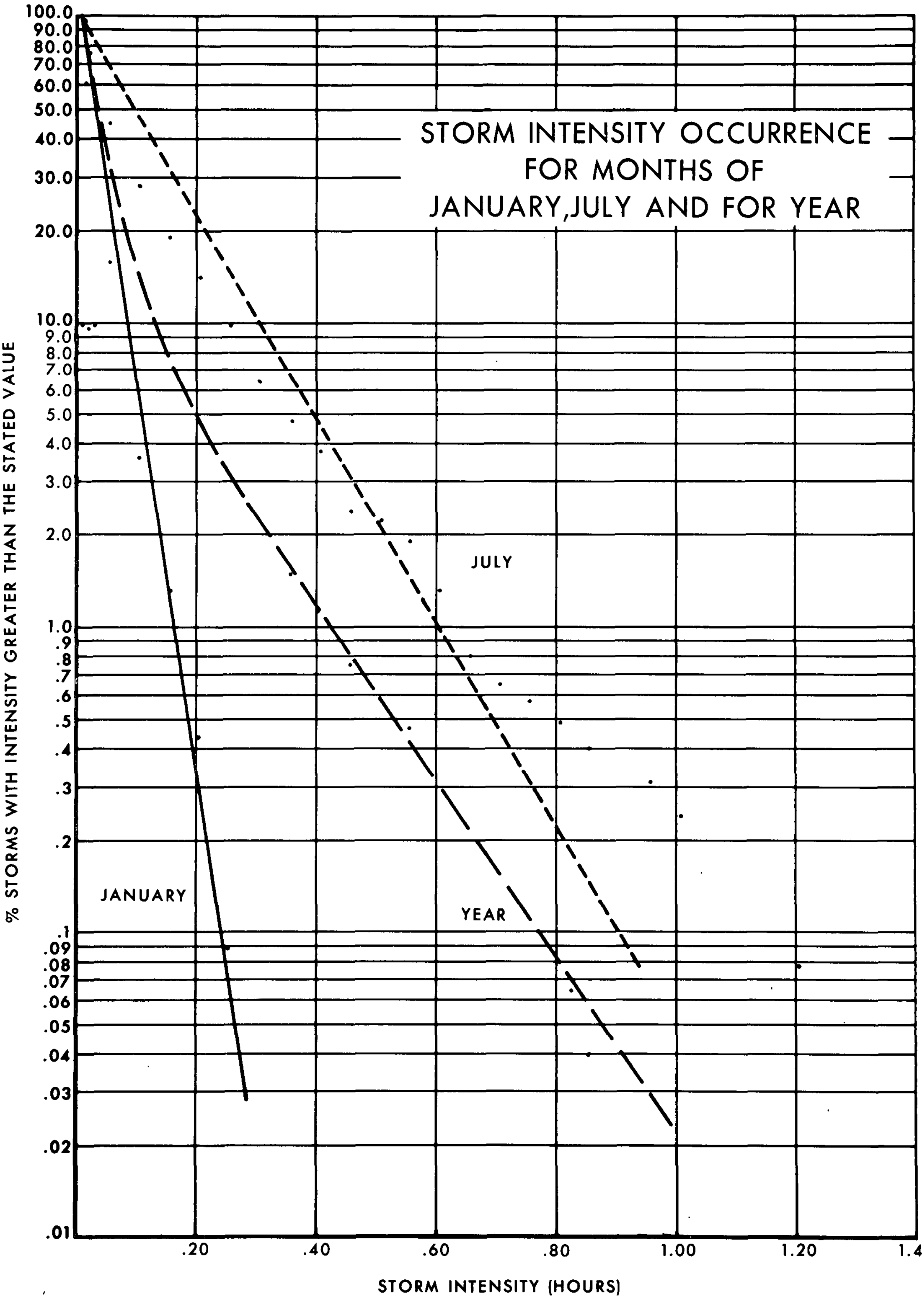
The maximum "interval between storms" usually occurs in the summer and fall months. Consequently, if the hydraulics of the system are susceptible to solids deposition, sufficient solids may build up such that the quality of the overflow is affected. Part of the difficulty in predicting overflow quality is due to the fact that the duration and intensity of the storm after a given interval also affects the quality. For example, a high intensity storm will produce relatively high concentrations of solids, while for the same preceding storm interval, a low intensity storm would have relatively low concentration of solids.

SUMMARY

Precipitation in the Delaware Estuary is generally abundant and averages approximately 42 inches per year. Precipitation is greatest during the summer (August = 4.63") months, and least during the winter months. The recent drought (September, 1962 to August, 1966) stands without precedent for both its long duration and its large precipitation deficiency.

The results of statistical analyses of 74 years of precipitation records at Philadelphia, Pa. indicate that storm intensity and storm duration can be described by an exponential type of probability distribution function. Mean storm intensity varied from 0.04 in./hr. in February to 0.15 in./hr. in August. Mean storm duration varied from 5.2 hours in February to 2.1 hours in July. This is an indication of long storms during the winter months and shower activity in the summer months. Maximum storm intensity and duration were 1.40 in./hr. and 46 hours respectively.

The "interval between storms" did not show any well defined probability distribution. However, when all intervals less than or equal to twenty hours were excluded, the data did exhibit an exponential distribution. The "interval between storms" (>20 hours) varied from 2.74 days in March to 5.17 days in October. The maximum interval between storms was recorded in the 601-720 hour interval during October. October had the largest number of "intervals between storms" greater than 360 hours. Further studies are needed to relate these analyses to the problems of stormwater overflows. These analyses would be a valuable aid in the design of stormwater overflow control facilities.


STORM INTENSITY OCCURRENCE
FOR MONTHS OF
JANUARY,JULY AND FOR YEAR
% STORMS WITH INTENSITY GREATER THAN THE STATED VALUE
100.0
90.0
80.0
70.0
60.0
50.0
40.0
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10.0
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7.0
6.0
5.0
4.0
3.0
2.0
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JULY
JANUARY
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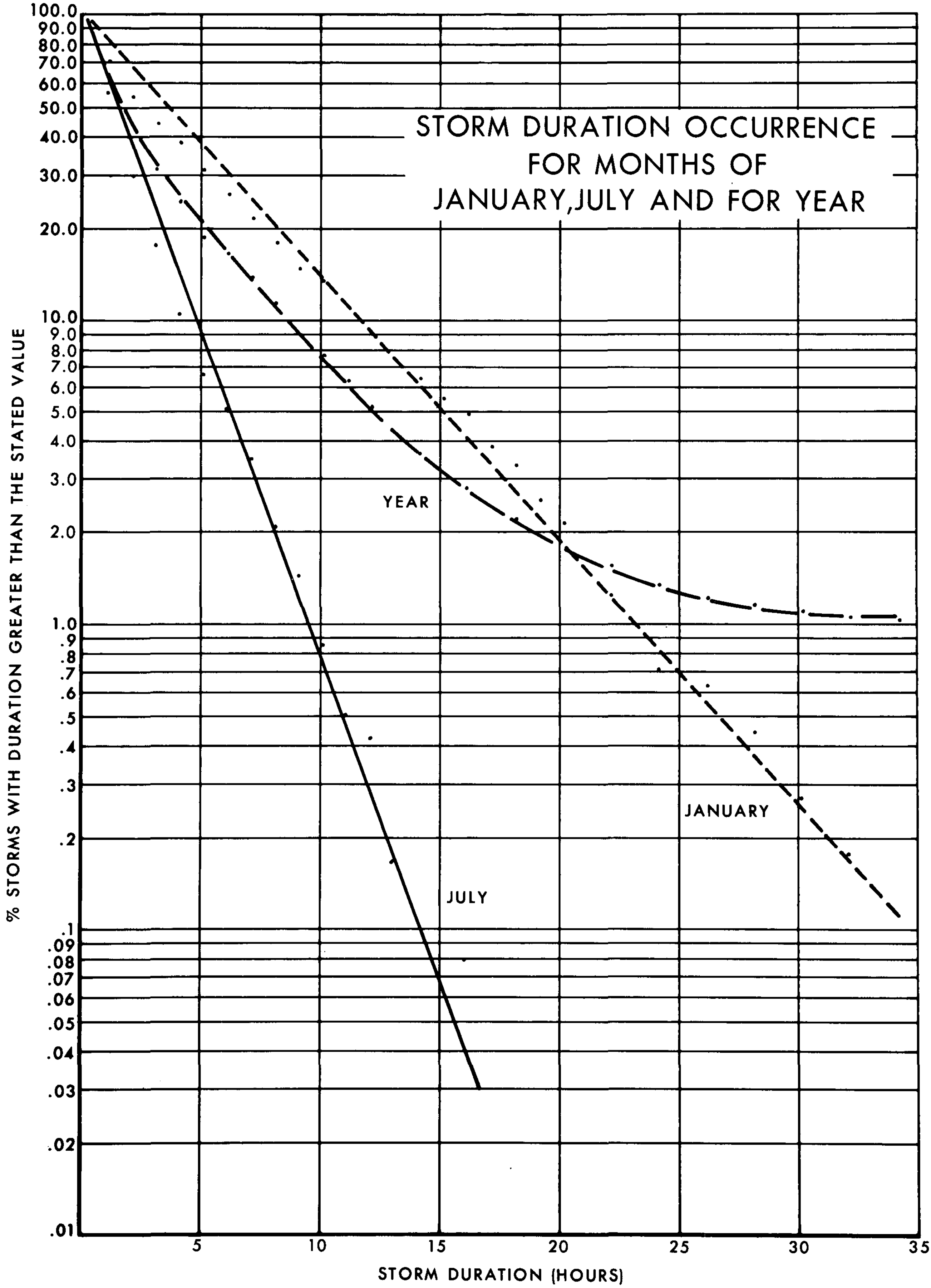
STORM INTENSITY (HOURS)

Figure I-A-1


STORM DURATION OCCURRENCE
FOR MONTHS OF
JANUARY,JULY AND FOR YEAR
% STORMS WITH DURATION GREATER THAN THE STATED VALUE
STORM DURATION (HOURS)
YEAR
JANUARY
JULY
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
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8.0
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Figure I-A-2

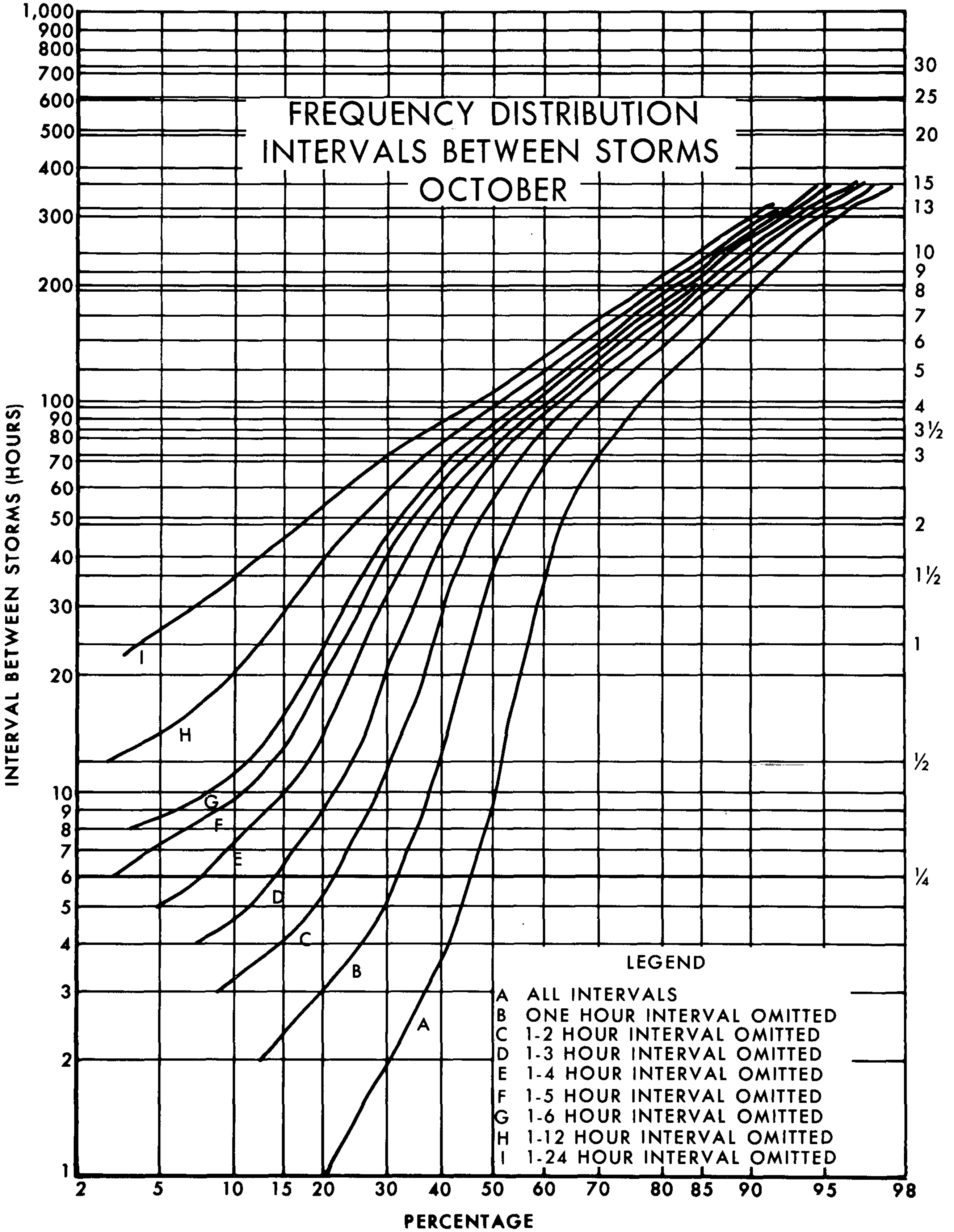
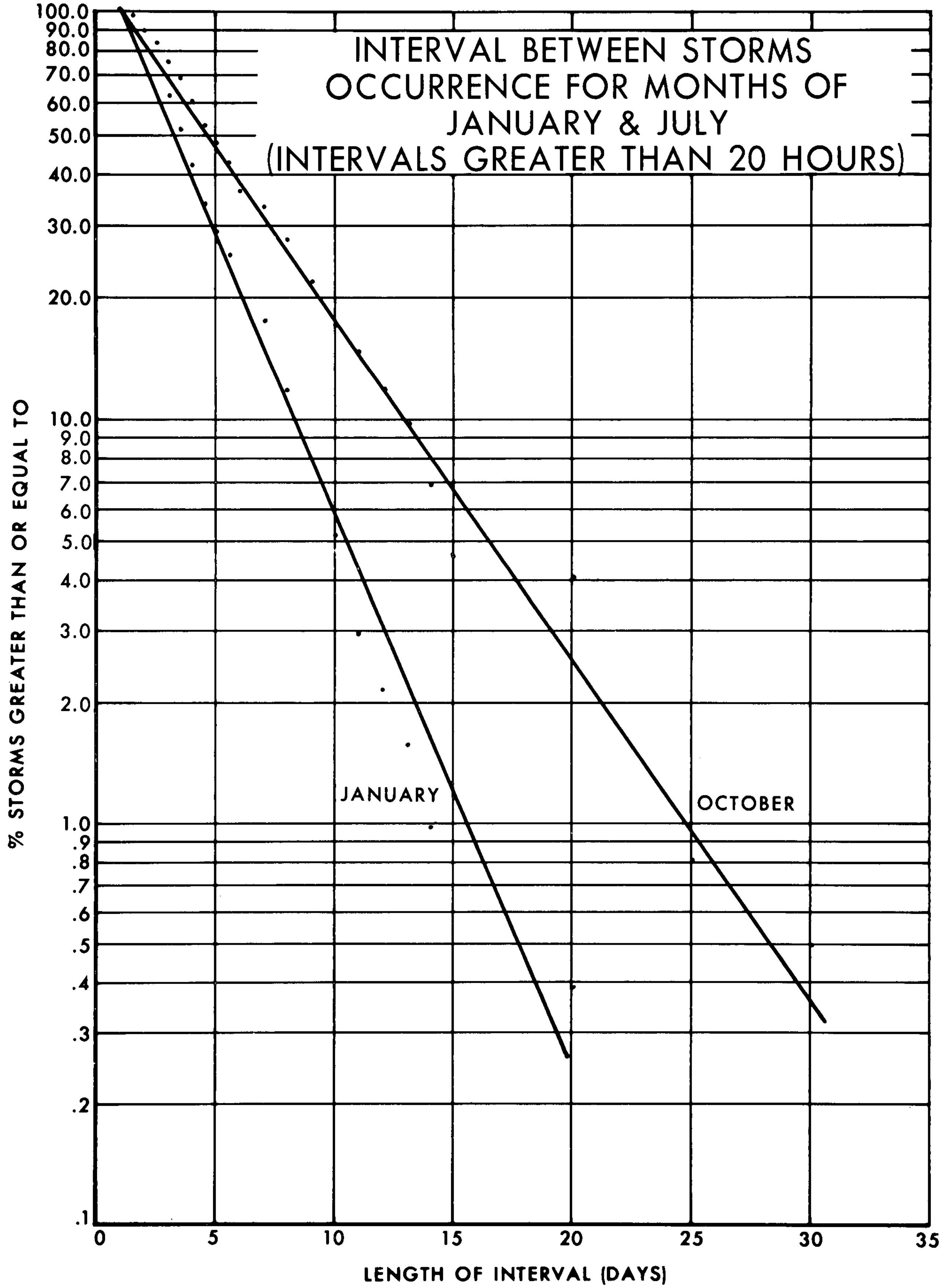

FREQUENCY DISTRIBUTION
INTERVALS BETWEEN STORMS
OCTOBER
INTERVAL BETWEEN STORMS (HOURS)
INTERVAL BETWEEN STORMS (DAYS)
PERCENTAGE
1,000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
30
25
20
15
13
10
9
8
7
6
5
4
3½
3
2
1½
1
½
¼
2
5
10
15
20
30
40
50
60
70
80
85
90
95
98
A
B
C
D
E
F
G
H
I
LEGEND
A ALL INTERVALS
B ONE HOUR INTERVAL OMITTED
C 1-2 HOUR INTERVAL OMITTED
D 1-3 HOUR INTERVAL OMITTED
E 1-4 HOUR INTERVAL OMITTED
F 1-5 HOUR INTERVAL OMITTED
G 1-6 HOUR INTERVAL OMITTED
H 1-12 HOUR INTERVAL OMITTED
I 1-24 HOUR INTERVAL OMITTED

Figure I-A-3



INTERVAL BETWEEN STORMS
OCCURRENCE FOR MONTHS OF
JANUARY & JULY
(INTERVALS GREATER THAN 20 HOURS)
% STORMS GREATER THAN OR EQUAL TO
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
JANUARY
OCTOBER
0
5
10
15
20
25
30
35
LENGTH OF INTERVAL (DAYS)

Figure I-A-4

CHAPTER I

SECTION B

RUNOFF TO ESTUARY

Fresh water inflow to the Delaware Estuary is largely from drainage of the upper and central sections of the Delaware River Basin, i.e., the area above Trenton. The fresh water flow progresses over a series of rock ledges at the Fall Line and becomes mixed with the waters of the Delaware Estuary at Trenton, New Jersey. At this point the tidal motion of the estuary becomes a limiting variable on the downstream movement of fresh water inflow. In examining the dynamics of the estuary, the total fresh water inflow to the estuary must be considered, i.e., from (1) the basin above Trenton, (2) tributaries entering the estuary below Trenton and (3) water and waste discharges not reflected in either (1) or (2).

To provide future estimates of expected inflow to the Delaware Estuary, it is well to examine the existing conditions. Within the 86 mile reach of the Delaware Estuary, there are approximately one hundred tributaries. The major tributaries are gaged; however, the fresh water flow resulting from the ungaged tributaries must be estimated. Future controls of inflow due to upstream storage are discussed in the latter part of this section.

FRESH WATER INFLOW AT TRENTON

The Delaware River Basin above Trenton drains an area that extends as far as the western slopes of the Catskill Mountains of New York State. Runoff from the rugged terrain of Pennsylvania and New York is transported to the mainstem of the Delaware River through the discharges of the numerous tributaries. The collective flows from above the Fall Line enter the estuary at Trenton, New Jersey. This flow is referred to hereafter as the Trenton flow.

Gage height records of the Trenton flow are available from the courtesy of the U. S. Department of Interior's Geological Survey. Daily discharges, in cubic feet per second, are published annually by the Geological Survey. For the 52 year period of record starting in 1913, the unadjusted Trenton flow is 11,680 cfs[7]. This unadjusted flow does not include the withdrawal by the City of Trenton of approximately 50 cfs and the diversion for the New York City water supply. Table 9 lists the respective mean annual unadjusted Trenton flows with corresponding recurrence interval. For flow uniformity, the Trenton mean annual flows are based on the climatic year (April-March). Low-flow frequency curves were constructed for the existing data of the Trenton flow discharges.

This section was prepared by Wayne A. Blackard, U.S. Environmental Protection Agency, Rockville, Md.

TABLE 9

DELAWARE RIVER AT TRENTON, N. J.
MEAN ANNUAL FLOW

(cfs) (1913-1963)

(CLIMATIC YEAR)

Rank	Recurrence Interval (Years)	Probability (% of Time) ≤	Mean Annual Flow* (cfs)
1	52.00	1.9	5,755
2	26.00	3.8	7,695
3	17.33	5.7	7,820
4	13.00	7.7	7,970
5	10.40	9.6	8,327
6	8.67	11.5	9,051
7	7.43	13.5	9,169
8	6.50	15.4	9,339
9	5.77	17.3	9,528
10	5.20	19.2	9,649
11	4.73	21.1	9,723
12	4.33	23.1	9,741
13	4.00	25.0	9,750
14	3.71	27.0	9,751
15	3.47	28.8	9,940
16	3.25	30.8	10,062
17	3.06	32.7	10,142
18	2.89	34.6	10,205
19	2.74	36.5	10,268
20	2.60	38.5	10,389
21	2.48	40.3	10,688
22	2.36	42.4	10,738
23	2.26	44.2	10,935
24	2.17	46.1	11,453
25	2.08	48.1	11,611
26	2.00	50.0	11,646
27	1.93	51.8	11,701
28	1.86	53.8	11,739
29	1.79	55.9	11,751
30	1.73	57.8	11,970
31	1.68	59.5	11,989
32	1.63	61.3	12,082
33	1.58	63.3	12,417
34	1.53	65.4	12,606
35	1.49	67.1	12,706

*Unadjusted for diversions

TABLE 9 (Cont'd)

DELAWARE RIVER AT TRENTON, N. J.
MEAN ANNUAL FLOW

(cfs) (1913-1963)

(CLIMATIC YEAR)

Rank	Recurrence Interval (Years)	Probability (% of Time) ≤	Mean Annual Flow* (cfs)
36	1.44	69.4	12,758
37	1.41	70.9	12,843
38	1.36	73.5	13,533
39	1.33	75.2	13,564
40	1.30	76.9	13,803
41	1.27	78.7	14,104
42	1.24	80.6	14,234
43	1.21	82.6	14,903
44	1.18	84.7	14,950
45	1.16	86.2	15,018
46	1.13	88.5	15,115
47	1.11	90.1	15,151
48	1.08	92.6	15,315
49	1.06	94.3	15,920
50	1.04	96.2	16,523
51	1.02	98.0	17,530

*Unadjusted for diversions

These low-flow frequency curves were constructed as follows:

1. Rank the flows (Trenton mean annual) in ascending order with reference to the climatic year.

2. Compute the recurrence interval by the relationship:

$$T = \frac{N+1}{M}$$

$$P = \frac{1}{T}$$

where: T = Recurrence interval

P = Probability of a flow (Trenton mean annual) occurring that is equal or less than the predicted flow.

M = Rank in order of magnitude

N = Number of years record

The computations described for the Trenton mean annual flow are presented in Table 9. The resulting probability graph (Figure I-B-1) is the low-flow frequency curve for the Trenton mean annual flow. Table 10, taken from the low-flow frequency curves, summarizes the Trenton mean annual flows for the indicated recurrence interval.

MONTHLY FLOW SEQUENCES

It is often helpful to estimate the within-year variations of a given mean annual flow. The method that will be discussed here was developed by Frank H. Rainwater, FWPCA, and is one of many techniques used for estimating monthly fluctuations of the annual flow.

This technique involves the following steps:

a. A low-flow frequency distribution for the annual mean stream flow is constructed.

b. The median monthly mean flow for each month is computed.

c. The ratio of the median monthly flow to the annual mean flow for each month is determined. See Table 11.

d. These ratios are applied to the annual mean discharge at the desired recurrence interval to obtain the flow distribution.

The ratios as applied to the annual flows for the various recurrence intervals are represented by Table 12. It should be recalled that the monthly flow sequences are upper bound estimates, i.e., the flows would be equal to or less than that shown with the given probability.

LOW-FLOW FREQUENCY CURVES - TRENTON FLOW

When estimating the interaction between fresh water flow and water quality it is important to investigate low-flow regimes other than the annual. Prolonged lower flows may exist that are not represented by mean annual conditions. To describe the characteristics of the major tributaries, low-flow frequency curves were computed for durations of 7, 30, and 120 days. Construction of these distributions was as previously described, with the substitution of the mean low-flow of the desired duration for the mean annual flow. Table 13 and Figure I-B-2 present the 7, 30, and 120 day low-flow frequency curves for Trenton. Table 14 summarizes the unadjusted mean low-flows for the respective recurrence intervals.

TABLE 10

TRENTON MEAN ANNUAL LOW FLOW

Recurrence Interval (Years)	Probability of Occurrence (% of time flows are equal to or less than)	Annual Average Flow (cfs)
1.11	90	15,500
5	20	9,400
10	10	8,500
25	4	7,600
50	2	7,100

TABLE 11

Ratio of Median Monthly Flow
to Annual Mean Flow at Trenton

(1913-1963 Climatic Year)

Month		Median Monthly Flow (cfs)	Ratio = Median Monthly Flow / Annual Mean
4		23,690	2.30
5		11,900	1.16
6		6,970	0.68
7		5,120	0.50
8		4,050	0.39
9		3,850	0.37
10		4,515	0.44
11		9,630	0.94
12		10,500	1.02
1		11,200	1.09
2		11,000	1.07
3		20,970	2.04
	Sum =	123,395	12.00

$$\text{Annual Mean} = \frac{123{,}395}{12} = 10{,}283 \text{ cfs}$$

TABLE 12

DELAWARE RIVER MONTHLY FLOWS
(RAINWATER COMPUTATIONAL METHOD)

Month	Recurrence Interval (Years)				
	1.11	5	10	25	50
	Probability of Occurrence (% of time flows are equal to or less than)				
	90	20	10	4	2
4	35,650	21,600	19,550	17,500	16,350
5	18,000	10,900	9,850	8,800	8,250
6	10,550	6,400	5,800	5,200	4,850
7	7,750	4,700	4,250	3,800	3,550
8	6,050	3,650	3,300	2,950	2,750
9	5,750	3,500	3,150	2,800	2,650
10	6,800	4,150	3,750	3,350	3,100
11	14,550	8,850	8,000	7,150	6,650
12	15,800	9,600	8,650	7,750	7,250
1	16,900	10,250	9,250	8,300	7,750
2	16,600	10,050	9,100	8,150	7,600
3	31,600	19,200	17,350	15,500	14,500

Flows rounded to the nearest 50 cfs.

TABLE 13

DELAWARE RIVER AT TRENTON, N. J.
LOWEST CONSECUTIVE DAY MEAN DISCHARGE

(1913-1965 CLIMATIC YEAR)

Rank	Recurrence Interval (years)	Probability (% of time) ≤	Flow 7-Day	Flow 30-Day	Flow 120-Day
1	54.00	1.9	1,309	1,545	1,966
2	27.00	3.7	1,340	1,582	2,150
3	18.00	5.6	1,351	1,615	2,233
4	14.00	7.1	1,423	1,617	2,312
5	11.00	9.1	1,493	1,715	2,353
6	9.00	11.1	1,560	1,740	2,355
7	7.70	13.0	1,614	1,777	2,446
8	6.70	14.9	1,622	1,781	2,525
9	6.00	16.7	1,627	1,820	2,544
10	5.40	18.5	1,639	1,826	2,546
11	4.90	20.4	1,661	1,887	2,607
12	4.50	22.2	1,669	1,901	2,742
13	4.20	23.8	1,670	1,904	2,777
14	3.80	26.3	1,697	1,909	2,784
15	3.60	27.8	1,737	2,022	2,845
16	3.40	29.4	1,781	2,073	2,944
17	3.20	31.3	1,836	2,074	2,974
18	3.00	33.3	1,871	2,162	3,145
19	2.80	35.7	1,890	2,170	3,222
20	2.70	37.0	1,951	2,185	3,377
21	2.60	38.5	1,951	2,285	3,606
22	2.40	41.7	2,000	2,292	3,810
23	2.30	43.5	2,000	2,357	3,901
24	2.25	44.4	2,019	2,454	3,929
25	2.16	46.3	2,021	2,639	4,104
26	2.10	47.6	2,050	2,673	4,161
27	2.00	50.0	2,119	2,691	4,281
28	1.90	52.6	2,238	2,737	4,283
29	1.86	53.8	2,244	2,785	4,343
30	1.80	55.6	2,390	2,854	4,394
31	1.74	57.5	2,563	2,947	4,752
32	1.68	59.5	2,570	3,024	4,774
33	1.63	61.3	2,691	3,043	4,889
34	1.58	63.3	2,721	3,074	5,143
35	1.54	64.9	2,762	3,113	5,535

TABLE 13 (Cont'd)

DELAWARE RIVER AT TRENTON, N. J.
LOWEST CONSECUTIVE DAY MEAN DISCHARGE

(1913-1965 CLIMATIC YEAR)

Rank	Recurrence Interval (years)	Probability (% of time) ≤	Flow 7-Day	Flow 30-Day	Flow 120-Day
36	1.50	66.7	2,773	3,161	5,586
37	1.45	69.0	2,793	3,196	5,611
38	1.42	70.4	2,796	3,285	5,677
39	1.38	72.5	2,844	3,327	5,996
40	1.35	74.1	2,899	3,433	6,021
41	1.31	76.3	2,990	3,438	6,204
42	1.28	78.1	3,213	3,467	6,357
43	1.25	80.0	3,214	3,794	6,363
44	1.22	82.0	3,231	3,937	6,462
45	1.20	83.3	3,259	4,003	6,744
46	1.17	85.5	3,297	4,027	7,184
47	1.14	87.7	3,397	4,037	7,694
48	1.12	89.3	3,404	4,252	7,790
49	1.10	90.9	3,947	5,056	8,039
50	1.08	92.6	4,012	5,794	8,667
51	1.05	95.2	4,536	5,867	9,499
52	1.03	97.1	4,604	5,939	12,226
53	1.01	99.0	6,574	7,974	14,142

TABLE 14

DELAWARE RIVER AT TRENTON, N. J.
MEAN LOW FLOW

(1913-1963 CLIMATIC YEAR)

Recurrence Interval (Years)	Probability of Occurrence (% of time flows are equal to or less than)	Mean Low Flow (cfs)		
		7-Day	30-Day	120-Day
5	20	1,600	1,900	2,700
10	10	1,500	1,700	2,400
25	4	1,400	1,600	2,100
50	2	1,300	1,500	2,000

Flows rounded to 100 cfs.

TIME SERIES ANALYSES - TRENTON FLOW

To better understand the nature of the flow variability of the Delaware at Trenton, several time series analyses were performed. Two groups of data were analyzed; mean monthly flows from 1914-1963 (600 values) and mean daily flows for 1960-1962 (1095 values). The latter group was analyzed to provide some insight into the day to day variability while the former group was examined to obtain information on the month to month variations. By far the greater amount of information was obtained from the monthly data.

The autocovariance function given by

$$R(\tau) = \sum_{t=1}^{N-\tau} \frac{(qt-\bar{q})\ (qt+\tau - \bar{q})}{N-t} \qquad (1)$$

where

qt = flow at time t; $t = 1,2,3,\ldots N$

$\bar{q}$ = mean value of q

τ = time lag, $\tau = 0,1,2,\ldots m$

was computed for each group. The formal Fourier transformation of this function, known as the power spectrum was also estimated for each group utilizing the following relationships:

$$V_r = \Delta\tau[R_0 + 2 \sum_{i=1}^{m-1} R_i \cos \frac{ir\pi}{m} + R_m \cos r\pi] \quad r=0,1,2,\ldots m \qquad (2)$$

$$U_0 = 1/2\ (V_0 + V_1)$$

$$U_r = 1/4\ V_{r-1} + 1/2\ V_r + 1/4\ V_{r+1}, \quad 1 \leq r \leq m-1$$

$$U_m = 1/4\ V_{m-1} + 1/2\ V_m$$

where

V_r = the estimate of the "unsmoothed" record (contains all harmonics)

and

U_r = the "smoothed" estimate of the power spectrum (removal of some harmonics).

The power spectrum analysis basically distributes the total variance of a given record into individual frequency "bands". As such, it provides information on any predominant frequencies in the record that may not be obvious from a mere visual inspection. Frequency as used here refers to a time definition (cycles per time) as opposed to a probabilistic definition. The reciprocal of frequency is therefore the period of the particular phenomenon. More detailed information on the use of the power spectrum is given in References 8 and 9.

For some of the analyses, the "removal" of the annual flow variation was carried out via a harmonic analysis. The details of this procedure are given in Chapter IVB - Statistical Analyses.

Figure I-B-3 presents the 100 lag autocovariance function and Figure I-B-4 presents the power spectrum for the monthly flow series both before and after the removal of the annual periodicity (the 50th harmonic). The periodicity shown in the autocovariance function of the data before removal results in the pronounced peak in the spectrum of Figure I-B-4 and is a direct result of the annual periodicity in flow.

The annual harmonic which was removed from the record accounted for about 23% of the total variance and had an amplitude about the mean (12,340 cfs) of 6800 cfs and a time of maximum at 60 days from January 1 (about March 1). Removal of this harmonic had a pronounced effect on the analyses as shown in Figures I-B-3 and I-B-4. The autocovariance function after removal oscillates around zero without any noticeable features. However, the spectrums indicate that both before and after removal of the annual harmonic, some significant peaks appear to be present at the 2nd (6 month) and 3rd (4 month) harmonics of the annual. In addition, some low frequency (long period) components on the order of 2 and 5 years also appear to be present. These peaks are not evidenced in the autocovariance function and one may be misled into thinking that the spectrum of the function after removal shown in Figure I-B-3 should be completely flat. Figure I-B-4 spectrums indicate that these peaks are still present. Indeed, it is these harmonics (which as shown, have amplitudes of greater than 1000 cfs) which generate the "blockiness" in a flow record; i.e., the tendency for records not to be exactly periodic but rather sharply "steeped" during the spring and fall. From a systems analysis viewpoint, one may visualize these higher harmonics as the result of passing an annual variability in rainfall through a nonlinear drainage basin; the non-linearities giving rise to the higher harmonics.

The analyses of the daily data for the three year period (1960-1962) indicated a predominance of low frequency components with the spectrum decreasing in an exponential fashion with frequency. This is a reflection of the general persistence of day to day type of flow phenomena.

SYNTHETIC GENERATION OF FLOW AT TRENTON

Mathematical analysis of the time variability of quality in the estuary requires relatively long periods of flow records which are utilized as input data into the large dynamic dissolved oxygen model (see Chapter IV). The technique used to generate flow sequences for the Delaware at Trenton is fully described in several references[10,11,12] and will not be discussed in detail here. Briefly, the historical flow record is used to obtain regression coefficients between the flows in successive months. The first step is to compute the linear regression coefficients between the flow in the jth month and the flow in the j+1st month, designated as βj. This is done for each of the twelve months. These coefficients are related to the normalized autocovariance values at lag one discussed previously. In order to preserve both the mean and the variance of the historical trace, a random component must be added. The end result is the following equation which is used to generate the synthetic flows:

$$X_i+1,j+1 = \mu_{j+1} + \beta_{j+1} (X_i - \mu_j) + t_{i+1} \sigma_{j+1} [1-\rho^2_{j+1}]0.5 \qquad (3)$$

where

$X_i+1,j+1$	=	flow in time period i+1 and season j+1
μ_{j+1}	=	mean flow during season j+1
β_{j+1}	=	regression coefficient in season j+1 on flows in season j
σ_{j+1}	=	standard deviation of flows in season j+1
ρ_{j+1}	=	correlation coefficient between flows in seasons j and j+1
t_{i+1}	=	standardized random deviate with zero mean and unit variance.

The historical record at Trenton was analyzed to determine the necessary components to be used in the above analysis. These included for each month, the mean, standard deviation, skewness, correlation coefficient between successive months, the standard error, the regression coefficient and the coefficient of variation. These quantities were computed for both the untransformed data and for a log transformation of the data. A synthetic trace of 300 years of record was thus generated via equation(3).

In order to verify that the synthetic trace does indeed preserve all of the major statistical features of the historical trace, three spectral analyses were carried out on one hundred year groups of the generated trace. These spectrums were then compared to the spectrum of the historical record. The results are shown in Figure I-B-5.

The four curves shown in Figure I-B-5 indicate that for all practical purposes the spectrum is preserved in generating the flow sequence. There are some minor deviations, especially in the low frequency end of the spectrum where several of the synthetic traces did not apparently preserve the 2 and 5 year peaks although there is some hint of peaks in the first one hundred year trace.

As indicated, the results of this synthetic generation will be used more extensively in the simulation of long term water quality variations under particular waste control schemes.

LOW-FLOW FREQUENCY CURVES FOR SCHUYLKILL RIVER

The major tributary of the Delaware Estuary is the Schuylkill River. The discharges from the Schuylkill River enter the estuary at Philadelphia, Penna. at mile 92.04 (confluence of Schuylkill River and Delaware Estuary). Approximately 8.5 miles upstream from the confluence is a physical obstruction (Fairmount Dam) separating the estuarine and fresh water sections of the Schuylkill River. The drainage area above Fairmount Dam is 1893 square miles. For the 33 year period of record starting in 1931 the adjusted mean annual flow of the Schuylkill River is 2900 cfs. The adjusted flow includes the withdrawal of approximately 300 cfs by the City of Philadelphia.

To be consistent in comparing the respective stream flows, low-flow frequency curves were constructed for the Schuylkill River. Tabulated in Table 15 and presented in Figure I-B-6 are the 7, 30, and 120-day low-flow frequency curves for the Schuylkill River.

Table 16 summarizes the Schuylkill River adjusted mean low flows.

CONTROL OF INFLOW BY UPSTREAM STORAGE

The inflow to the estuary at Trenton can be controlled by releases from present and proposed upstream storage. Information concerning the effect of various flow regimes on water quality can be obtained from Chapter IV or from the report "Water Quality Control Study, Tocks Island Reservoir".[13]

The primary inflow functions to the Delaware Estuary are: 1) the Trenton flow as recorded at Trenton, New Jersey, and 2) the Schuylkill flow as recorded at Philadelphia, Penna. Present (1965) minimum average observed daily flows for these primary focal points of inflow are 2500 cfs and 350 cfs, respectively. The minimum average daily flow at Trenton (2500 cfs) is for the record drought (to 1963) and is based upon releases from New York City reservoirs maintaining 1750 cfs at Montague. The Schuylkill flows are not presently regulated by upstream storage; however, they have been adjusted to include the diversions by the City of Philadelphia.

TABLE 15

SCHUYLKILL RIVER AT PHILADELPHIA, PENNA.
LOWEST CONSECUTIVE DAY MEAN DISCHARGE (CFS)
(1932-1964)
(CLIMATIC YEAR)

Rank	Recurrence Interval (years)	Probability (% of time) ≤	Flow 7-Day	Flow 30-Day	Flow 120-Day
1	34.00	2.9	292	324	434
2	17.00	5.9	300	332	495
3	11.33	8.8	314	346	516
4	8.50	11.8	336	357	548
5	6.80	14.7	349	452	600
6	5.67	17.6	380	459	651
7	4.86	20.6	389	460	683
8	4.25	23.5	407	503	709
9	3.78	26.5	434	512	777
10	3.40	29.4	438	517	777
11	3.09	32.4	461	537	855
12	2.83	35.3	473	544	873
13	2.62	38.2	495	569	920
14	2.43	41.2	502	570	1,007
15	2.27	44.1	507	603	1,040
16	2.13	46.9	507	611	1,143
17	2.00	50.0	560	688	1,149
18	1.89	52.9	577	726	1,159
19	1.79	55.9	610	730	1,183
20	1.70	58.8	615	751	1,206
21	1.62	61.7	616	756	1,373
22	1.54	64.9	623	770	1,396
23	1.48	67.6	631	784	1,442
24	1.42	70.4	672	788	1,512
25	1.36	73.5	680	798	1,537
26	1.31	76.3	682	827	1,552
27	1.26	79.4	720	838	1,662
28	1.21	82.6	744	1,072	1,756
29	1.17	85.5	760	1,079	1,844
30	1.13	88.5	835	1,136	1,994
31	1.10	90.9	860	1,205	2,394
32	1.06	94.3	909	1,212	2,407
33	1.03	97.1	1,297	1,571	3,149

TABLE 16

SCHUYLKILL RIVER AT PHILADELPHIA, PENNA.
ADJUSTED MEAN LOW FLOWS
(1932-1964)

Recurrence Interval (Years)	Probability of Occurrence (% of time flow is equal to or less than)	Mean Low Flow (cfs)		
		7-Day	30-Day	120-Day
5	20	390	440	700
10	10	330	360	540
25	4	300	330	460
50	2	280	320	410

Studies by the Delaware Estuary Comprehensive Project have indicated the need for chloride control in the Delaware Estuary. Chloride control can be obtained through the implementation of stream flow regulation, i.e., the conservation of the Delaware River water resources.

The Corps of Engineers report[14] provides detailed descriptions of the construction and operation of a number of dams and reservoirs on the Delaware River and its tributaries. Further investigations on the effects of fresh water inflow on chloride control are discussed in the Tocks Island Report[13]. For the purposes described herein the incremental fresh water flows due to the estimated storage of the proposed reservoirs are presented in Table 17.

Upon completion of the presently proposed reservoirs, the incremental flow additions through stream flow regulation is estimated to be 1194 cfs. The fresh water increase for Trenton and the Schuylkill are 995 cfs and 199 cfs, respectively.

DISTRIBUTION OF RUNOFF ALONG ESTUARY

Incremental fresh water flows to the Delaware Estuary result from tributary discharges. In some cases, the flows can be accurately determined, i.e., for the gaged tributaries; however, estimates must be made for the ungaged tributaries.

The Delaware Estuary Study area drainage basin was divided into sub-basins as presented in Figure I-B-7. The sub-basins were chosen relative to the sections of the estuary used for computational purposes (see Chapter IVH). Application to the sub-basins of a runoff per square mile coefficient provides the incremental flow per estuary section.

For the gaged tributary areas (U.S.G.S. gaging Stations) the runoff per square mile relationships were calculated from the mean annual flow per square mile of drainage area. Applying these coefficients to the ungaged areas results in their corresponding average annual discharges. A summary of the mean annual discharges per estuary section is tabulated in Table 18.

TABLE 17

CUMULATIVE FLOWS

Corps of Engineers Project	Flow Increments CFS	Cumulative Minimum Flows - CFS: Delaware River @ Trenton	Schuylkill River @ Phila.	Total
None	-	2500 (c)	350	2850
Beltzville	94 (a)	2594	-	2944
Tocks Island	530 (b)	3124	-	3474
Blue Marsh	65	-	415	3539
Trexler	55	3179	-	3594
Prompton	57	3236	-	3651
Aquashicola	63	3299	-	3714
Maiden Creek	134	-	549	3848
Bear Creek	196	3495	-	4044

(a) Assumes 56 cfs for water supply and 38 cfs for water quality control.

(b) Of a total flow increment of 980 cfs, 450 cfs is planned for out of the basin diversion and hence is not included.

(c) Minimum average daily flow during record drought (to 1963) and is based upon releases from New York City reservoirs maintaining 1750 cfs at Montague.

TABLE 18

RUNOFF AND DRAINAGE AREAS PER ESTUARY SECTION

Estuary Section	Tributary	Location	Station Code	Period of Record	Drainage Area (Sq. Miles)	Mean Annual Flow (cfs)	Runoff per Sq. Mile (cfs)	Acc. Drainage Area (Sq. Mile)	Acc. Flows Mean Annual (cfs)
Above 1	Delaware River	Trenton, N.J.	0	1912-64	6,780	11,680	1.72	6,780	11,680
1	Assunpink Creek	Trenton, N.J.	3	1923-64	89.4	119	1.33		
1		Penna.	1		5.1	7.5	(1.48)		
1		New Jersey	2		3.1	4.6	(1.48)	6,877.6	11,811
2	Crosswicks Creek	Extonville, N.J.	5	1940-64	83.6	126	1.51		
2		Penna.	4		4.3	6.4	(1.48)		
2		New Jersey	6		102.3	151.4	(1.48)	7,067.8	12,095
3		Penna.	7		17.4	25.8	(1.48)		
3		New Jersey	8		7.1	10.5	(1.48)	7,092.3	12,131
4		Penna.	9		14.8	21.9	(1.48)		
4		New Jersey	10		49.8	73.7	(1.48)	7,156.9	12,227
5	Neshaminy Creek	Langhorne, Pa.	11	1934-64	210	274	1.31		
5		Penna.	12		35.2	52.1	(1.48)		
5		New Jersey	13		7.8	11.5	(1.48)	7,409.9	12,564
6	N.B. Rancocas Creek	Pemberton, N.J.	16	1921-64	111	169	1.52		
6	S.B. Rancocas Creek	Vincetown, N.J.	17	1961-64	53.3	78.9	(1.48)		
6		Penna.	14		28.3	41.9	(1.48)		
6		New Jersey	15		160.6	273.7	(1.48)	7,763.1	13,128
7		Penna.	18		50.6	74.9	(1.48)		
7		New Jersey	19		14.9	22.1	(1.48)	7,828.6	13,225
8		Penna.	20		11.1	16.4	(1.48)		
8		New Jersey	21		30.7	45.4	(1.48)	7,870.4	13,287
9		Penna.	22		31.2	46.2	(1.48)		
9		New Jersey	23		3.9	5.8	(1.48)	7,905.5	13,339
10		Penna.	24		5.7	8.4	(1.48)		
10		New Jersey	25		3.9	5.8	(1.48)	7,915.1	13,359

TABLE 18 (Cont'd.)

RUNOFF AND DRAINAGE AREAS PER ESTUARY SECTION

Estuary Section	Tributary	Location	Station Code	Period of Record	Drainage Area (Sq. Miles)	Mean Annual Flow (cfs)	Runoff per Sq. Mile (cfs) *	Acc. Drainage Area (Sq. Mile)	Acc. Flows Mean Annual (cfs)
11	Cooper River	Haddonfield, N.J.	28	1963-64	17.4	25.8	(1.48)		
11		Penna.	26		4.8	7.1	(1.48)		
11		New Jersey	27		30.3	44.8	(1.48)	7,967.6	13,392
12		Penna.	29		3.4	5.0	(1.48)		
12		New Jersey	30		0.8	1.2	(1.48)	7,971.8	13,398
13		Penna.	31		2.5	3.7	(1.48)		
13		New Jersey	32		10.0	14.8	(1.48)	7,984.3	13,416
14		Penna.	33		0.8	1.2	(1.48)		
14		New Jersey	34		62.0	91.8	(1.48)	8,047.1	13,509
15	Schuylkill River	Phila., Penna.	35	1931-64	1,893	2,900	1.53		
15		Penna.	36		19.9	29.5	(1.48)		
15		New Jersey	37		14.5	21.5	(1.48)	9,974.5	16,460
16	Mantua Creek	Pitman, N.J.	40	1940-64	6.8	11.5	1.69		
16		Penna.	38		6.2	9.2	(1.48)		
16		New Jersey	39		55.1	81.5	(1.48)	10,042.6	16,563
17	Darby Creek	Darby, Pa.	41	1964-64	37.4	55.4	(1.48)		
17	Cobbs Creek	Darby, Pa.	42	1964-64	22.0	32.6	(1.48)		
17		Penna.	43		81.7	120.9	(1.48)		
17		New Jersey	44		19.0	28.1	(1.48)	10,202.7	16,800
18	Chester Creek	Chester, Pa.	45	1931-64	61.1	80.8	1.32		
18		Penna.	46		14.0	20.7	(1.48)		
18		New Jersey	47		58.8	87.0	(1.48)	10,336.6	16,988
19		Penna. & Del.	48		14.3	21.2	(1.48)		
19		New Jersey	49		46.6	69.0	(1.48)	10,397.5	17,078
20		Delaware	50		15.0	22.2	(1.48)		
20		New Jersey	51		3.9	57.7	(1.48)	10,416.4	17,158

TABLE 18 (Cont'd.)

RUNOFF AND DRAINAGE AREAS PER ESTUARY SECTION

Estuary Section	Tributary	Location	Station Code	Period of Record	Drainage Area (Sq. Miles)	Mean Annual Flow (cfs)	Runoff per Sq. Mile (cfs)	Acc. Drainage Area (Sq. Mile)	Acc. Flows Mean Annual (cfs)
21	Brandywine River	Wilmington, Del.	55	1946-64	314	453	1.44		
21	Christina River	Cooch's Bridge, Del.	54	1943-63	20.5	26.2	1.28		
21	White Clay Creek	Newark, Del.	53	1931-63	87.8	108	1.23		
21	Red Clay Creek	Wooddale, Del.	52	1943-63	47.0	63.1	1.34		
21		Delaware	56		79.4	117.5	(1.48)		
21		New Jersey	57		2.0	3.0	(1.48)	10,967.1	17,929
22		Delaware	58		2.7	4.0	(1.48)		
22		New Jersey	59		2.1	3.1	(1.48)	10,971.9	17,936
23		Delaware	60		3.0	4.4	(1.48)		
23		New Jersey	61		1.9	2.1	(1.48)	10,976.8	17,943
24		Delaware	62		3.9	5.8	(1.48)		
24		New Jersey	63		2.7	4.0	(1.48)	10,983.4	17,952
25		Delaware	64		12.2	18.1	(1.48)		
25		New Jersey	65		1.3	1.9	(1.48)	10,996.9	17,972
26		Delaware	66		20.1	29.7	(1.48)		
26		New Jersey	67		2.0	3.0	(1.48)	11,019.0	18,005
27		Delaware	68		1.1	1.6	(1.48)		
27		New Jersey	69		4.1	6.1	(1.48)	11,024.2	18,013
28	Salem River	Woodstown, N.J.	72	1940-64	14.6	19.0	1.30		
28		Delaware	70		29.4	43.5	(1.48)		
28		New Jersey	71		100.6	148.9	(1.48)	11,168.8	18,224
29	Alloway Creek	Alloway, N.J.	75	1952-64	21.9	24.4	1.11		
29		Delaware	73		14.6	21.6	(1.48)		
29		New Jersey	74		43.3	64.1	(1.48)	11,248.6	18,334
30		Delaware	76		80.6	119.3	(1.48)		
30		New Jersey	77		5.5	8.1	(1.48)	11,334.7	18,462

*(1.48) = Average of Gaged Runoff Coefficients.

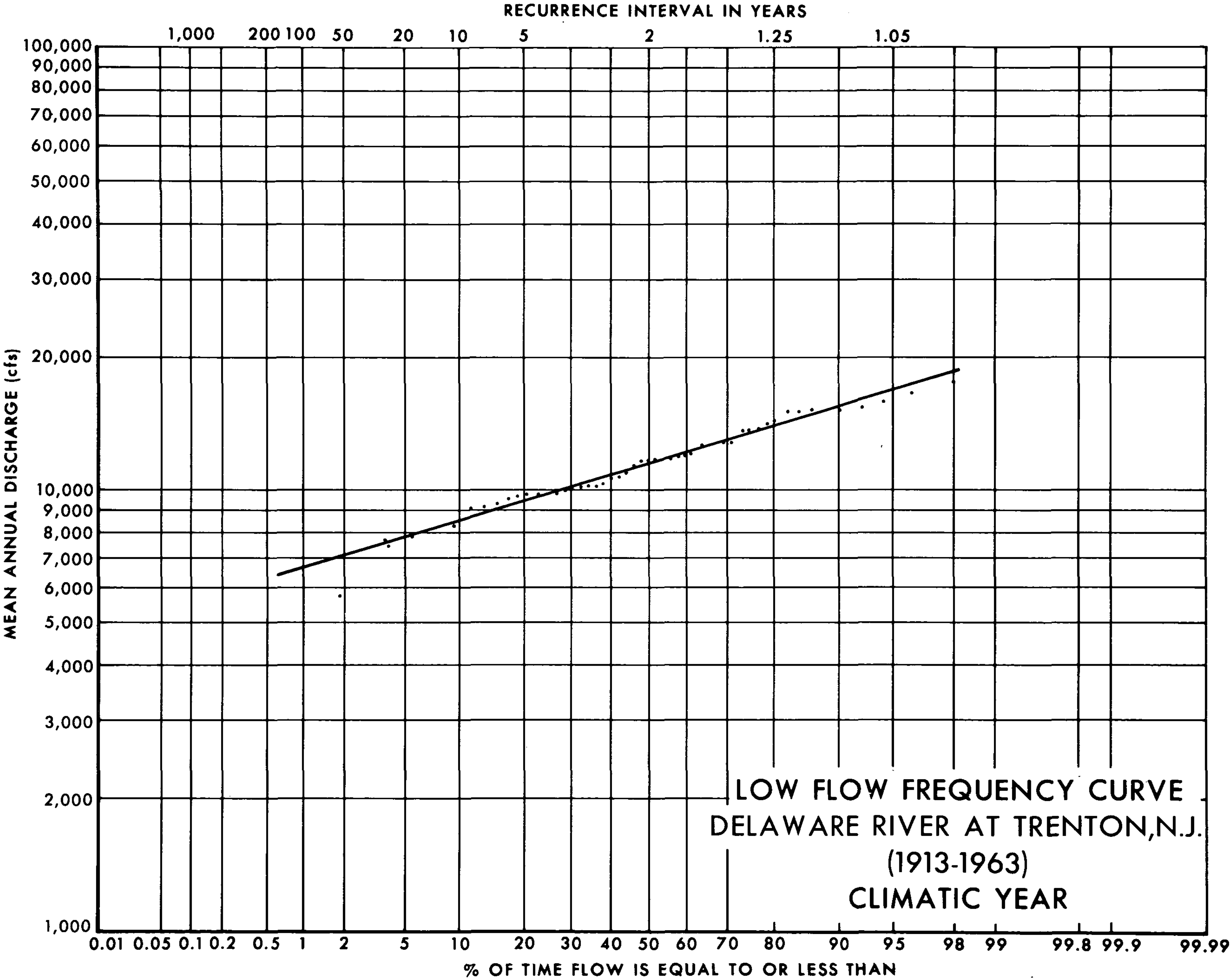

RECURRENCE INTERVAL IN YEARS
1,000
200
100
50
20
10
5
2
1.25
1.05
MEAN ANNUAL DISCHARGE (cfs)
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
% OF TIME FLOW IS EQUAL TO OR LESS THAN
LOW FLOW FREQUENCY CURVE
DELAWARE RIVER AT TRENTON, N.J.
(1913-1963)
CLIMATIC YEAR

Figure I-B-1

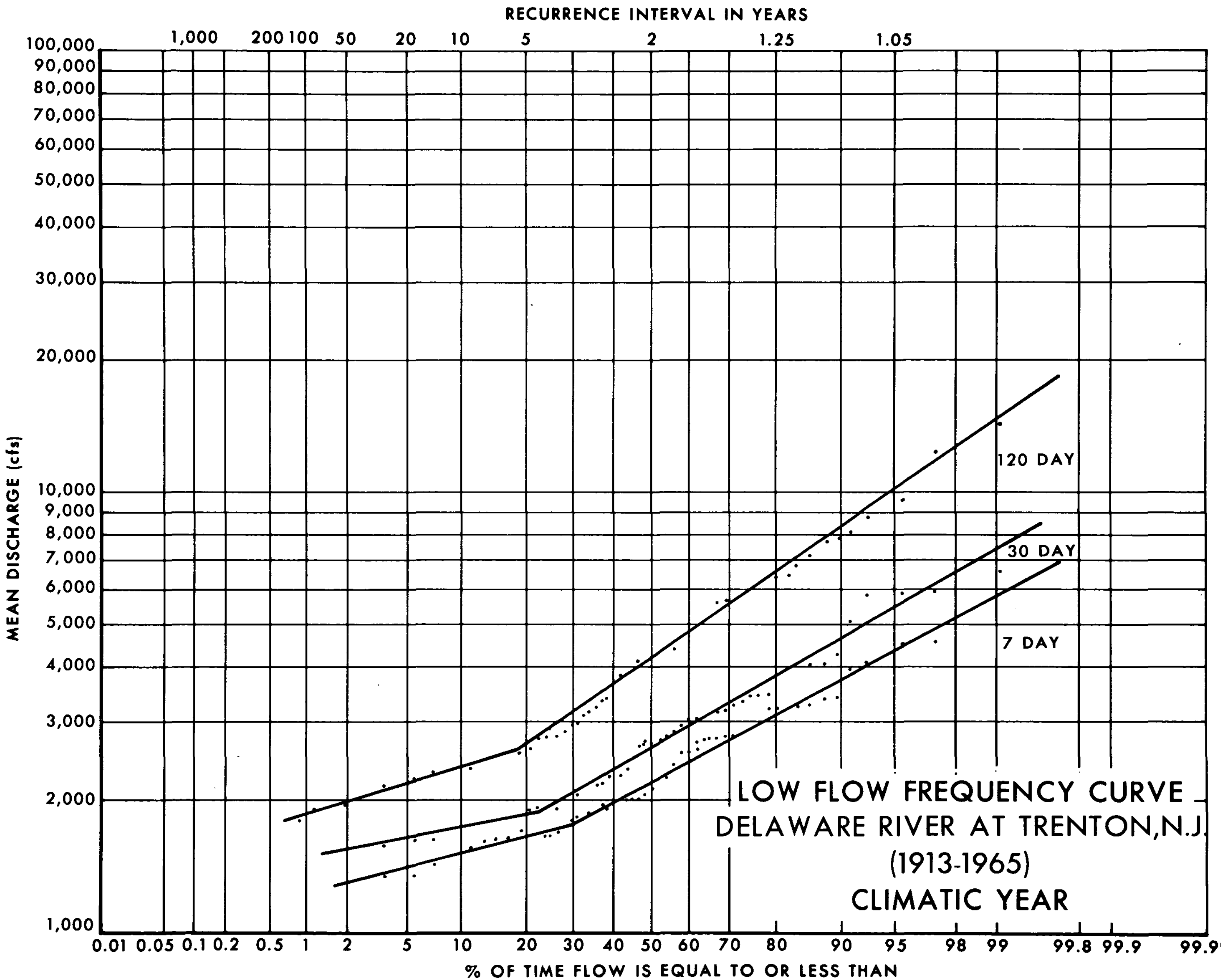

LOW FLOW FREQUENCY CURVE
DELAWARE RIVER AT TRENTON, N.J.
(1913-1965)
CLIMATIC YEAR
RECURRENCE INTERVAL IN YEARS
MEAN DISCHARGE (cfs)
% OF TIME FLOW IS EQUAL TO OR LESS THAN
120 DAY
30 DAY
7 DAY

Figure I-B-2

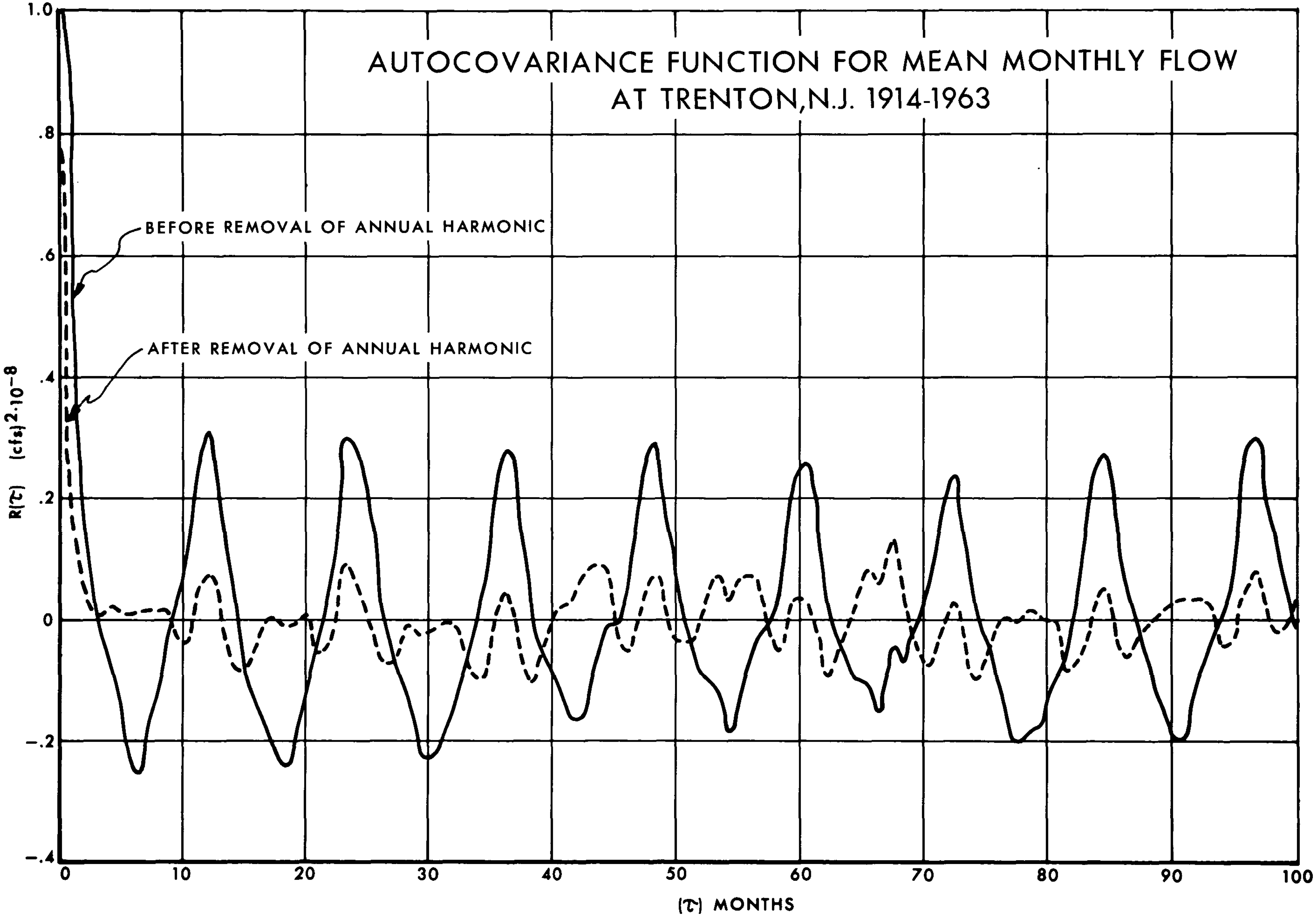

AUTOCOVARIANCE FUNCTION FOR MEAN MONTHLY FLOW
AT TRENTON, N.J. 1914-1963
BEFORE REMOVAL OF ANNUAL HARMONIC
AFTER REMOVAL OF ANNUAL HARMONIC
R(τ) (cfs)²·10⁻⁸
1.0
.8
.6
.4
.2
0
-.2
-.4
0
10
20
30
40
50
60
70
80
90
100
(τ) MONTHS

Figure I-B-3

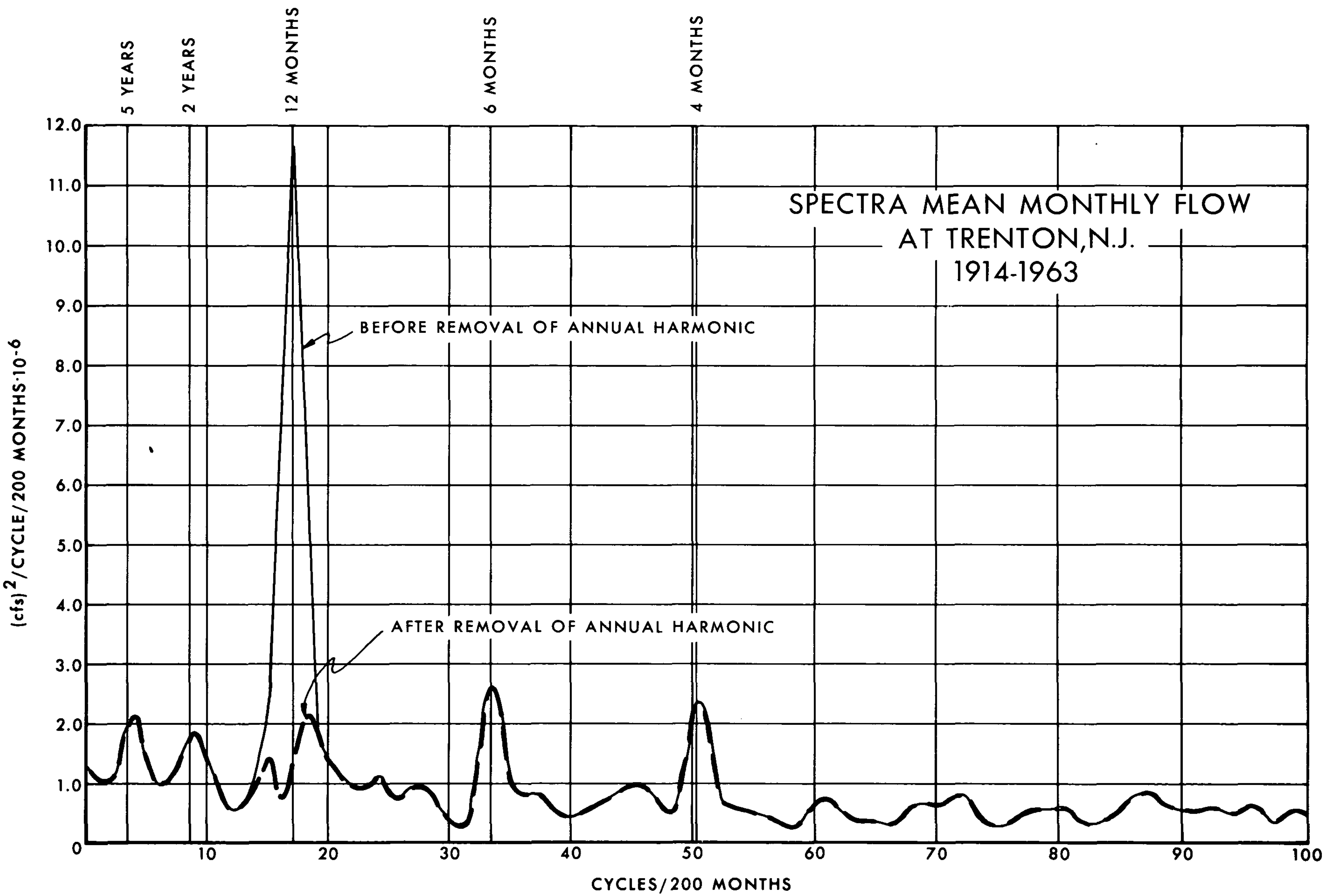

SPECTRA MEAN MONTHLY FLOW
AT TRENTON, N.J.
1914-1963
5 YEARS
2 YEARS
12 MONTHS
6 MONTHS
4 MONTHS
BEFORE REMOVAL OF ANNUAL HARMONIC
AFTER REMOVAL OF ANNUAL HARMONIC
(cfs)²/CYCLE/200 MONTHS·10⁻⁶
CYCLES/200 MONTHS
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
10
20
30
40
50
60
70
80
90
100

Figure I-B-4

PAGE NOT

AVAILABLE

DIGITALLY

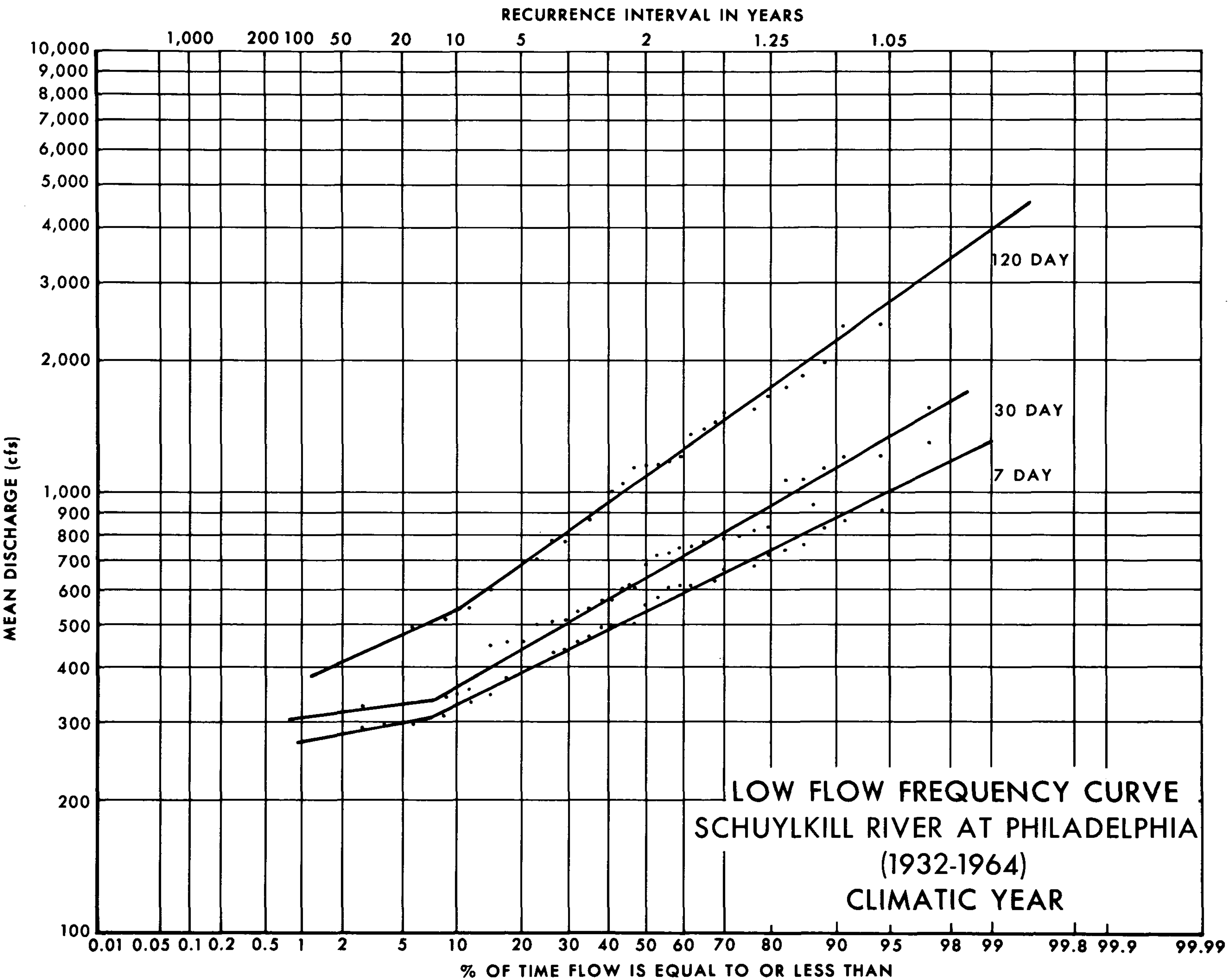

RECURRENCE INTERVAL IN YEARS
1,000
200
100
50
20
10
5
2
1.25
1.05
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
900
800
700
600
500
400
300
200
100
MEAN DISCHARGE (cfs)
120 DAY
30 DAY
7 DAY
LOW FLOW FREQUENCY CURVE
SCHUYLKILL RIVER AT PHILADELPHIA
(1932-1964)
CLIMATIC YEAR
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
% OF TIME FLOW IS EQUAL TO OR LESS THAN

Figure I-B-6

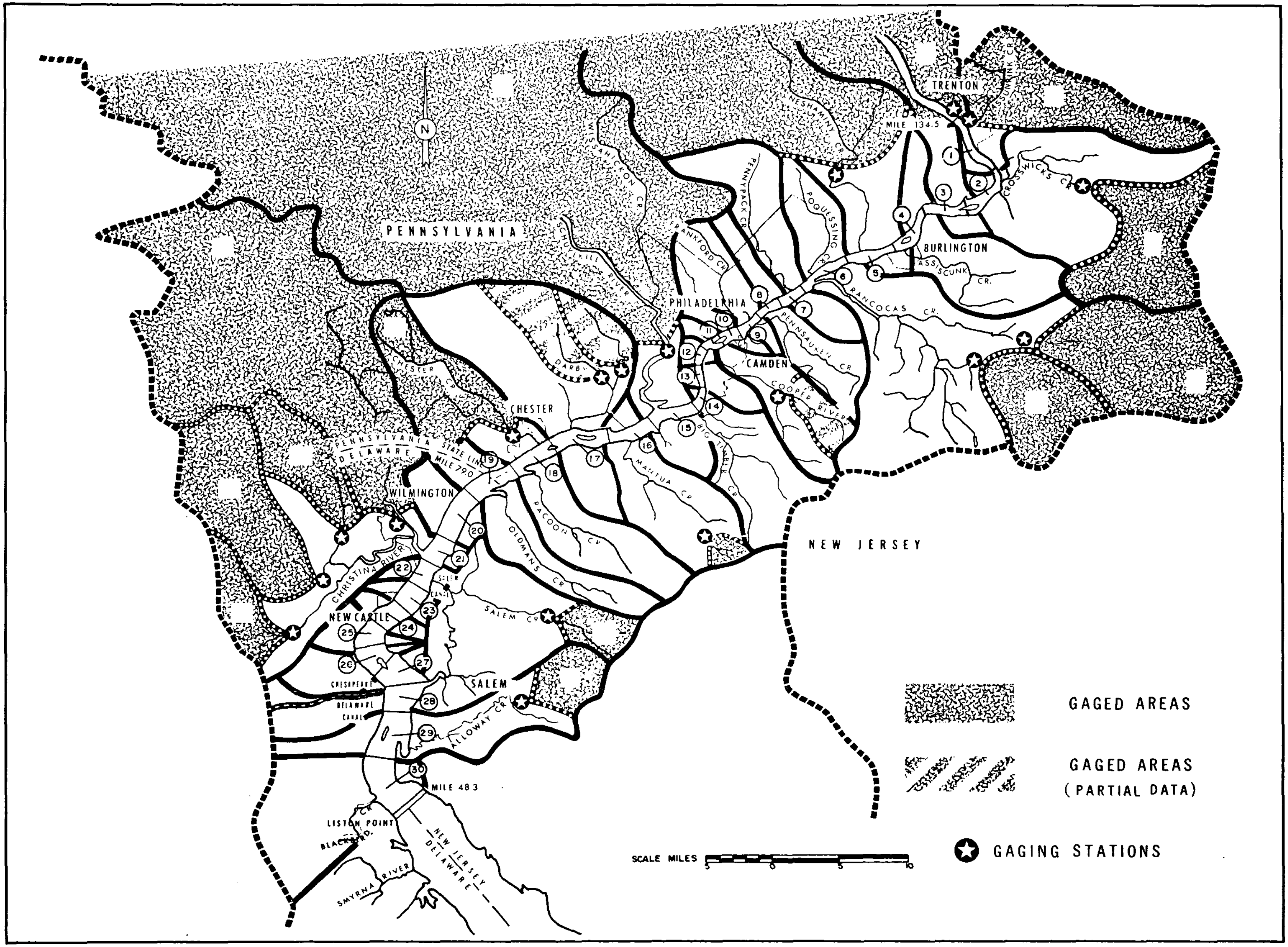

PENNSYLVANIA
NEW JERSEY
TRENTON
MILE 134.5
NESHAMINY CR.
CROSSWICKS CR.
BURLINGTON
ASSISCUNK CR.
PENNYPACK CR.
POQUESSING CR.
FRANKFORD CR.
PHILADELPHIA
CAMDEN
RANCOCAS CR.
PENNSAUKEN CR.
COOPER RIVER
BIG TIMBER CR.
MANTUA CR.
RACOON CR.
OLDMANS CR.
SALEM CR.
SALEM
ALLOWAY CR.
SCHUYLKILL RIVER
WISSAHICKON CR.
DARBY
CHESTER CR.
CHESTER
PENNSYLVANIA-DELAWARE STATE LINE
MILE 79.0
WILMINGTON
CHRISTINA RIVER
NEW CASTLE
SALEM CANAL
CHESAPEAKE DELAWARE CANAL
MILE 48.3
LISTON POINT
SMYRNA RIVER
NEW JERSEY
DELAWARE
GAGED AREAS
GAGED AREAS (PARTIAL DATA)
GAGING STATIONS
SCALE MILES

Figure I-B-7

CHAPTER I

SECTION C

ESTUARINE DYNAMICS

TIDAL CURRENT INVESTIGATIONS

To fill some of the gaps in existing hydrodynamic data on the Delaware Estuary, the DECS embarked on a tidal current measurement program. The objectives of this program were to:

a. more accurately define the current pattern over a tidal cycle;

b. relate long and short term changes in the tidal current pattern to climatological data (wind, etc.) and fresh water inflow;

c. determine net downstream movement over a tidal cycle as a function of fresh water inflow;

d. attempt to qualitatively evaluate turbulence patterns from current velocity and direction data.

Experiments conducted at the U. S. Army Engineers Waterways Experiment Station, Vicksburg, Miss., on the physical model of the Delaware Estuary have aided in the development of information relative to tidal diffusion, advection, time of travel and distribution of wastes[15]. The U.S.G.S. maintains data measuring stations on the Delaware Estuary to record fresh water inflow (Delaware River at Trenton, Schuylkill River, other tributaries) and tide height at several points along the estuary[16]. Periodic measurements of tidal current velocities are also conducted at selected stations to obtain correlations with the tide stage and slope data for the computation of mass movement over a tidal cycle[17][18].

The entire length of the Delaware Estuary from Trenton, N. J., to Delaware Bay contains a shipping channel with an average depth of 35'-45' and a width of 300'-1000'. Within this channel and its associated anchorages moves the greater mass of water influenced by tidal action. Currents in the estuary are almost entirely of tidal origin. Proximity to the ocean through Delaware Bay permits the occurrence of regular tidal cycles of 12 hours and 25 minutes duration. In the lower estuary the tidal phenomenon produces a change in current direction of 180° every six hours and 12 minutes, with current velocities for the flood and ebb tides being approximately equal. As one progresses upstream, the physical configuration of the estuary gradually alters the effects of the tidal phenomenon. Localized shore to shore restrictions produce higher current velocities;

This section was prepared by Albert W. Bromberg, U.S. Environmental Protection Agency, Edison, N.J.

the gradual narrowing of the estuary channel from the bay to Trenton produces greater tidal variation with distance from the ocean; the influence of surface water and ground water inflow alters the length and velocity of the ebb versus the flood tide. Tidal height, as affected by the combined influence of lunar and solar bodies, changes in relation to the position of these bodies with each other and the earth. Table 19 indicates the range of tidal height as experienced in the Delaware Estuary.[19]

The presence of large dominant weather systems in the eastern United States also has an effect on tidal height. An extreme example of this occurred in the estuary between Dec. 31, 1962 and Jan. 2, 1963.[20] A deep low pressure system remained stationary off the east coast generating strong (average 35-45 MPH) northwest winds. These winds, blowing approximately parallel to the axis of the estuary offset the tidal phenomenon for the entire period. High tide levels were considerably below normal low tide levels for the entire period, producing navigation hazards and exposing many industrial water supply intakes. When the winds ceased, permitting the return of normal tidal conditions, high salinity water encroached far beyond its seasonal norm[21]. The estuary required approximately 30 days to return to normal salinity condition.

TABLE 19

TIDAL HEIGHT RANGES IN THE DELAWARE ESTUARY

Point Along Delaware Estuary	Miles from Delaware Bay Mouth	Tide Range	
		Mean (Feet)	Spring (Feet)
Cape May, N.J.	0	4.3	5.2
Cape Henlopen, Del.	0	4.1	4.9
Liston Point, Del.	48.3	5.7	6.4
Philadelphia, Pa.	100.0	5.9	6.2
Trenton, N.J.	132.0	6.8	7.1

CURRENT MEASUREMENT PROGRAM

The instrumentation chosen to measure current velocity was the Woods Hole Recording Current Meter (See Figure I-C-1). It is a self-contained digital recording meter capable of measuring current direction and speed in a range of below 0.05 knots (.08 ft./sec.) to 5 knots (8.4 ft./sec). All data are recorded on 16mm photographic film. A 100' roll of film is capable of storing 9600 sets of rotor speed, vane and compass direction readings at a film advance rate of 1/8 inch per minute. Recording continuously, the instrument can operate for six and one-half (6-1/2) days; recording at one-hour intervals (a one minute reading per hour), it can operate for four hundred (400) days.

All data are transmitted to the camera field of view via optical fibers. Vane and compass are coded in Gray binary form and require seven (7) channels each. Current speed is recorded as a series of light pulses on two (2) channels, one each for the ones and tens count. Inclination of the instrument from the vertical is recorded as elongated light pulses, each pulse corresponding to 5° of tilt. Two (2) additional channels provide a read pulse signal and a reference signal intensity.

Operational characteristics of the various instrument components are as follows:

Savonius Rotor

Starting speed, .01 knots (.017'/sec.); maximum speed, 5.0 knots (8.4'/sec.). Approximate rotation rate 80 rpm/knot. Accuracy at .01 knot, ± 50%, greater than 0.3 knot, ± 3%.

Directional Vane

Sensitive within 10° at .01 knot, 2° at .025 knot; resolution 2.5°.

Compass

Sensitivity better than 2°, resolution 2.5°.

Maximum tilt angle before binding, 45°.

Inclinometer

Tilt error, 3% at 5°, 6% at 10°, 12% at 20°, 20% at 30°.

(Tilt of instrument causes low velocity readings).

The instrument is powered by a six (6) volt dry cell battery, which is sufficient for a fourteen (14) month recording period. It is constructed of aluminum, weighing 90 lbs. in air and 10 lbs. in water. A tensile load of 7000 lbs. may be applied across the instrument in a mooring system.

Heavy shipping traffic in the estuary necessitated the selection of current measuring stations outside of the main channel but still in areas where representative hydrodynamic conditions existed. In consultation with the U. S. Army Corps of Engineers, the following guidelines were established for placing semi-permanent instrument stations in the estuary:

a. Trenton to Philadelphia - no closer than 50' to the edge of the ship channel.

b. Philadelphia to Delaware Bay - no closer than 100' to the edge of the ship channel.

Using these guidelines, four current measurement stations were chosen along the length of the estuary. (See Figure I-C-2).

Based on the records of the manufacturer as to the uses of the Wood's Hole Current Meter, the DECS was the first to install them in an estuarine system. The conditions which exist in such a system (high current velocity, six foot tidal variation, heavy ship traffic, relatively shallow depth, etc.) necessitated the design of a different type of mooring system. Utilizing the equipment and facilities available through the U. S. Coast Guard, Gloucester City, N. J., a set of mooring systems were fabricated and installed with satisfactory results.

The tidal current meters were an integral part of the mooring system. They were suspended at a fixed depth below a surface buoy, the fixed depth being equal to one half of the mean depth at the particular station. The overall length of the mooring system was equal to the maximum expected depth at high tide. (See Figure I-C-3).

Realizing the complexity of the phenomena which were under investigation, the study attempted to measure estuary responses to input conditions which covered as wide a range as possible. In particular, it was of interest to measure the effect of transient peak fresh water inflows that occur at Trenton during the spring. Unfortunately, natural occurrences prevented the collection of data during the desired periods. The drought conditions which prevailed in the northeastern U. S. during the study period (fall 1962 - spring 1965) minimized the occurrence of any well defined peak flows. Although flows of greater than 60,000 cfs have occurred at Trenton in the past, only spike flows of this magnitude were realized during the study period. Instrumentation was not in place for either of these events because they occurred during the winter and spring ice flow conditions. Other pronounced peaks of lower magnitude occurred during the study period, but these again were during the winter or masked by the overall flow regime.

Table 20 contains a log of all instrument installation during the study period including the time and date of installation and removal and remarks pertinent to the instrument location, data recording interval and condition of the film record.

A current measurement station was located at the Burlington-Bristol Bridge (mile 117.5) early in the program, but was eliminated after the loss of one instrument. Due to an instrument malfunction, no useful data were gathered during the one recording period at this station.

The film processing and reading services provided by the instrument manufacturer were utilized for processing all original data film records. This service provided the following:

a. Point graph of rotor speed (knots) versus Direction (degrees). (Figure I-C-4).

b. Polar coordinate histogram of current direction (degrees). (Figure I-C-5).

c. Histogram of rotor speed (knots) versus number of occurrences. (Figure I-C-6).

d. Analog strip chart plot of rotor speed, direction and inclination.

e. Data transcribed to computer magnetic tape in IBM 7 channel binary format.

Upon examination of the data records from each current meter station, the degree of tilt of the instrument from the vertical during most of the recording period was unusually high (20^{o}-40^{o}). However, it was concluded that this condition could not be avoided regardless of the type of mooring system in view of the high velocities encountered (1.5'/sec. ave. - 3.0'/sec. max.) based on actual current velocity measurement.

Although the study collected current data at only one point of the cross-section at each station, data are available to obtain velocity relationships for part or all of the cross-section at the respective stations.

A current meter was on location approximately 800 yards upstream of the Tacony-Palmyra Bridge recording continuously during the U.S.G.S. calibration study at Palmyra, N. J.[18], in May, 1963. Cross-sectional velocity data has been collected by the U.S.G.S. at the Delaware Memorial Bridge[17]. Two additional current meters were installed for a 24-hour period between September 5-6, 1963, at the Fort Mifflin station for correlation purposes.

TABLE 20

TIDAL CURRENT MEASURING STATIONS IN THE DELAWARE ESTUARY

LOCATION	TIME OF RECORD	REMARKS
Tacony-Palmyra Bridge Latitude - 40° 00' 50" Longitude - 75° 00' 10" Mile 107.5	1130 EST March 26, 1964 to 0830 EST May 11, 1964	Installed with directional vane. Data recorded at one-half hour intervals.
	0920 EST May 11, 1964 to 1620 EST May 19, 1964	Installed with directional vane. Data recorded continuously.
	0930 EDST June 9, 1964	Instrument and Buoy reported lost on June 22, 1964. Bottom searched by diver with no results.
	0940 EST October 12, 1964 to 1810 EST December 21, 1964	Data recorded at one-hour intervals. Inclinometer malfunctioned for entire recording period.
	1130 EST March 9, 1965 to 2110 EST May 26, 1965	Data recorded at one-hour intervals. Inclinometer malfunctioned for portion of recording period.
Fort Mifflin Latitude - 39° 52' 40" Longitude - 75° 12' 20" Mile 91.8	June 4, 1963 to June 11, 1963	Data recorded continuously. (Trial run of instrument).
	1210 EST July 12, 1963 to 0730 EST December 18, 1963	Data recorded at one hour intervals. Inclinometer did not record for entire period.
	1105 EST September 5, 1963 0940 EST September 6, 1963	Data recorded continuously. Savonius rotor located 9' below water surface. No inclinometer. Special 24 hour study.

TABLE 20 (Cont'd.)

TIDAL CURRENT MEASURING STATIONS IN THE DELAWARE ESTUARY

LOCATION	TIME OF RECORD	REMARKS
Fort Mifflin Latitude - 39° 52' 40" Longitude - 75° 12' 20" Mile 91.8	1120 EST September 5, 1963 to 0920 EST September 6, 1963	Data recorded continuously. No inclinometer. Instrument located S 38° E True Bearing, 750 yards from above position. Meter at mid-depth. Special 24-hour study.
	1815 EST March 26, 1964 to 0600 EST July 17, 1964	Data recorded at one-hour intervals.
	1120 EST October 12, 1964 0845 EST December 21, 1964	Data recorded at one-hour intervals.
	1540 EST March 30, 1965 to 0820 EST May 20, 1965	Data recorded at one-hour intervals. Latter portion of record affected by bad battery or a short in the camera motor.
Delaware Memorial Bridge Latitude - 39° 40' 25" Longitude - 75° 31' 15" Mile 68.0	1540 EST March 26, 1964 to 1030 EST July 28, 1964	Data recorded at one-hour intervals. Inclinometer record is spotty.
	1330 EST October 12, 1964 to 1105 EST December 21, 1964	Data recorded at one-hour intervals.
	0915 EST March 9, 1965 to 1850 EST May 20, 1965	Data recorded at one-hour intervals. Inclinometer not operating properly-Camera motor not operating properly upon post-installation check. Latter portion of data record may be affected.

RESULTS OF ANALYSES OF TIDAL CURRENT DATA

In order to analyze the data more efficiently, a computer program was prepared which accepted the data in the form recorded by the meter and performed the following operations: (a) for each location, all current speed values within a 180° arc facing downstream were designated positive (b) for the 180° arc facing upstream, the speed values were designated negative and (c) for each value, the necessary corrections were performed to compensate for the vertical tilt of the instrument at the time of recording. The result of this operation was a time series of current values oscillating around a zero value with positive values being oriented in a general downstream direction and negative values in a upstream direction.

As indicated previously, one of the objectives of the current measurement program was to "track" a mass of fresh water inflow through the estuary. Unfortunately, hydrologic conditions during the investigations were such as to preclude any definitive analyses of this type. However, some useful information was obtained through the application of time series techniques (see Runoff to Estuary, Chapter One, Section B). A number of different analyses were performed on the data including harmonic analysis, filtering of data and power spectral analysis. Fourier analyses of the record for the semi-diurnal harmonic and a group of four side-band harmonics indicated that this band accounted for about 85% of the total variance of the record. The semi-diurnal amplitude was about 0.98 knots.

Figure I-C-7 illustrates the results from a power spectrum computation on the residual 15% of the data obtained at the Ft. Mifflin station during the period October 1964 to December 1964. The predominance of the semi-diurnal tidal effect in this residual variance is quite striking but of equal interest is the occurrence of the second and third harmonics of the 12.4 hour phenomena. Indeed, these latter two periodicities account for as much variance as the diurnal harmonic indicating the relative significance of these higher harmonics. The presence of these higher harmonics may be a result of the non-cyclical nature of the tidal curve at the head end of an estuary and reflect the dampening of the tidal wave and the influence of changes in fresh water inflow. It is also interesting to note that for the October-December, 1964 record, there is no significant long period component reflecting the relative steady-state conditions in fresh water inflow. (Flow conditions as measured at Trenton were between 2000-3000 cfs).

Figures I-C-8, I-C-9, and I-C-10 illustrate the results of power spectrum analyses on the residual variance for three stations for March-May, 1965. The fresh water inflow during this time period decreased steadily with occasional small transient increases. Flows at Trenton of about 13,000 cfs were recorded at the beginning of the period, tapering off to about 3000 cfs at the end of the period (Figure I-C-11). Although some difficulty was experienced in recording the data at the three stations, the general patterns are of interest. The presence of the higher harmonics can again be seen at the Tacony Bridge and Ft. Mifflin stations but is not as evident at the Delaware Memorial Bridge station except at the 4.16 hr. period. This may again reflect the influence of dampening of the tidal wave and fresh water flow on the tidal velocity pattern. It would be valuable to attempt to measure the current patterns during periods of high transient runoff and compare the resultant spectrums with those obtained above under relatively steady-state conditions. The influence of the long period effect (gradual decrease in flow) is also most pronounced at the upstream Tacony Bridge station as shown by the increase in power at the low frequency end.

The results of the above analyses thus indicate the relative importance of examining the entire spectrum of tidal and fresh water phenomena and not just a single isolated frequency such as the semi-diurnal.

CHAPTER ONE

HYDROLOGY

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(20) Record Low Tide, December 31, 1962, Delaware River, Lendo, A.C., U.S.G.S. Water Supply Paper 1586-E, 1966.

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WOODS HOLE CURRENT METER

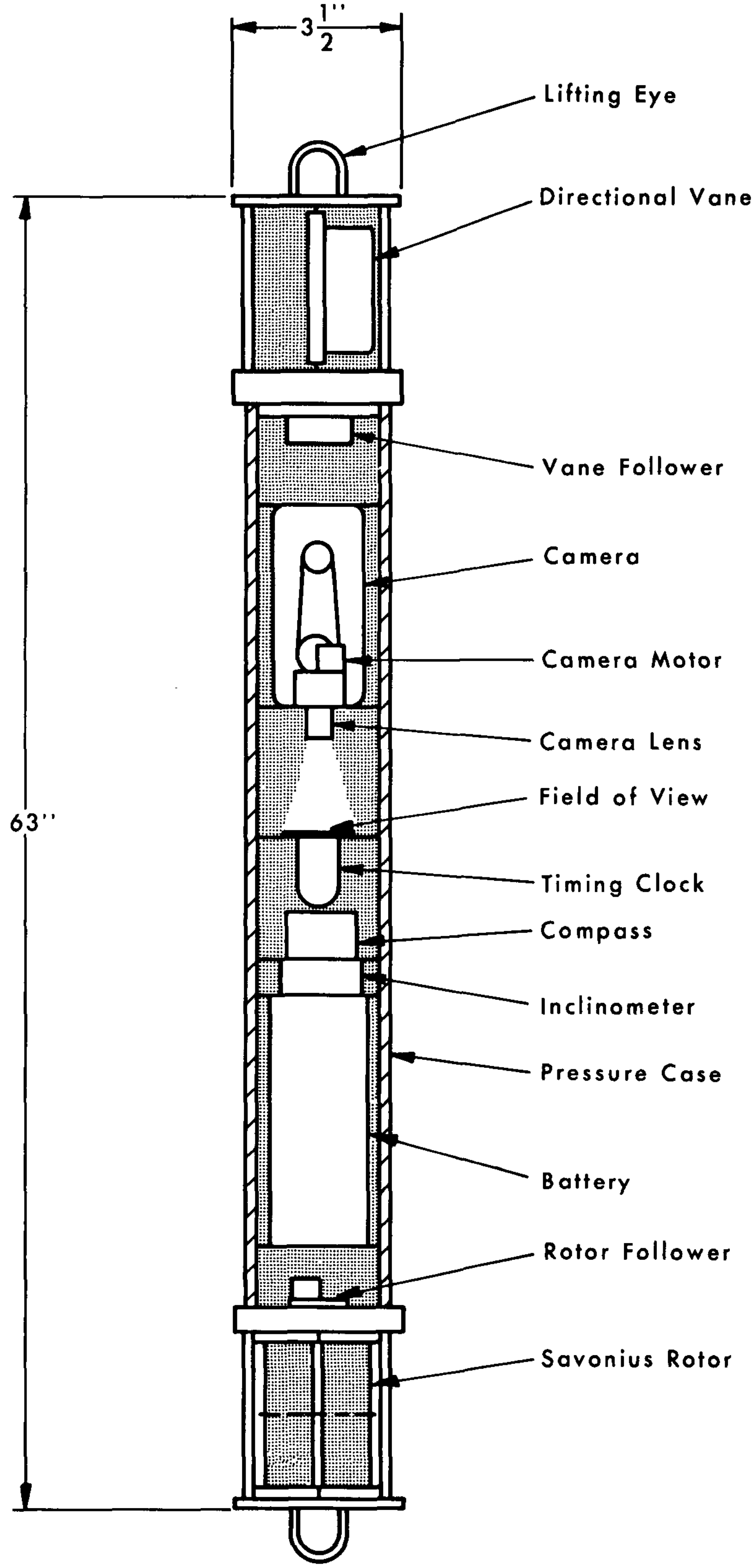


Figure I-C-1

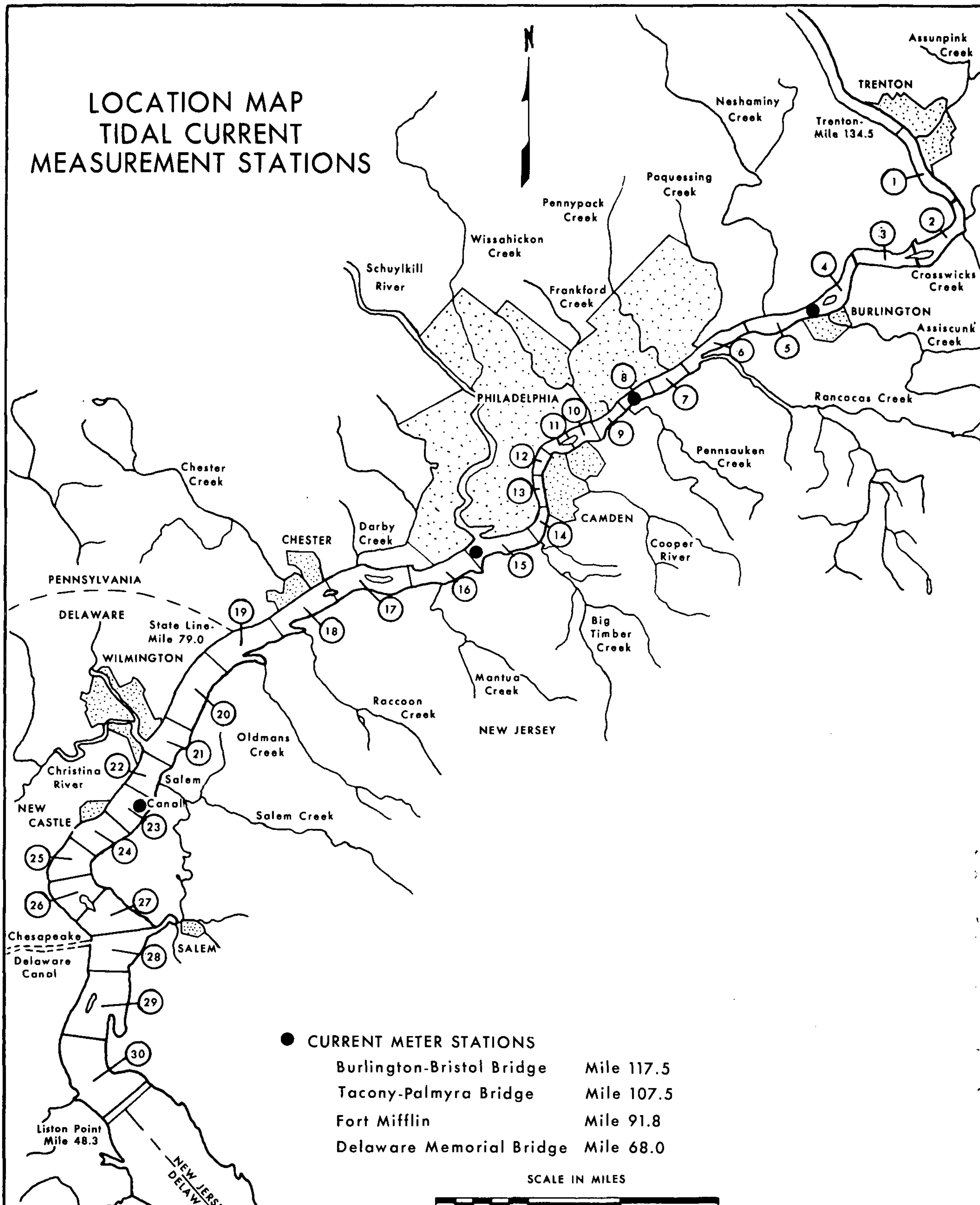

LOCATION MAP
TIDAL CURRENT
MEASUREMENT STATIONS
N
Assunpink Creek
TRENTON
Trenton-Mile 134.5
Neshaminy Creek
Paquessing Creek
Pennypack Creek
Wissahickon Creek
Schuylkill River
Frankford Creek
Crosswicks Creek
BURLINGTON
Assiscunk Creek
Rancocas Creek
PHILADELPHIA
Pennsauken Creek
CAMDEN
Cooper River
Chester Creek
CHESTER
Darby Creek
PENNSYLVANIA
DELAWARE
State Line-Mile 79.0
WILMINGTON
Big Timber Creek
Mantua Creek
Raccoon Creek
NEW JERSEY
Oldmans Creek
Christina River
Salem
Canal
Salem Creek
NEW CASTLE
Chesapeake
Delaware Canal
SALEM
Liston Point Mile 48.3
NEW JERSEY
DELAWARE
Smyrna River
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
CURRENT METER STATIONS
Burlington-Bristol Bridge Mile 117.5
Tacony-Palmyra Bridge Mile 107.5
Fort Mifflin Mile 91.8
Delaware Memorial Bridge Mile 68.0
SCALE IN MILES
5
0
5
10
CIRCLED NUMBERS REFER TO DECS SECTIONS

Figure I-C-2

CURRENT METER MOORING SYSTEM

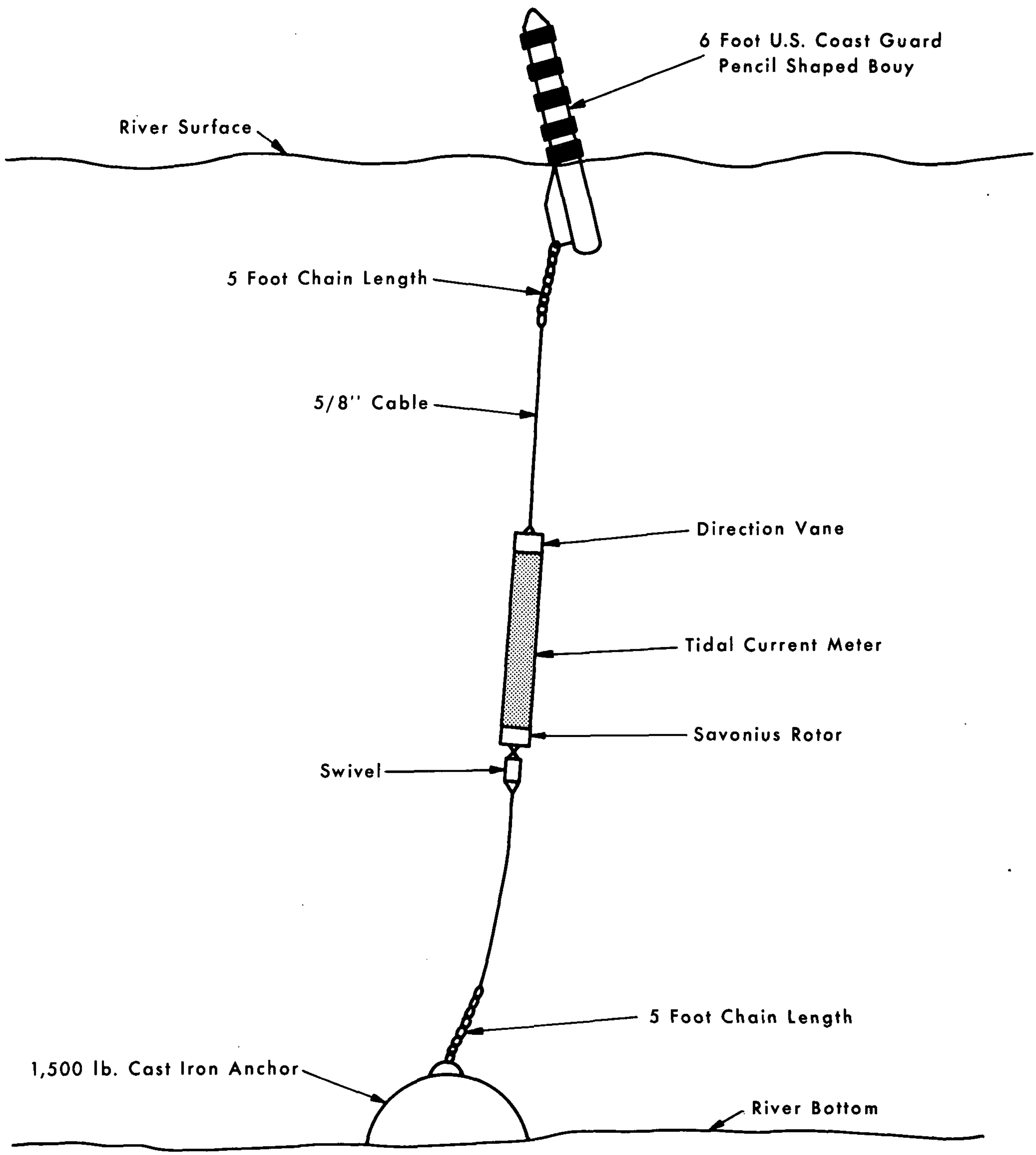


Figure I-C-3

PLOT OF ROTOR SPEED vs DIRECTION

DELAWARE MEMORIAL BRIDGE

10/12/64

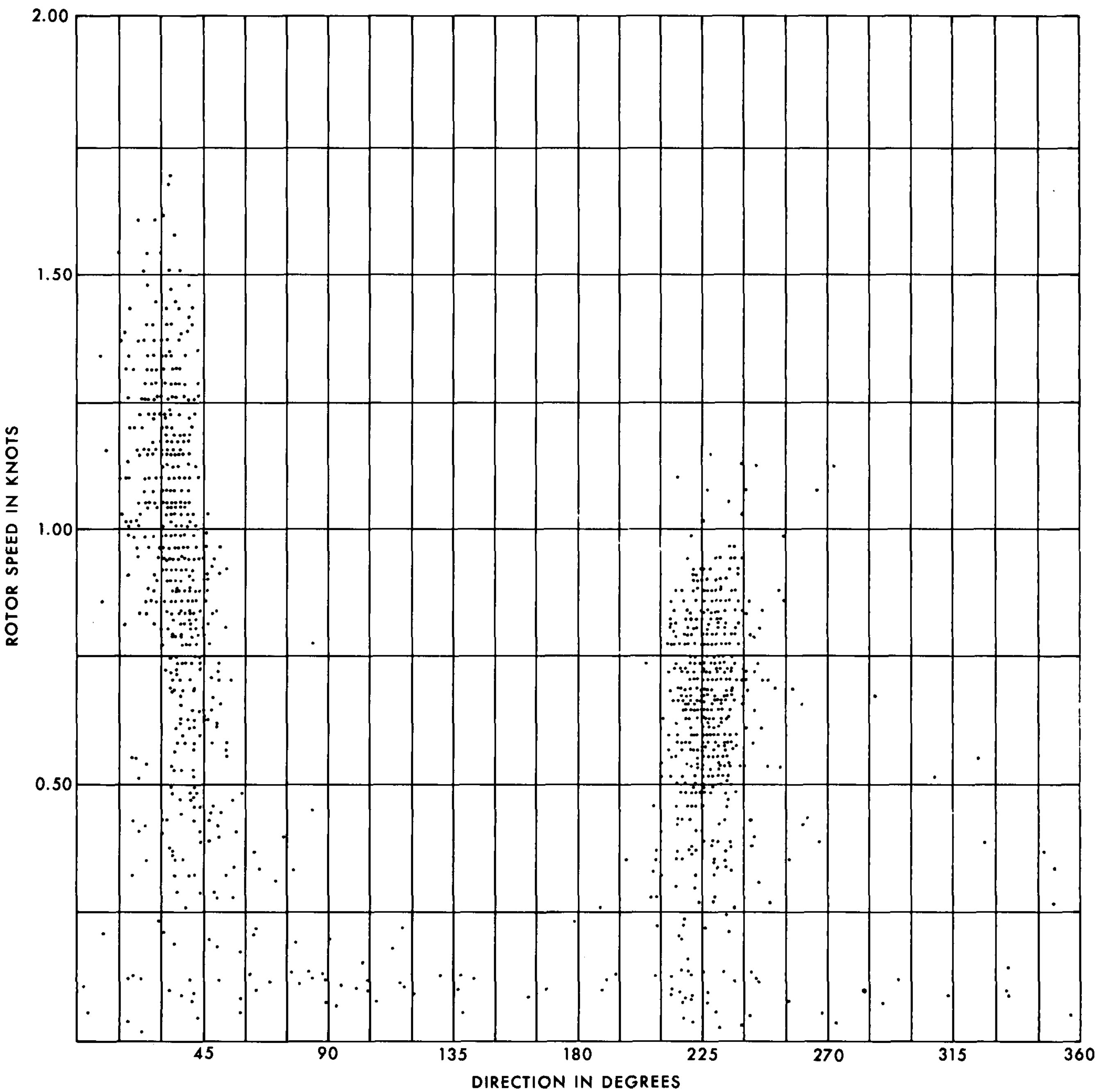


Figure I-C-4

POLAR COORDINATE HISTOGRAM PLOT OF DIRECTION FOR DELAWARE MEMORIAL BRIDGE 10/12/64

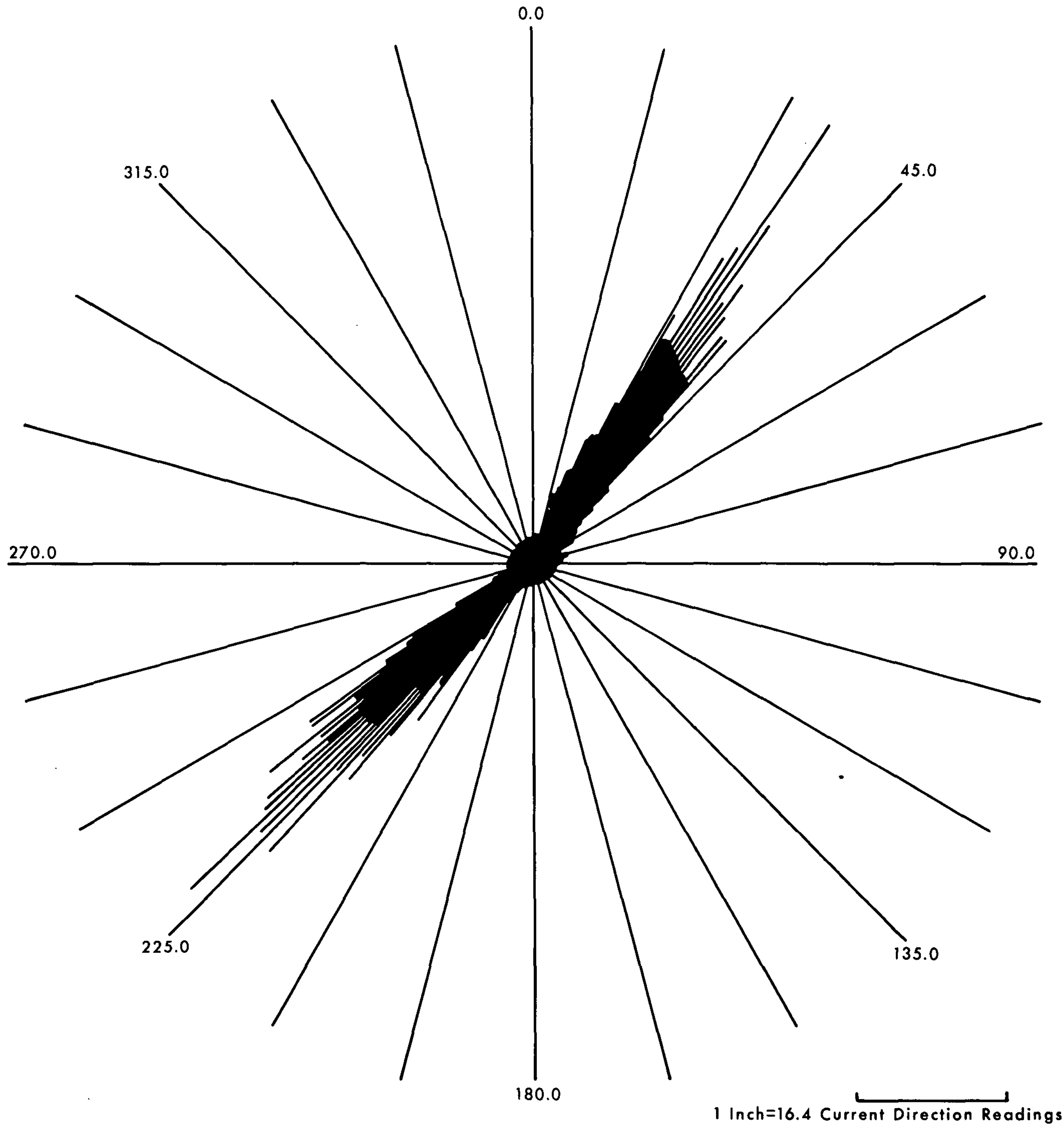


Figure I-C-5

HISTOGRAM OF ROTOR SPEED
DELAWARE MEMORIAL BRIDGE
10/12/64

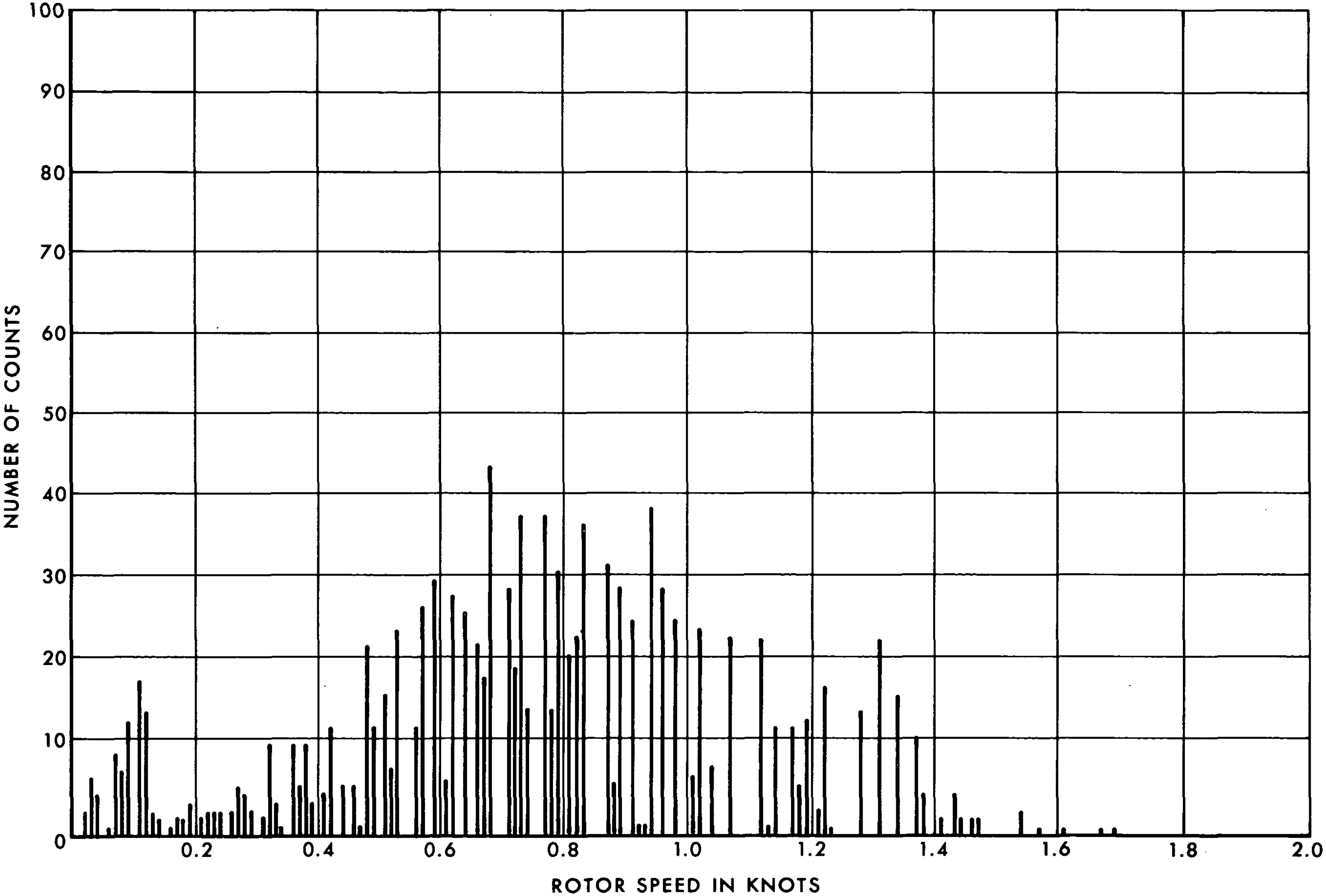


Figure I-C-6

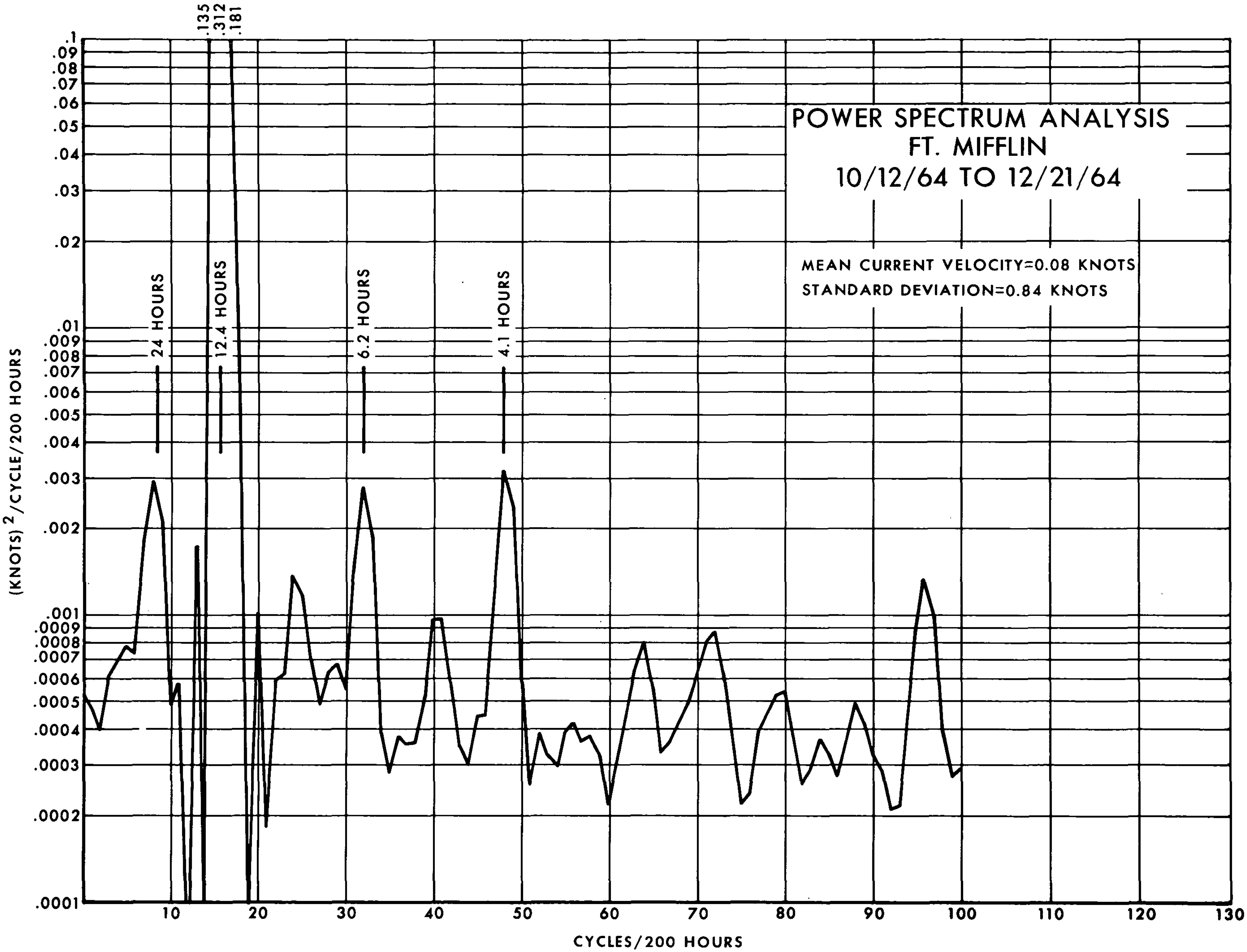

POWER SPECTRUM ANALYSIS
FT. MIFFLIN
10/12/64 TO 12/21/64
MEAN CURRENT VELOCITY=0.08 KNOTS
STANDARD DEVIATION=0.84 KNOTS
24 HOURS
12.4 HOURS
6.2 HOURS
4.1 HOURS
.135
.312
.181
(KNOTS)^2/CYCLE/200 HOURS
CYCLES/200 HOURS
.1
.09
.08
.07
.06
.05
.04
.03
.02
.01
.009
.008
.007
.006
.005
.004
.003
.002
.001
.0009
.0008
.0007
.0006
.0005
.0004
.0003
.0002
.0001
10
20
30
40
50
60
70
80
90
100
110
120
130

Figure I-C-7

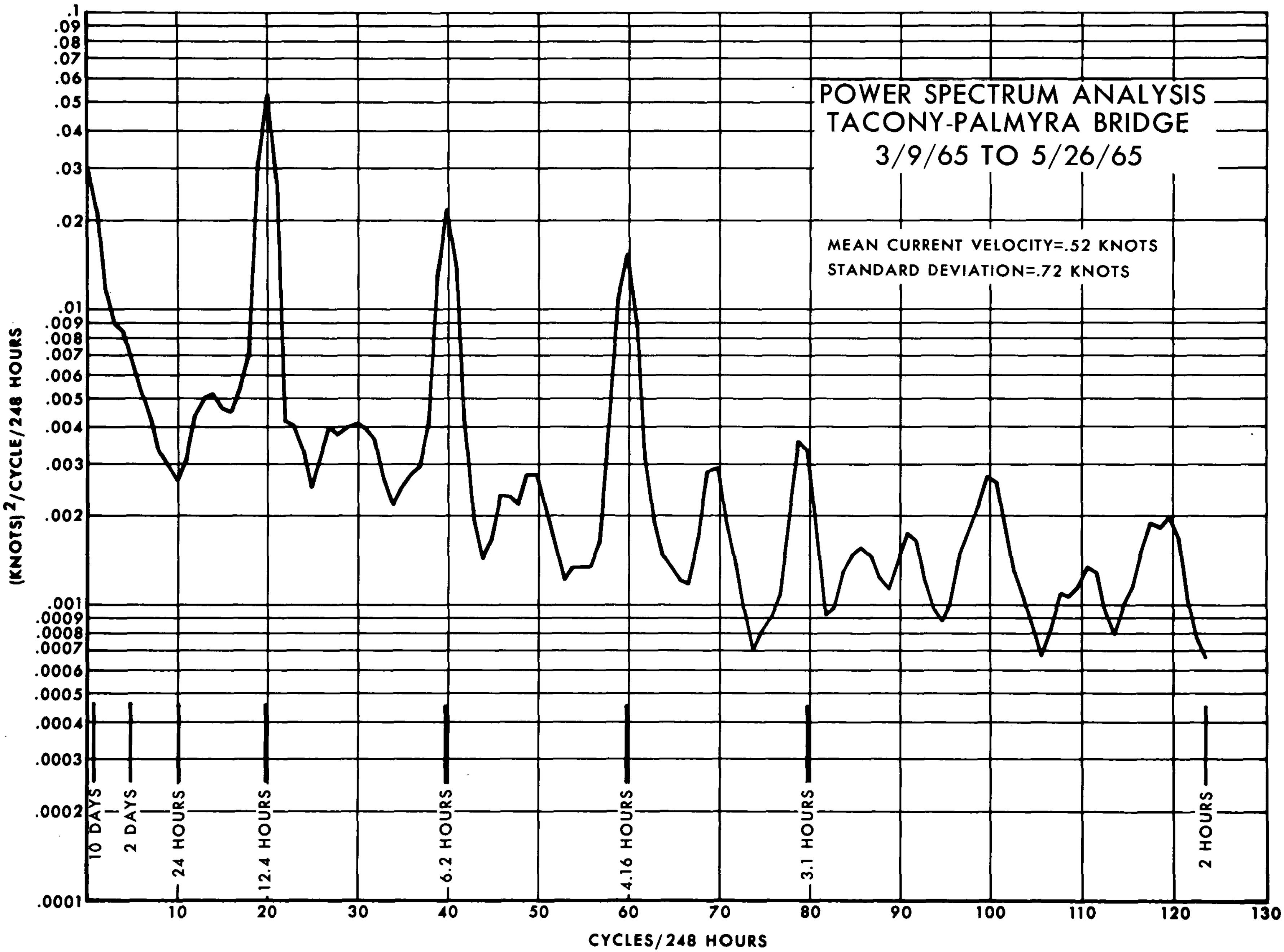

POWER SPECTRUM ANALYSIS
TACONY-PALMYRA BRIDGE
3/9/65 TO 5/26/65
MEAN CURRENT VELOCITY=.52 KNOTS
STANDARD DEVIATION=.72 KNOTS
(KNOTS)²/CYCLE/248 HOURS
CYCLES/248 HOURS
10 DAYS
2 DAYS
24 HOURS
12.4 HOURS
6.2 HOURS
4.16 HOURS
3.1 HOURS
2 HOURS
.1
.09
.08
.07
.06
.05
.04
.03
.02
.01
.009
.008
.007
.006
.005
.004
.003
.002
.001
.0009
.0008
.0007
.0006
.0005
.0004
.0003
.0002
.0001
10
20
30
40
50
60
70
80
90
100
110
120
130

Figure I-C-8

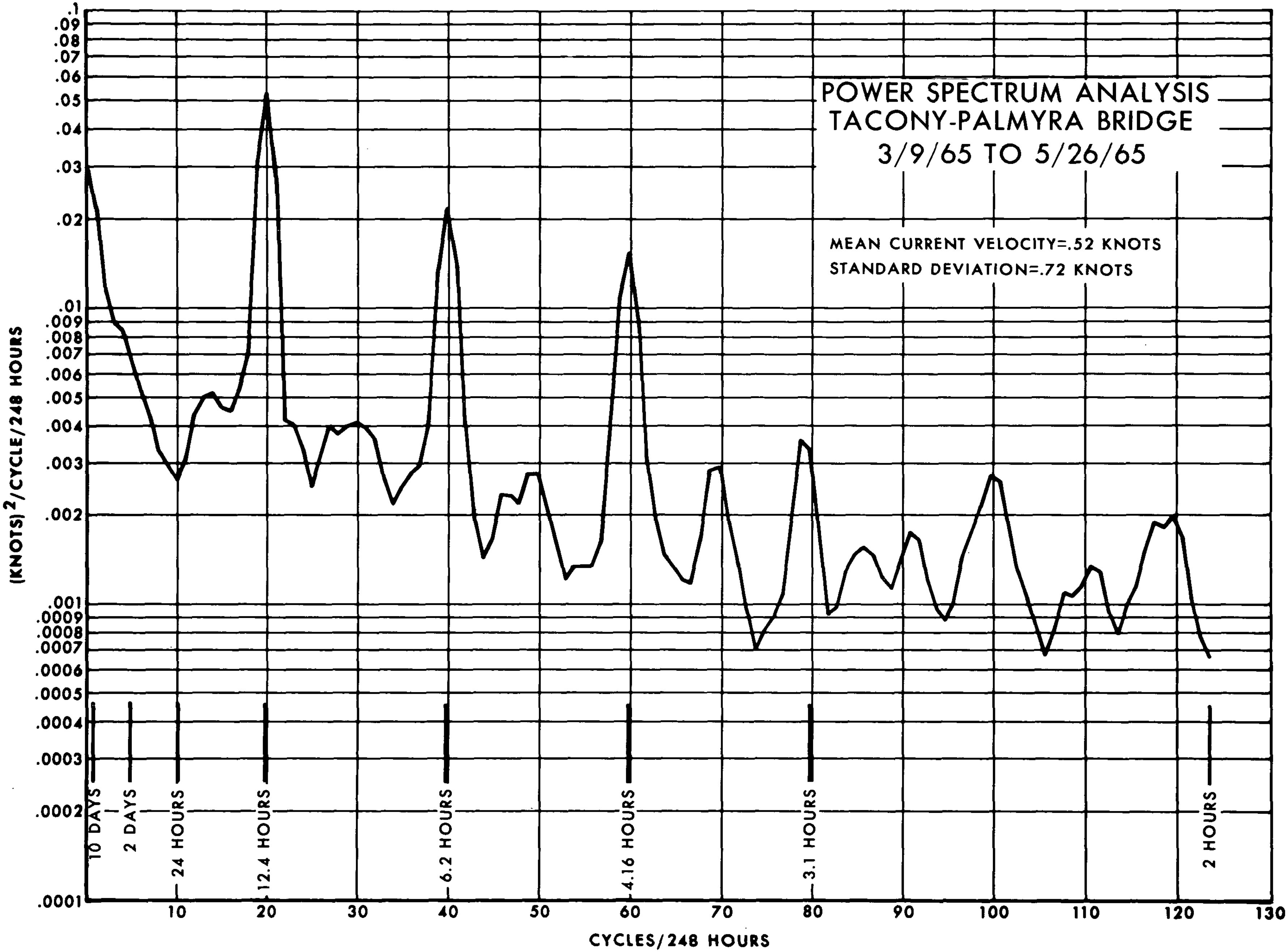

POWER SPECTRUM ANALYSIS
TACONY-PALMYRA BRIDGE
3/9/65 TO 5/26/65
MEAN CURRENT VELOCITY=.52 KNOTS
STANDARD DEVIATION=.72 KNOTS
(KNOTS)²/CYCLE/248 HOURS
CYCLES/248 HOURS
10 DAYS
2 DAYS
24 HOURS
12.4 HOURS
6.2 HOURS
4.16 HOURS
3.1 HOURS
2 HOURS
.1
.09
.08
.07
.06
.05
.04
.03
.02
.01
.009
.008
.007
.006
.005
.004
.003
.002
.001
.0009
.0008
.0007
.0006
.0005
.0004
.0003
.0002
.0001
10
20
30
40
50
60
70
80
90
100
110
120
130

Figure I-C-8

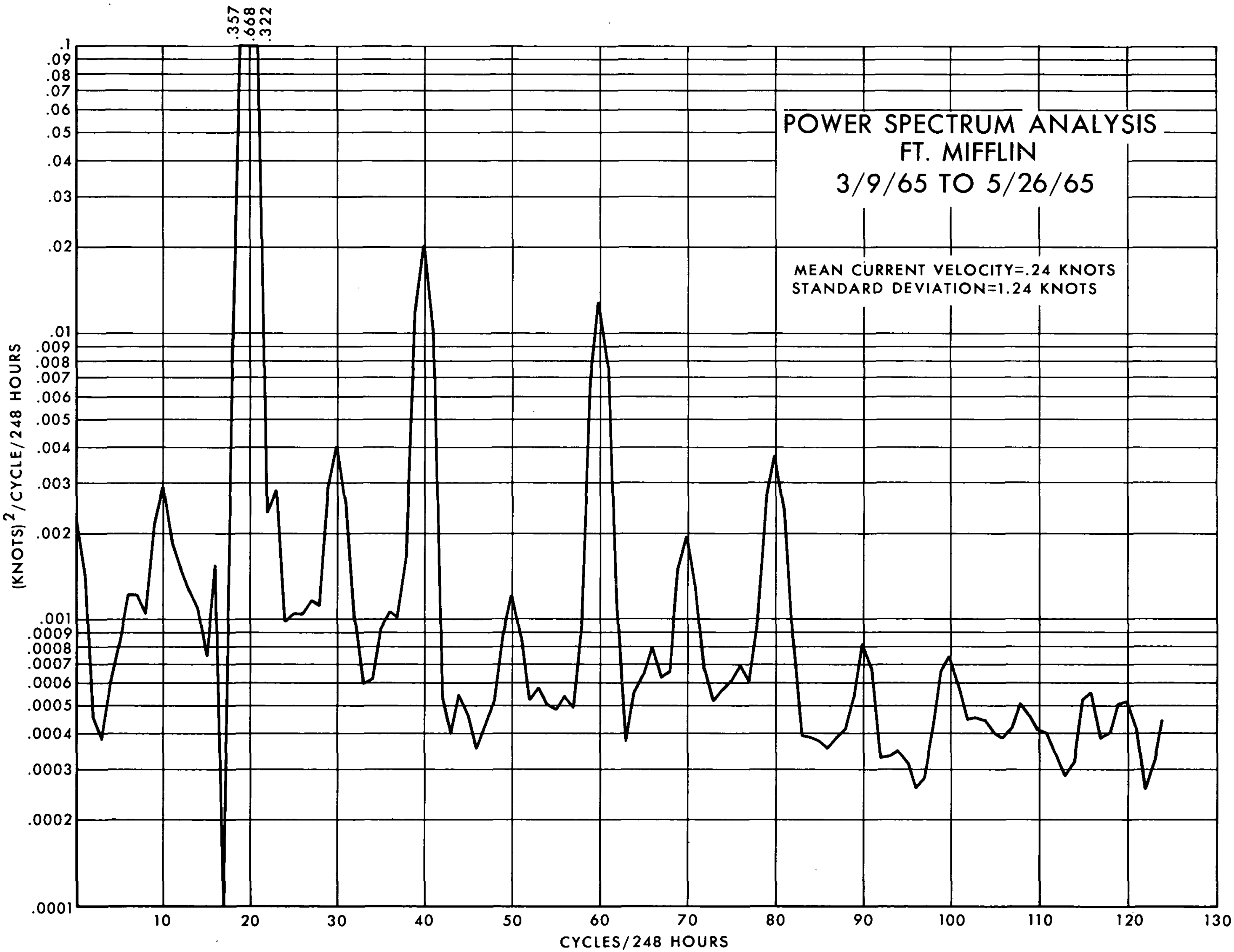
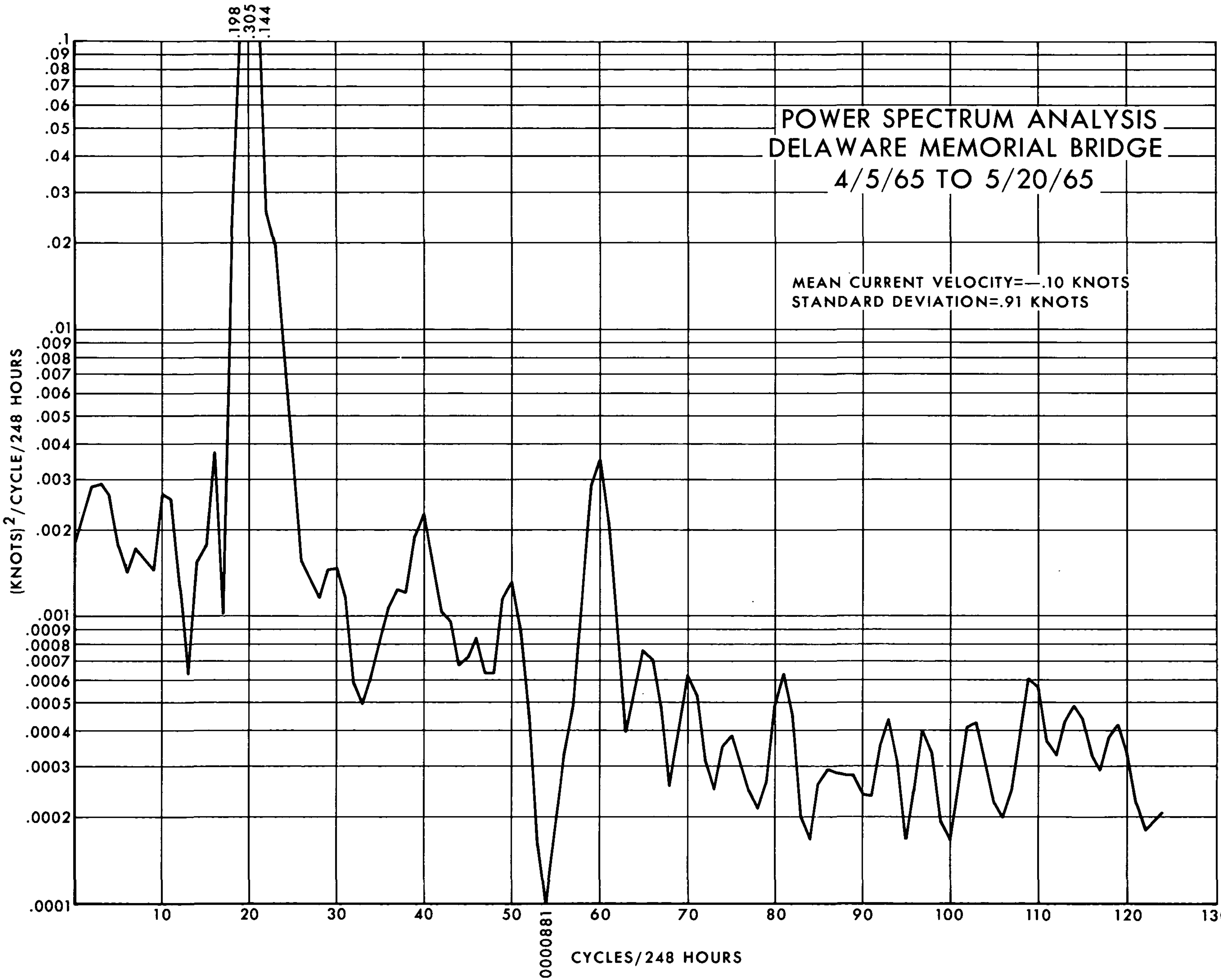

POWER SPECTRUM ANALYSIS
FT. MIFFLIN
3/9/65 TO 5/26/65
MEAN CURRENT VELOCITY=.24 KNOTS
STANDARD DEVIATION=1.24 KNOTS
.357
.668
.322
(KNOTS)^2/CYCLE/248 HOURS
CYCLES/248 HOURS

Figure I-C-9


POWER SPECTRUM ANALYSIS
DELAWARE MEMORIAL BRIDGE
4/5/65 TO 5/20/65
MEAN CURRENT VELOCITY=—.10 KNOTS
STANDARD DEVIATION=.91 KNOTS
(KNOTS)2/CYCLE/248 HOURS
CYCLES/248 HOURS
.198
.305
.144
.0000881
.1
.09
.08
.07
.06
.05
.04
.03
.02
.01
.009
.008
.007
.006
.005
.004
.003
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.001
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.0008
.0007
.0006
.0005
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.0003
.0002
.0001
10
20
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Figure I-C-10

WATER FLOW
USGS STATION 1-4635
DELAWARE RIVER AT TRENTON, N.J.
OCT., 1964 - SEPT., 1965
WATER YEAR

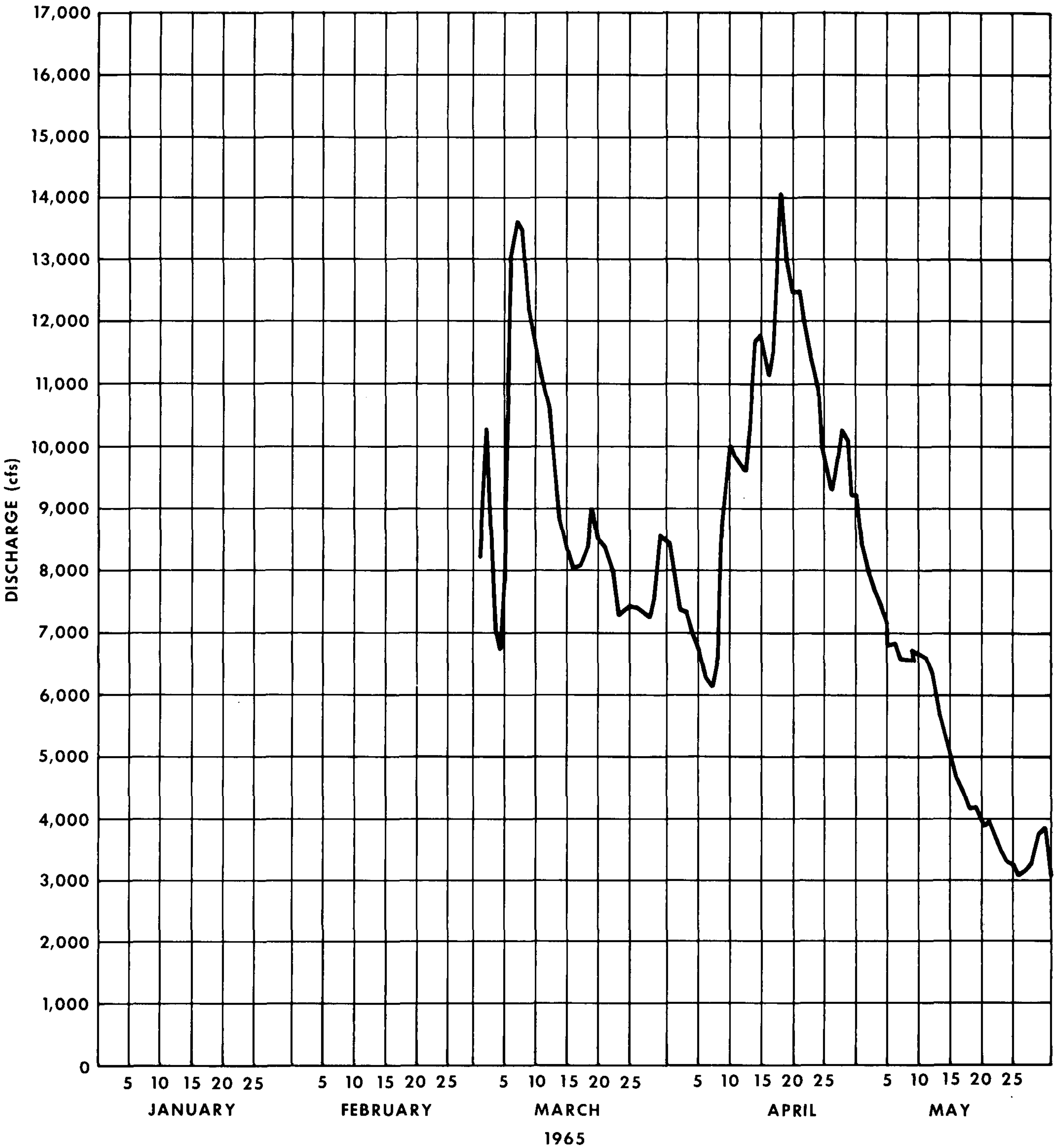

Figure I-C-11