HOPE CREEK GENERATING STATION
EXTREME EVENT SITE FLOODING
METEOROLOGY

July 6, 1984

Prepared by:
Meteorological Evaluation Services, Inc.
Amityville, New York

Maynard E. Smith
Frank P. Castelli

Prepared for:
Public Service Electric & Gas Company

HOPE CREEK GENERATING STATION
EXTREME EVENT SITE FLOODING
METEOROLOGY

The probability of extreme wind speeds is examined for the Hope Creek site. The study is divided into two major parts. The first part examines the probabilities of extreme wind speeds due to any sources. The eleven-year onsite wind data record is used for this analysis. The first portion of this analysis provides data on the hourly winds. These are included largely for completeness, because a major surge requires about six hours to develop fully and hourly data are not pertinent for this problem. Consequently a similar set of probabilities was generated for six-hour periods.

The second part of the study examines the probabilities of hurricanes affecting the region. This part is divided into two separate sections, the probability of the probable maximum hurricane and the probability of a more typical hurricane. Along with the estimate of the probabilities of the occurrence of these hurricanes, estimates are given of the various parameters describing each hurricane type.

I. EXTREME WIND SPEED ANALYSIS

A. Hourly Averages

The probability of extreme wind speeds is analyzed for the Hope Creek site. The onsite 33-ft. wind data measured on the Artificial Island meteorological tower are used for this analysis. The period of record is June 1969 through May 1973 and January 1977 through December 1983.

The particularly open exposure of this site is not adequately duplicated at any of the National Weather Service (NWS) stations in the region. This, combined with the fact that hourly average sector-dependent extreme wind speed data is not generally available from NWS stations, convinced us that a statistical analysis of the onsite record should provide the most sound estimate of extreme wind speeds in the region.

The maximum hourly average wind speed is determined for each of the 16 directional wind sectors for each annual cycle. The annual maximum hourly wind speeds are ranked for each sector as shown in Table 1. These annual maximum values are then plotted in a Fisher-Tippett Type 2 (Frechet) distribution by using the probability:

$$p = m/(n+1)$$

where m is the order of a given maximum valve counting from the lowest to the highest, n is the total number of years, and p is the probability of the extreme wind speed being less than the plotted value. The Frechet distribution (see Figure 1) has been shown to be an acceptable method for determining low probability, extreme wind speeds.[1,2] A conservative line is fitted to the wind speed probability plot for each sector to determine the longer return period wind speeds.

The results of the hourly analysis are presented in Table 2. The extreme wind speeds are given for annual probabilities ranging from .05 to .005 for each sector. These annual probabilities correspond to return periods of 20 to 200 years. Hourly wind speeds greater than 65

TABLE 1

HOPE CREEK GENERATING STATION

33-FT. ARTIFICIAL ISLAND RANKED WIND SPEEDS

ONE-HOUR AVERAGES

(mph)

June 1969 through May 1973 and
January 1977 through December 1983

Wind Direction Sector	Rank										
	1	2	3	4	5	6	7	8	9	10	11
NNE	17	18	20	21	24	24	25	25	25	25	29
NE	16	16	18	19	20	22	24	24	25	29	40
ENE	15	16	16	17	17	19	19	20	20	21	22
E	12	13	15	15	16	16	17	17	18	22	24
ESE	14	15	16	18	18	19	20	25	25	29	30
SE	18	22	24	24	26	27	28	30	30	31	34
SSE	20	20	21	21	22	23	23	24	25	25	28
S	21	21	21	21	22	24	25	27	28	31	32
SSW	20	21	22	22	22	22	23	24	25	28	36
SW	18	22	22	22	23	24	26	26	28	31	34
WSW	19	19	20	20	23	25	25	25	27	30	40
W	25	25	27	28	30	30	30	32	32	36	39
WNW	25	25	26	26	26	27	29	30	32	32	35
NW	24	25	25	28	29	29	30	30	30	30	31
NNW	21	23	23	24	24	24	24	25	26	30	30
N	18	20	21	22	22	22	22	22	22	22	30

TABLE 2

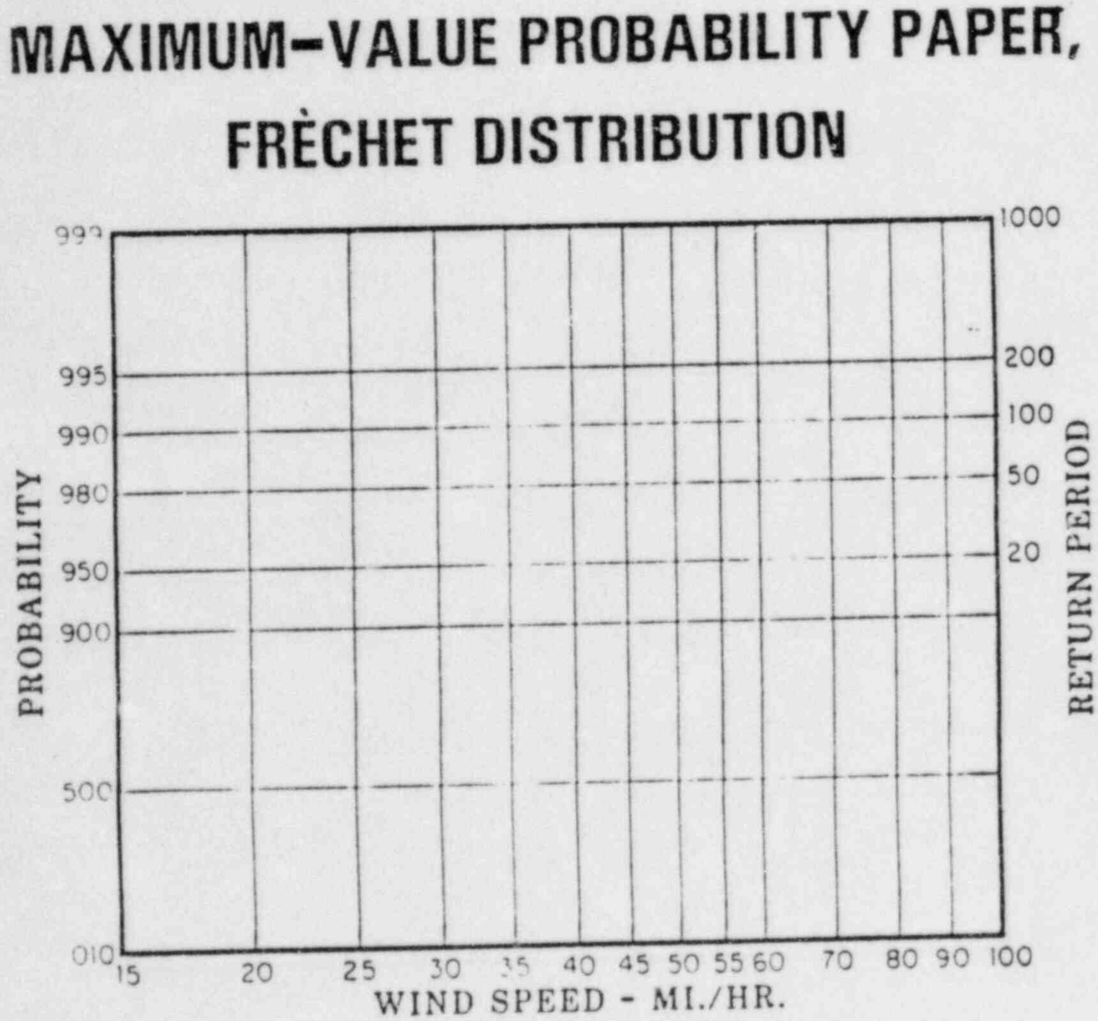
HOPE CREEK GENERATING STATION

ANNUAL PROBABILITIES OF EXTREME HOURLY 33-FT. WIND SPEEDS

BASED UPON 11 YEARS OF ARTIFICIAL ISLAND WIND DATA

Wind Direction Sector	Hourly Average Wind Speeds (mph) Annual Probabilities			
	.05	.02	.01	.005
Return Period (years)	(20)	(50)	(100)	(200)
NNE	32	37	42	47
NE	43	55	66	80
ENE	28	31	36	40
E	28	35	41	49
ESE	37	46	54	62
SE	43	51	59	67
SSE	32	37	40	43
S	38	45	51	58
SSW	39	49	58	68
SW	38	44	50	56
WSW	44	57	69	84
W	44	52	58	65
WNW	39	44	47	52
NW	33	36	37	39
NNW	36	42	48	54
N	35	46	56	68

Figure 1



(Form of Distribution for Determining Extreme Wind Speeds) mph are calculated for the northeast and west-southwest wind directions for the .01 and .005 probability levels (100-and 200-year return periods).

B. Six-Hour Averages

The wind must persist from a fairly constant direction for a prolonged period of time in order for an ocean surge to build. Consequently we examined the extreme wind speed events for six-hour running periods using the onsite data record. The wind direction had to persist within the following sectors for a period of six hours to be considered for the analysis, because other wind directions could not generate a major ocean surge at the Hope Creek site.

1. 79 - 125 °Az
2. 125 - 170 °Az
3. 79 - 170 °Az

The annual maximum six-hour wind speed averages are determined for each of these wind direction sectors. These annual maximum wind speeds are ranked for each sector as shown in Table 3. They are also plotted in a Fisher-Tippett Type 2 (Frechet) distribution, as were the hourly cases.

The results of the analysis are presented in Table 4. The extreme wind speeds are given for annual probabilities ranging from .05 to .001 for each sector. These annual probabilities correspond to return periods of 20 to 1000 years. The six-hour wind speeds in the 79 - 125° Az and 125 -170° Az

TABLE 3

HOPE CREEK GENERATING STATION

33-FT. ARTIFICIAL ISLAND RANKED WIND SPEEDS

SIX-HOUR AVERAGES

(mph)

June 1969 through May 1973 and
January 1977 through December 1983

Wind Direction Sector (°Az)	Rank 1	2	3	4	5	6	7	8	9	10	11
79 - 125	(No Cases)	8	11	12	12	15	15	15	15	21	23
125 - 170	16	21	21	21	21	22	22	24	24	24	25
79 - 170	16	21	21	22	22	23	24	24	25	26	30

TABLE 4

HOPE CREEK GENERATING STATION
ANNUAL PROBABILITIES OF EXTREME SIX-HOUR 33-FT. WIND SPEEDS
BASED UPON 11 YEARS OF ARTIFICIAL ISLAND WIND DATA

Wind Direction Sector	Six-Hour Average Wind Speeds (mph) Annual Probabilities					
	.05	.02	.01	.005	.002	.001
Return Period (years)	(20)	(50)	(100)	(200)	(500)	(1000)
79 - 125 (°Az)	25	28	31	34	38	42
125 - 170 (°Az)	27	30	31	33	36	38
79 - 170 (°Az)	32	37	41	45	52	57

sectors range up to approximately 40 mph at the .001 annual probability level. The combined 79 - 170°Az sector shows a six-hour average wind speed of 57 mph at the .001 probability level.

The six-hour wind speed averages are more pertinent to determining storm surges than the hourly wind speeds since significant surges can not be generated without a minimum of several hours of high wind speeds from a uniform direction.

Appendix A contains a list of the conservative treatments and assumptions that have been used in these onsite wind speed analyses.

II. HURRICANE ANALYSIS

A. Data Sources

Hurricanes have been a subject of interest to the general public as well as to meteorologists because of the extreme danger and damage associated with the more severe storms. Consequently, there is a large amount of historical data on which to base an analysis. By far the most valuable is the NOAA summary of the details of virtually all tropical storms and hurricanes that have occurred from 1871 through 1980.[3] The 1981 through 1983 hurricane seasons are summarized in references 4 through 6. From 1871 onward, the intensities, trajectories and effects of these storms are well documented.

However, prior to the beginning of formal meteorological records in this country, a great deal of information was recorded in newspapers, journals, magazines and personal chronicles. These data have been carefully culled and organized by Ludlum,[7] and it is therefore possible to extend the record back to approximately 1683. Of course, these earlier records are deficient in many details, but they can be relied upon for information about the major storms reaching the coastal regions because such storms were certainly newsworthy.

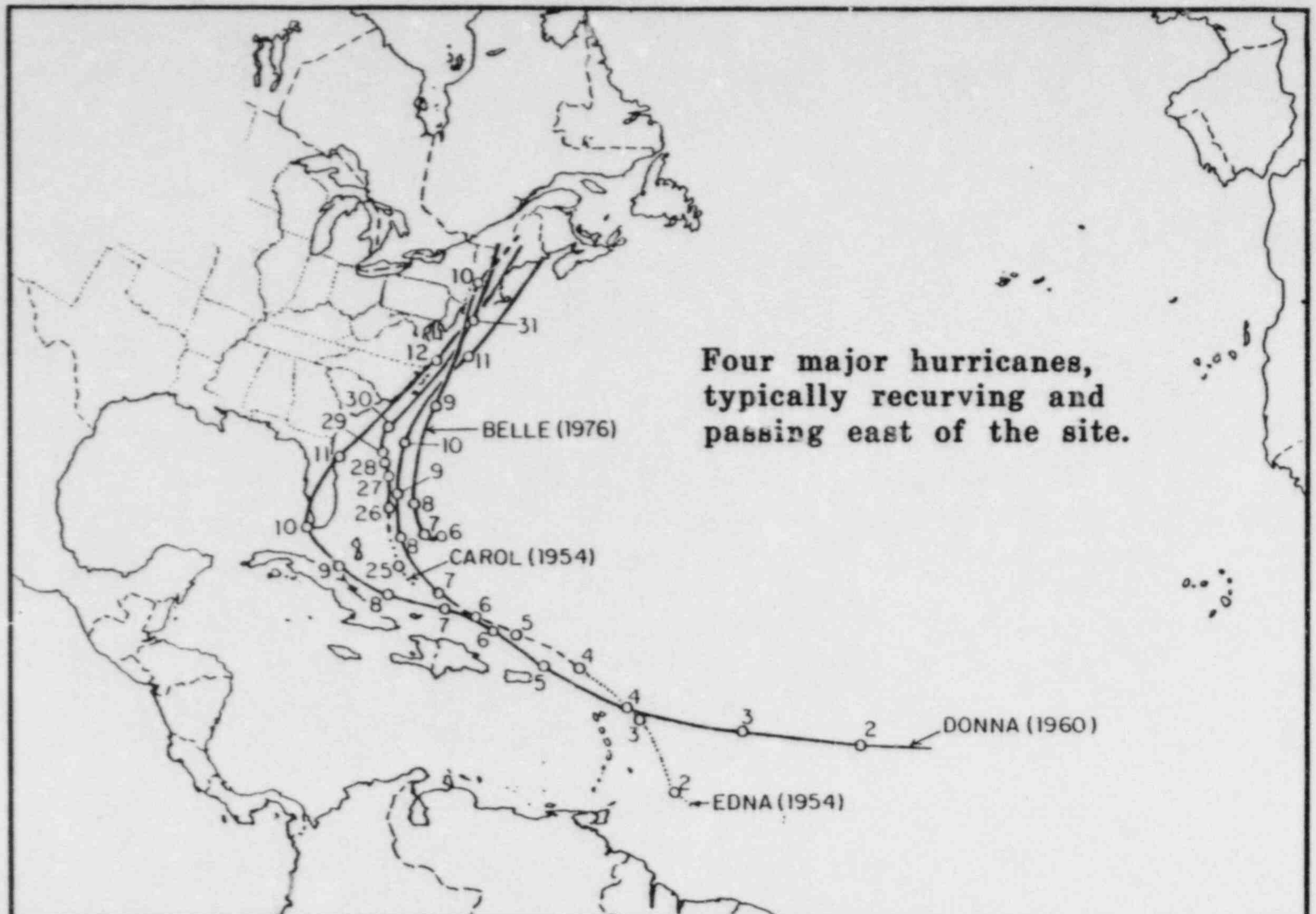
B. Typical Hurricanes Affecting the Hope Creek Site

The Delaware Bay area presents a curious anomaly on the east coast of the United States. It is very seldom affected by a hurricane moving into the coast directly from the ocean, whereas coastal regions both to the north and to the south often experience direct onslaughts. Also, the hurricanes that do pass close to the site are usually offshore, producing wind patterns that do not generate extreme tidal surges in Delaware Bay. In the following discussion, this distinction between the common hurricane and the hurricane producing a large tidal surge is maintained.

1. The Most Common Hurricane

As we have noted, between 1871 and 1983, detailed data on the tracks of hurricanes and tropical storms have been kept and summarized. We have examined these data in detail, and it is clear that the hurricane most commonly affecting the Hope Creek site is one which has approached the Cape Hatteras area moving on a northerly or north-northwesterly course, whereupon it has recurved and passed 50 to 100 miles east of the site moving toward the north-northeast or northeast. Figure 2 shows four such storms, all of which passed the area while retaining full hurricane characteristics. Hurricanes Carol and Edna in 1954 were nearly identical at the time they passed the New Jersey coast, both having skirted Cape Hatteras rather than passing over the Virginia tidal lands. Belle, the hurricane affecting the area in 1976 was quite similar, although its maximum winds were not as strong as the earlier storms. Donna passed very close to the site in 1960, although it had passed over part of Virginia before reaching the site area.

Figure 2


Four major hurricanes, typically recurving and passing east of the site.
BELLE (1976)
CAROL (1954)
DONNA (1960)
EDNA (1954)

None of these storms produced major tidal surges in the area, primarily because a long fetch of very high winds moving into Delaware Bay from the southeast or east-southeast was missing. In every case the strongest winds in the site area came from the northeast through north, and they tended to counteract rather than to augment a tidal surge.

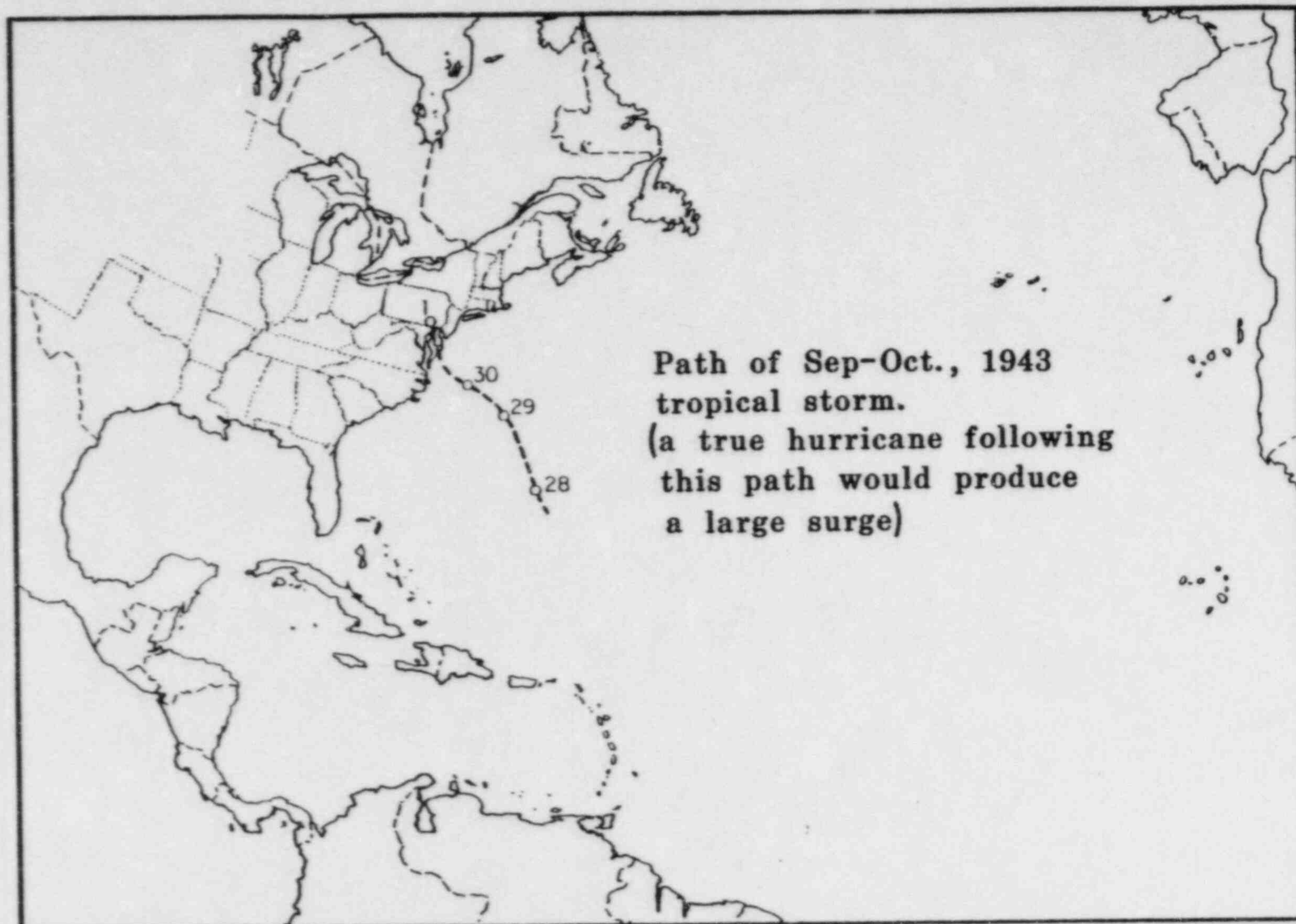
The records show 18 storms having hurricane characteristics passing within 100 miles to the east of the site between 1871 and 1983.

2. **The Hurricane Producing Extremely High Tidal Surges**

Because of the configuration of the land masses, a storm capable of creating absolute maximum tidal surges would have to move into the area from the east or southeast. Such a path would provide an intense wind field moving in the right direction without the weakening effect of the passage over land before reaching the site. Paths of this type are exceedingly rare at the latitude of Artificial Island; in fact, we were able to find only one such track and that was of a 1943 tropical storm, not a hurricane (Figure 3). Had this storm been a true hurricane, it would have produced a major tidal surge.

Our personal review of the storm tracks summarized in the 1981 NOAA document is supported by a study by Simpson and Lawrence (1971),[8] which they list only one hurricane moving in

Figure 3


30
29
28
Path of Sep-Oct., 1943
tropical storm.
(a true hurricane following
this path would produce
a large surge)

from the coast in the Delaware Bay area in 85 years of record, whereas the Virginia Capes to the south were affected by 19 true hurricanes in the same period and eastern Long Island to the northeast experienced 6. These relatively frequent situations in which the hurricane moves inland over the Carolinas or southern Virginia and then proceeds northward, passing to the west of the Artificial Island site, provide the southeast wind direction needed for a large tidal surge, but because of the extended movement over land the wind speeds are usually reduced from those of the true oceanic huricane. Between 1871 and 1983, seven such hurricanes passed within 100 miles to the west of the site.

Figure 4 shows the one true hurricane in the 111-year record that created a major tidal surge. It occurred in August 1933, according to the Corps of Engineers (1959) report.[9] This storm moved onshore directly over Cape Hatteras and then followed a track through northeastern Viginia and Maryland into Pennsylvania.

The winds in other storms that have passed west of the site on the required path seem to have dwindled in intensity so much that major surges have not occurred.

Fortunately, this storm occurred recently enough to assure good measurements. Table 5 summarizes the meteorological characteristics of this model hurricane.

Figure 4

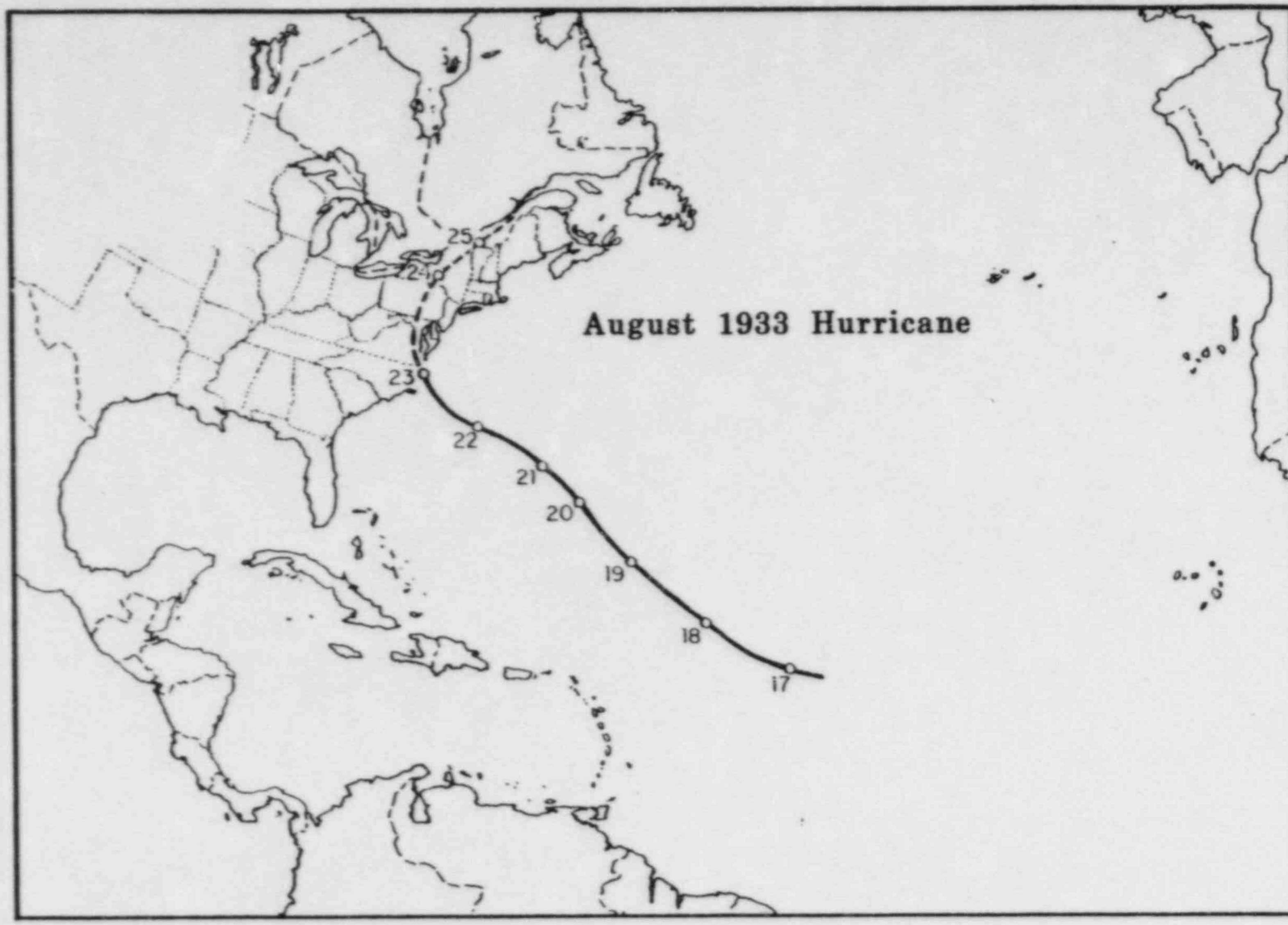


TABLE 5

HOPE CREEK GENERATING STATION
MODEL HURRICANE CHARACTERISTICS

Parameters	August 1933 Hurricane
Radius of maximum winds (nm)	54
Forward speed of translation (knots)	23
Central atmospheric pressure (in. Hg.)	29.07
Peripheral atmospheric pressure (in. Hg.)	29.92
Gradient wind speed (sustained) (mph)	58
Latitude of initial hurricane center (degrees north)	17
Angle between the forward storm motion and the radius of maximum winds (degrees)	45 (Approx.)
Annual probability	10^{-2}

In an attempt to extend our analysis of the typical hurricane frequency, we examined the data contained in the Ludlum document.[7] Although this volume does not include what we now know as conventional meteorological measurements, there is sufficient detail in the written accounts for one to judge the track of the storm, the wind direction pattern and the effects in most cases.

Of the 39 hurricanes listed as having occurred north of Cape Hattaras between 1683 and 1869, five evidently passed to the west of the Artificial Island site on a course that should have produced significant tidal surges in the Delaware Bay and in the river to the north. In our judgment, from the descriptions only one of these seemed to match the characteristics of the 1933 storm, and that hurricane occurred in 1846. There is little doubt from the summary of the news reports that sustained southeasterly winds prevailed in the area of the Delaware and extreme flooding occurred. At New Castle, Delaware, the storm surge was described as the greatest in 70 years, high enough to extinguish the fire in the boiler of a locomotive that had been stalled by the flooding.

We would therefore conclude that two of the hurricanes occurring in the last 300 years produced the major tidal surges of interest in this analysis, and this translates into a frequency of 6.7×10^{-3}. However, since the data are difficult to interpret before 1871, and four other storms evidently passed west of Artificial Island on approximately the correct course between 1683 and 1871, it is reasonable to set a recurrence interval for the typical hurricane at once in 100 years (10^{-2}).

C. Probable Maximum Hurricane

The probable maximum hurricane, as defined in references 10 and 11, is a purely hypothetical calculation, based on the possible coincidence of a series of maximized parameters. The table below shows these parameters for the coastal region in the vicinity of Artificial Island.

<u>Hurricane Parameters</u>

Radius of maximum Winds	27.0 nautical miles
Forward Speed of Translation	40.0 knots
Central Pressure Index	26.57 in. Hg.
Peripheral Pressure	30.12 in. Hg.
Gradient Wind Speed	142.7 mph

Estimating the probability of such a hurricane actually affecting the site is very difficult, primarily because its characteristics are deliberately maximized beyond anything that has been observed. The authors of the documents defining the PMH try to dissuade users from ascribing any specific probability to it, noting that it would be possible to develop probabilities for individual meteorological parameters in the storm, but that the combined frequencies "would have such a large uncertainty as to make the effort meaningless." However, with respect to the probability of having the single parameter, such as the lowest central pressure occur, they state that the recurrence interval might be once in 1000 to 10,000 years.

Taking the more conservative of these values, 10^{-3}, and multiplying it by 10^{-2} the frequency of naving any storm drive directly into the coast with no prior passage over land (the 1943 tropical storm), one derives a value of 10^{-5}. However, we recognize that the intensity and tracks of hurricanes may be subject to relatively short-term (50-100 year) variations in climatological conditions, and that the true probability of the PMH striking tne Artificial Island area could be somewhat larger. We therefore conclude that a very conservative value would be 5×10^{-5}.

A list of the conservatisms used in the hurricane analyses is given in Appendix A.

References

1. Thom H. C. S.: New Distribution of Extreme Winds in the United States, Journal of the Structural Division, Proceeding of the American Society of Civil Engineering (1968).

2. Hollister S. C.: The Engineering Interpretation of Weather Bureau Records for Wind Loadings on Structures, Proceedings of Technical Meeting Concerning Wind Loads on Buildings and Structures, National Bureau of Standards, Gaithersburg, Maryland, January 27-28, 1969. R. D. Marshall and H. C. S. Thom, Editors (1970).

3. Neumann C.J., Cry G. W., Caso E. L. and Jarvinen B. R.: Tropical Cyclones of the North Atlantic Ocean, U.S. Department of Commerce, Environmental Data Service, NOAA (1981).

4. Lawrence, M. B., 1981 Hurricane Season: Normal Activity But No Landfalls, Weatherwise, Volume 35, No. 1, Feb. 1982.

5. Clark, G.B.: 1982 Hurricane A Tranquil Season, Weatherwise, Volume 36, No. 1, Feb. 1983.

6. Gerrish, H. P. and Case, R. A.: Quietest in 52 Years, The Atlantic Hurricane Season, Weatherwise, Volume 37, No. 1, Feb. 1984.

7. Ludlum, D. M.: Early American Hurricanes 1492 - 1870, American Meteorological Society (1963).

8. Simpson R.H. and Lawrence M.B.: Atlantic Hurricane Frequencies Along the U.S. Coastline, NOAA Technical Memorandum NWS SR-58, June 1971.

9. Hurricane Surge Predictions for Delaware Bay and River, Department of the Army Corps of Engineers, Miscellaneous Paper No. 4-50 (1959).

10. Meteorological Criteria for Standard Project Hurricane and Probable Maximum Hurricane Wind Fields, Gulf and East Coasts of the United States, NOAA Technical Report NWS 23 (1979).

11. Meteorological Characteristics of the Probable Maximum Hurricane, Atlantic and Gulf Coasts of the United States, Weather Bureau Memorandum HUR 7-97 (1968).

HOPE CREEK GENERATING STATION
EXTREME EVENT SITE FLOODING
METEOROLOGY

APPENDIX A
CONSERVATIVE TREATMENTS

I. EXTREME WIND SPEED ANALYSIS

1. The lines fitted to the Frechet distribution plots of the extreme wind speeds were drawn in a conservative manner. The higher observed wind speeds were given more weight in the distribution.

2. The large width of the 79-170 (°Az) sector used as a persistence criteria for the six-hour wind speed analysis.

II. HURRICANE ANALYSIS

1. For the typical hurricane producing very serious surge effects, the intensity, course and transport speed would all have to be synchronized with the normal tidal oscillation. Therefore the value of 10^{-2} is conservative by a significant amount, probably by half an order of magnitude.

2. The great rarity of the PMH is emphasized by the fact that between 1899 and 1982, no storm having the calculated maximum wind value of 142 mph or greater (NOAA Classes 4 or 5) has made a landfall anywhere north of Cape Hatteras. A realistic probability is therefore more like 1×10^{-5}.