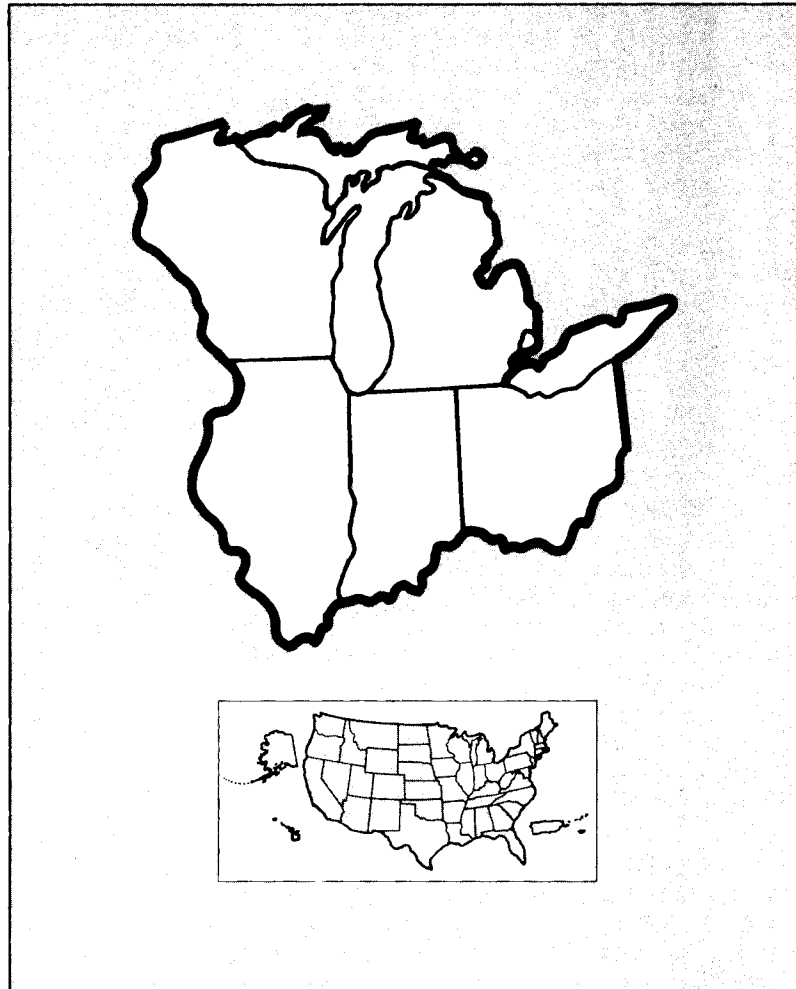


# **Wind Energy Resource Atlas: Volume 3 - The Great Lakes Region**



**Prepared for Pacific Northwest Laboratory  
Under Agreement B-87922-A-L**

**Pacific Northwest Laboratory  
Operated for the U.S. Department of Energy  
by Battelle Memorial Institute**



N O T I C E

This material was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, including maps, figures or tables, product or process disclosed, or represents that its use would not infringe privately owned rights.

The views, opinions and conclusions contained in this material are those of the contractor and do not necessarily represent those of the United States Government or the United States Department of Energy.

PACIFIC NORTHWEST LABORATORY  
*operated by*  
BATTELLE  
*for the*  
UNITED STATES DEPARTMENT OF ENERGY  
*Under Contract DE-AC06-76RLO 1830*

Printed in the United States of America  
Available from  
National Technical Information Service  
United States Department of Commerce  
5285 Port Royal Road  
Springfield, Virginia 22151

Price: Printed Copy \$\_\_\_\_\_ \*; Microfiche \$3.00

| *Pages  | NTIS<br>Selling Price |
|---------|-----------------------|
| 001-025 | \$4.00                |
| 026-050 | \$4.50                |
| 051-075 | \$5.25                |
| 076-100 | \$6.00                |
| 101-125 | \$6.50                |
| 126-150 | \$7.25                |
| 151-175 | \$8.00                |
| 176-200 | \$9.00                |
| 201-225 | \$9.25                |
| 226-250 | \$9.50                |
| 251-275 | \$10.75               |
| 276-300 | \$11.00               |

3 3679 00053 7623

PNL-3195 WERA-3  
UC-60

WIND ENERGY RESOURCE ATLAS  
Volume 3 - The Great Lakes Region

|             |                              |
|-------------|------------------------------|
| D. L. Paton | D. L. Elliott <sup>(a)</sup> |
| A. Bass     | W. R. Barchet <sup>(a)</sup> |
| D. G. Smith | R. L. George <sup>(a)</sup>  |

Environmental Research and Technology, Inc.  
696 Virginia Road  
Concord, Massachusetts 01742

February 1981

Prepared for  
Pacific Northwest Laboratory  
Under Agreement B-87922-A-L

Pacific Northwest Laboratory  
Richland, Washington 99352

<sup>(a)</sup>Pacific Northwest Laboratory



## PREFACE

For the purpose of assessing the national wind resource, the United States and its possessions have been divided into twelve regions. These wind resource assessments are presented in the form of an atlas for each region. The atlases depict in graphic, tabular, and narrative form the wind resource on a regional and state level. The information presented in the atlases will help guide homeowners, utilities, and industry in decisions concerning the use of the wind as a source of energy.

This atlas of the wind energy resource is composed of introductory and background information, a regional summary of the wind resource, and assessments of the wind resource in each state of the region. Chapter 1 provides background on how the wind resource is assessed and on how the results of the assessment should be interpreted. A description of the wind resource on a regional scale is then given in Chapter 2. The results of the wind energy assessments for each state are assembled in this chapter into an overview and summary of the various features of the regional wind energy resource. Chapter 3 provides an introduction and outline to the descriptions of the wind resource given for each state. Assessments for individual states are presented as separate chapters beginning with Chapter 4. The state wind energy resources are described in greater detail than is the regional wind energy resource, and features of selected stations are discussed. This preface outlines the use and interpretation of the information found in the state chapters.

Much of the information in Chapters 4 through 8 is given in graphic or tabular form. As is discussed in Section 3.1, the sequence of maps, tables, and graphs is the same in each state chapter. References to these figures and tables are made here with an asterisk (\*) in place of the chapter number (e.g., Figure \*.1, Table \*.2). Similar maps and tables are found in Chapter 2 on the regional wind resource. References to the regional maps and tables are made in brackets, ( ).

Figure \*.1 shows the major geographical (mountains, rivers) and cultural (cities, towns) features in the state (Figure 2.1 ). This map can be used to orient the reader to the state. Figure \*.2 portrays the topography of the state in shaded relief (Figure 2.2). The shaded relief allows the reader to visualize the character of the terrain surrounding locations of special interest. Superimposed on these state maps (but not the regional maps) is a grid of dashed lines one-third degree (20') longitude by one-quarter degree (15') latitude. This grid is repeated on nearly all subsequent maps to give the reader an adequate frame of reference for locating the same feature on different maps.

Figure \*.3 is a map of the land-surface form (Figure 2.3). The information presented in Sections 1.6 and 1.8 indicates how the land-surface form is used to designate the terrain features considered to have a typical good exposure to the wind. Awareness of what constitutes well-exposed terrain features is crucial to the proper interpretation of the maps of wind power density.

Figures \*.4 and \*.5 identify and locate wind data sites relevant to the assessment. All locations in each state for which the National Climatic Center (NCC) has wind data in its archives are shown and named in Figure \*.4. However, this assessment is based on a subset of NCC data augmented by data from other sources (see Sections 1.1 and 1.2). Figure \*.5 shows the location of all wind data sites used in the assessment. Sections 1.3

through 1.5 briefly describe the methods used to analyze the wind data and evaluate the wind power.

The wind energy resource for a state is illustrated using several maps. The wind power maps represent a careful synthesis of quantitative wind data guided by state-of-the-art concepts on air flow near the earth's surface. Section 1.6 describes how the analysis of the wind data is transformed into the map of annual wind power density found in Figure \*6 (Figure 2.4). This map gives the annual average wind power density at typically exposed sites. A discussion of the classes of wind power density in Section 1.7 gives the relationship between mean wind power density ( $\text{watts/m}^2$ ) and mean wind speed (m/s or mph).

A certainty rating is used to provide a measure of the ability to objectively evaluate the wind resource in a grid cell. The certainty ratings are given in the maps of Figure \*7. The degree of certainty with which the wind power can be estimated depends on the quality and quantity of wind data, the complexity of the terrain and concern over the variability of the wind resource over short distances. How these factors are combined to assign a certainty rating is discussed in Section 1.9.

The terrain feature with typical good exposure to the wind in a particular land-surface form provides a convenient and essential reference point on which to base the analyses of the wind resource shown in Figure \*6. However, a substantial portion of the terrain may have poorer than typical exposure to the wind and will have a lower wind resource than shown on the wind power maps. The maps of Figure \*8 provide an estimate of the percentage of area in each grid cell that may experience at least each of four different wind power classes. Section 1.10 discusses the assumptions underlying the evaluation of the areal distribution of the wind resource. The area of the state estimated to experience a particular wind power class is given in Table \*.1 (Table 2.2). This table summarizes the contribution made by each grid cell to the areal distribution of wind power for the state.

The annual average wind power density compresses into a single statistic time-varying trends on several time scales, e.g., annual, seasonal, monthly, and daily. In this atlas, the seasonal evolution of the geographical distribution of wind power is shown at the state level. The maps of Figure \*.9 give the average wind power density for winter, spring, summer, and autumn. The interpretation of the seasonal average wind power maps is identical to that for the annual average wind power map. (For the region, Figure 2.5 shows only the season of maximum power.)

Additional information on the time variation and other characteristics of the wind resource in each state is presented for selected locations for which the National Climatic Center placed 1-hourly or 3-hourly time-series data on magnetic tape. Descriptions of the characteristics of the wind resource presented for these stations are given in Section 3.2. The urge to consider information pertaining to one of these sites as representative of some other location must be tempered with the realization that wind characteristics are extremely site-dependent. The degree of correspondence between the wind characteristics at one site and those at another site depends on the similarity between the topographical setting of the sites, the weather patterns that affect the sites, and the obstructions to the wind in the vicinity of the sites.

Table \*.2 identifies the stations, and gives their location (see also Figures \*.4 and \*.5) and annual average wind speed and power density. Figure \*.10 shows how the yearly mean speed and power varied during the period of record. The monthly mean wind speed and power over the course of a year are shown in Figure \*.11. The hourly mean wind speed over the course of a day is shown in Figure \*.12 with a separate curve for each season. Figures \*.11 and \*.12 indicate the time of year and time of day, respectively, the wind resource is available. Figure \*.10, on the other hand, indicates the year-to-year variability that might be expected in the yearly mean resource.

The frequency of occurrence of winds from a particular direction and of winds with a particular speed is shown in Figures \*.13 and \*.14, respectively. The information on wind direction may be important in assessing the availability of the wind resource relative to surrounding terrain or nearby obstructions. However, it is also important to realize that the wind direction statistics are highly dependent on the location of the instrument site relative to obstructions and major terrain features, e.g., valleys, ridges, and mountain ranges.

Figures \*.15 and \*.16 portray speed and power frequency statistics in the form of speed and power exceedance curves, respectively. The fraction of the total period of record the speed equals or exceeds a given value is shown in Figure \*.15. The power exceedance curve in Figure \*.16 gives the fraction of the period of record for which the power exceeds a given value.

As has been shown in the preceding discussion, the order of presentation of the wind resource in this atlas proceeds from a regional perspective in Chapter 2, to a state perspective in the first part of each state chapter, to individual station descriptions in the last part of the state chapters. Attention given to Chapter 1 and Chapter 3 will make it possible for the reader to properly interpret the wind resource presentations.



#### ACKNOWLEDGEMENTS

The authors would like to thank the Computer Services Division of Environmental Research & Technology, Inc. (ERT), especially to Dr. John A. Nuber, Richard W. Drost and Paula Silvia, for their cooperation and support. We also acknowledge with special thanks the help of Robert D'Errico and members of ERT's Air Quality Studies Division. Finally, special acknowledgment is due to L. Divone and G. Tennyson of DOE, for their support and encouragement as well as for their understanding of the many technical aspects and associated difficulties in producing this atlas.



CONTENTS

|  | <u>Page</u> |
|--|-------------|
| CHAPTER 1: REGIONAL WIND ENERGY RESOURCE ASSESSMENT. . . . . | 7           |
| 1.1 IDENTIFICATION OF WIND DATA SOURCES . . . . .            | 2           |
| 1.2 WIND DATA SCREENING . . . . .                            | 2           |
| 1.3 TIME SCALES IN REGIONAL ASSESSMENTS . . . . .            | 3           |
| 1.4 EVALUATION OF WIND DATA . . . . .                        | 3           |
| 1.4.1 Vertical Adjustment. . . . .                           | 4           |
| 1.5 QUALITATIVE WIND INDICATORS . . . . .                    | 4           |
| 1.6 WIND POWER MAPS . . . . .                                | 5           |
| 1.7 WIND POWER DENSITY CLASSES. . . . .                      | 5           |
| 1.8 CLASSES OF LAND-SURFACE FORM . . . . .                   | 5           |
| 1.9 CERTAINTY RATING. . . . .                                | 6           |
| 1.10 AREAL DISTRIBUTION OF THE WIND RESOURCE . . . . .       | 7           |
| CHAPTER 2: REGIONAL FEATURES . . . . .                       | 11          |
| 2.1 GEOGRAPHY AND TOPOGRAPHY . . . . .                       | 11          |
| 2.2 CLIMATE . . . . .  | 11          |
| 2.3 WIND POWER IN THE GREAT LAKES REGION. . . . .            | 12          |
| 2.3.1 Certainty Rating of the Wind Resource . . . . .        | 12          |
| 2.3.2 Areal Distribution . . . . .                           | 12          |
| 2.4 SEASONAL VARIATIONS IN THE WIND RESOURCE . . . . .       | 13          |
| 2.5 MAJOR WIND RESOURCE AREAS . . . . .                      | 13          |
| 2.5.1 The Shores of Lake Michigan . . . . .                  | 13          |
| 2.5.2 Michigan Coastline of Lake Huron . . . . .             | 14          |
| 2.5.3 Shoreline of Lake Erie . . . . .                       | 14          |
| 2.5.4 Shoreline of Lake Superior . . . . .                   | 14          |
| CHAPTER 3: STATE FEATURES . . . . .                          | 23          |
| 3.1 MAPS OF STATE FEATURES . . . . .                         | 23          |
| 3.2 FEATURES OF SELECTED STATIONS . . . . .                  | 24          |
| 3.2.1 Interannual Wind Power and Speed . . . . .             | 24          |
| 3.2.2 Monthly Average Wind Power and Speed . . . . .         | 25          |
| 3.2.3 Diurnal Wind Speed by Season . . . . .                 | 25          |
| 3.2.4 Directional Frequency and Average Speed. . . . .       | 25          |
| 3.2.5 Annual Average Wind Speed Frequency . . . . .          | 25          |
| 3.2.6 Annual Average Wind Speed and Power Duration. . . . .  | 25          |
| CHAPTER 4: ILLINOIS . . . . .                                | 27          |
| 4.1 ANNUAL AVERAGE WIND POWER . . . . .                      | 27          |
| 4.1.1 Certainty Rating of the Wind Resource . . . . .        | 28          |
| 4.1.2 Areal Distribution . . . . .                           | 28          |
| 4.2 SEASONAL WIND POWER . . . . .                            | 28          |
| 4.2.1 Winter . . . . .                                       | 28          |
| 4.2.2 Spring . . . . .                                       | 28          |
| 4.2.3 Summer . . . . .                                       | 28          |
| 4.2.4 Autumn . . . . .                                       | 28          |
| 4.3 FEATURES OF SELECTED STATIONS . . . . .                  | 29          |
| 4.3.1 Interannual Wind Power and Speed . . . . .             | 29          |
| 4.3.2 Monthly Average Wind Power and Speed . . . . .         | 30          |
| 4.3.3 Diurnal Wind Speed by Season . . . . .                 | 30          |
| 4.3.4 Directional Frequency and Average Speed. . . . .       | 30          |
| 4.3.5 Annual Average Wind Speed Frequency . . . . .          | 30          |
| 4.3.6 Annual Average Wind Speed and Power Duration. . . . .  | 30          |
| CHAPTER 5: INDIANA . . . . .                                 | 55          |
| 5.1 ANNUAL AVERAGE WIND POWER . . . . .                      | 55          |
| 5.1.1 Certainty Rating of the Wind Resource . . . . .        | 55          |
| 5.1.2 Areal Distribution . . . . .                           | 55          |

CONTENTS (Continued)

|   | <u>Page</u> |
|---|-------------|
| 5.2 SEASONAL WIND POWER . . . . .                           | 56          |
| 5.2.1 Winter . . . . .                                      | 56          |
| 5.2.2 Spring . . . . .                                      | 56          |
| 5.2.3 Summer . . . . .                                      | 56          |
| 5.2.4 Autumn . . . . .                                      | 56          |
| 5.3 FEATURES OF SELECTED STATIONS . . . . .                 | 56          |
| 5.3.1 Interannual Wind Power and Speed . . . . .            | 57          |
| 5.3.2 Monthly Average Wind Power and Speed . . . . .        | 57          |
| 5.3.3 Diurnal Wind Speed by Season . . . . .                | 57          |
| 5.3.4 Directional Frequency and Average Speed. . . . .      | 57          |
| 5.3.5 Annual Average Wind Speed Frequency . . . . .         | 58          |
| 5.3.6 Annual Average Wind Speed and Power Duration. . . . . | 58          |
| <br>CHAPTER 6: MICHIGAN . . . . .                           | <br>83      |
| 6.1 ANNUAL AVERAGE WIND POWER . . . . .                     | 83          |
| 6.1.1 Certainty Rating of the Wind Resource . . . . .       | 84          |
| 6.1.2 Areal Distribution . . . . .                          | 84          |
| 6.2 SEASONAL WIND POWER . . . . .                           | 84          |
| 6.2.1 Winter . . . . .                                      | 85          |
| 6.2.2 Spring . . . . .                                      | 85          |
| 6.2.3 Summer . . . . .                                      | 85          |
| 6.2.4 Autumn . . . . .                                      | 85          |
| 6.3 FEATURES OF SELECTED STATIONS . . . . .                 | 85          |
| 6.3.1 Interannual Wind Power and Speed . . . . .            | 86          |
| 6.3.2 Monthly Average Wind Power and Speed . . . . .        | 87          |
| 6.3.3 Diurnal Wind Speed by Season . . . . .                | 87          |
| 6.3.4 Directional Frequency and Average Speed. . . . .      | 87          |
| 6.3.5 Annual Average Wind Speed Frequency . . . . .         | 87          |
| 6.3.6 Annual Average Wind Speed and Power Duration. . . . . | 87          |
| <br>CHAPTER 7: OHIO . . . . .                               | <br>109     |
| 7.1 ANNUAL AVERAGE WIND POWER . . . . .                     | 111         |
| 7.1.1 Certainty Rating of the Wind Resource . . . . .       | 111         |
| 7.1.2 Areal Distribution . . . . .                          | 112         |
| 7.2 SEASONAL WIND POWER . . . . .                           | 112         |
| 7.2.1 Winter . . . . .                                      | 112         |
| 7.2.2 Spring . . . . .                                      | 112         |
| 7.2.3 Summer . . . . .                                      | 112         |
| 7.2.4 Autumn . . . . .                                      | 112         |
| 7.3 FEATURES OF SELECTED STATIONS . . . . .                 | 113         |
| 7.3.1 Interannual Wind Power and Speed . . . . .            | 113         |
| 7.3.2 Monthly Average Wind Power and Speed . . . . .        | 113         |
| 7.3.3 Diurnal Wind Speed by Season . . . . .                | 114         |
| 7.3.4 Directional Frequency and Average Speed. . . . .      | 114         |
| 7.3.5 Annual Average Wind Speed Frequency . . . . .         | 114         |
| 7.3.6 Annual Average Wind Speed and Power Duration. . . . . | 114         |
| <br>CHAPTER 8: WISCONSIN . . . . .                          | <br>139     |
| 8.1 ANNUAL AVERAGE WIND POWER . . . . .                     | 139         |
| 8.1.1 Certainty Rating of the Wind Resource . . . . .       | 140         |
| 8.1.2 Areal Distribution . . . . .                          | 140         |
| 8.2 SEASONAL WIND POWER . . . . .                           | 140         |
| 8.2.1 Winter . . . . .                                      | 140         |
| 8.2.2 Spring . . . . .                                      | 140         |
| 8.2.3 Summer . . . . .                                      | 140         |
| 8.2.4 Autumn . . . . .                                      | 140         |

CONTENTS (Continued)

|   | <u>Page</u> |
|---|-------------|
| 8.3 FEATURES OF SELECTED STATIONS . . . . .                 | 141         |
| 8.3.1 Interannual Wind Power and Speed . . . . .            | 141         |
| 8.3.2 Monthly Average Wind Power and Speed . . . . .        | 141         |
| 8.3.3 Diurnal Wind Speed by Season . . . . .                | 141         |
| 8.3.4 Directional Frequency and Average Speed. . . . .      | 142         |
| 8.3.5 Annual Average Wind Speed Frequency . . . . .         | 142         |
| 8.3.6 Annual Average Wind Speed and Power Duration. . . . . | 142         |
| REFERENCES . . . . .  | 167         |
| INDEX . . . . .   | 169         |



LIST OF FIGURES

|   | <u>Page</u> |
|---|-------------|
| 1.1 Geographic Divisions for Regional Wind Energy Assessments. . . . .  | 1           |
| 2.1 Geographic Map of the Great Lakes Region . . . . .                  | 16          |
| 2.2 Topographic Map of the Great Lakes Region . . . . .                 | 17          |
| 2.3 Classes of Land-Surface Form in the Great Lakes Region . . . . .    | 18          |
| 2.4 Annual Average Wind Power in the Great Lakes Region . . . . .       | 20          |
| 2.5 Seasonal Maximum Wind Power in the Great Lakes Region . . . . .     | 22          |
| 4.1 Geographic Map of Illinois . . . . .                                | 32          |
| 4.2 Topographic Map of Illinois. . . . .                                | 33          |
| 4.3 Land-Surface Form Map for Illinois . . . . .                        | 34          |
| 4.4 NCC Station Locations in Illinois . . . . .                         | 36          |
| 4.5 Location of Stations Used in Illinois Resource Assessment. . . . .  | 37          |
| 4.6 Illinois Annual Average Wind Power . . . . .                        | 38          |
| 4.7 Certainty Rating of Illinois Wind Resource. . . . .                 | 40          |
| 4.8 Areal Distribution of Wind Resource in Illinois. . . . .            | 42          |
| 4.9 Seasonal Average Wind Power in Illinois . . . . .                   | 44          |
| 4.10 Interannual Wind Power and Speed for Illinois . . . . .            | 47          |
| 4.11 Monthly Average Wind Power and Speed for Illinois . . . . .        | 48          |
| 4.12 Diurnal Wind Speed by Season for Illinois . . . . .                | 49          |
| 4.13 Directional Frequency and Average Wind Speed for Illinois. . . . . | 50          |
| 4.14 Annual Average Wind Speed Frequency for Illinois . . . . .         | 51          |
| 4.15 Annual Average Wind Speed Duration for Illinois. . . . .           | 52          |
| 4.16 Annual Average Wind Power Duration for Illinois. . . . .           | 53          |
| 5.1 Geographic Map of Indiana . . . . .                                 | 60          |
| 5.2 Topographic Map of Indiana . . . . .                                | 61          |
| 5.3 Land-Surface Form Map for Indiana . . . . .                         | 62          |
| 5.4 NCC Station Locations in Indiana. . . . .                           | 64          |
| 5.5 Location of Stations Used in Indiana Resource Assessment . . . . .  | 65          |
| 5.6 Indiana Annual Average Wind Power . . . . .                         | 66          |
| 5.7 Certainty Rating of Indiana Wind Resource . . . . .                 | 68          |
| 5.8 Areal Distribution of Wind Resource in Indiana . . . . .            | 70          |
| 5.9 Seasonal Average Wind Power in Indiana . . . . .                    | 72          |
| 5.10 Interannual Wind Power and Speed for Indiana . . . . .             | 75          |

LIST OF FIGURES (Continued)

|  | <u>Page</u> |
|--|-------------|
| 5.11 Monthly Average Wind Power and Speed for Indiana . . . . .          | 76          |
| 5.12 Diurnal Wind Speed by Season for Indiana . . . . .                  | 77          |
| 5.13 Directional Frequency and Average Wind Speed for Indiana. . . . .   | 78          |
| 5.14 Annual Average Wind Speed Frequency for Indiana . . . . .           | 79          |
| 5.15 Annual Average Wind Speed Duration for Indiana. . . . .             | 80          |
| 5.16 Annual Average Wind Power Duration for Indiana. . . . .             | 81          |
| 6.1 Geographic Map of Michigan. . . . .                                  | 88          |
| 6.2 Topographic Map of Michigan . . . . .                                | 89          |
| 6.3 Land-Surface Form Map for Michigan . . . . .                         | 91          |
| 6.4 NCC Station Locations in Michigan . . . . .                          | 92          |
| 6.5 Location of Stations Used in Michigan Resource Assessment . . . . .  | 93          |
| 6.6 Michigan Annual Average Wind Power . . . . .                         | 94          |
| 6.7 Certainty Rating of Michigan Wind Resource . . . . .                 | 96          |
| 6.8 Areal Distribution of Wind Resource in Michigan . . . . .            | 98          |
| 6.9 Seasonal Average Wind Power in Michigan . . . . .                    | 100         |
| 6.10 Interannual Wind Power and Speed for Michigan . . . . .             | 103         |
| 6.11 Monthly Average Wind Power and Speed for Michigan . . . . .         | 104         |
| 6.12 Diurnal Wind Speed by Season for Michigan. . . . .                  | 105         |
| 6.13 Directional Frequency and Average Wind Speed for Michigan . . . . . | 106         |
| 6.14 Annual Average Wind Speed Frequency for Michigan . . . . .          | 107         |
| 6.15 Annual Average Wind Speed Duration for Michigan. . . . .            | 108         |
| 6.16 Annual Average Wind Power Duration for Michigan . . . . .           | 109         |
| 7.1 Geographic Map of Ohio . . . . .                                     | 116         |
| 7.2 Topographic Map of Ohio . . . . .                                    | 117         |
| 7.3 Land-Surface Form Map for Ohio . . . . .                             | 118         |
| 7.4 NCC Station Locations in Ohio . . . . .                              | 120         |
| 7.5 Location of Stations Used in Ohio Resource Assessment . . . . .      | 121         |
| 7.6 Ohio Annual Average Wind Power . . . . .                             | 122         |
| 7.7 Certainty Rating of Ohio Wind Resource . . . . .                     | 124         |
| 7.8 Areal Distribution of Wind Resource in Ohio . . . . .                | 126         |
| 7.9 Seasonal Average Wind Power in Ohio . . . . .                        | 128         |
| 7.10 Interannual Wind Power and Speed for Ohio. . . . .                  | 131         |

LIST OF FIGURES (Continued)

|   | <u>Page</u> |
|---|-------------|
| 7.11 Monthly Average Wind Power and Speed for Ohio . . . . .              | 132         |
| 7.12 Diurnal Wind Speed by Season for Ohio. . . . .                       | 133         |
| 7.13 Directional Frequency and Average Wind Speed for Ohio . . . . .      | 134         |
| 7.14 Annual Average Wind Speed Frequency for Ohio . . . . .               | 135         |
| 7.15 Annual Average Wind Speed Duration for Ohio . . . . .                | 136         |
| 7.16 Annual Average Wind Power Duration for Ohio . . . . .                | 137         |
| 8.1 Geographic Map of Wisconsin. . . . .                                  | 144         |
| 8.2 Topographic Map of Wisconsin . . . . .                                | 145         |
| 8.3 Land-Surface Form Map for Wisconsin . . . . .                         | 146         |
| 8.4 NCC Station Locations in Wisconsin . . . . .                          | 148         |
| 8.5 Location of Stations Used in Wisconsin Resource Assessment . . . . .  | 149         |
| 8.6 Wisconsin Annual Average Wind Power . . . . .                         | 150         |
| 8.7 Certainty Rating of Wisconsin Wind Resource . . . . .                 | 152         |
| 8.8 Areal Distribution of Wind Resource in Wisconsin . . . . .            | 154         |
| 8.9 Seasonal Average Wind Power in Wisconsin . . . . .                    | 156         |
| 8.10 Interannual Wind Power and Speed for Wisconsin . . . . .             | 159         |
| 8.11 Monthly Average Wind Power and Speed for Wisconsin . . . . .         | 160         |
| 8.12 Diurnal Wind Speed by Season for Wisconsin. . . . .                  | 161         |
| 8.13 Directional Frequency and Average Wind Speed for Wisconsin . . . . . | 162         |
| 8.14 Annual Average Wind Speed Frequency for Wisconsin . . . . .          | 163         |
| 8.15 Annual Average Wind Speed Duration for Wisconsin . . . . .           | 164         |
| 8.16 Annual Average Wind Power Duration for Wisconsin . . . . .           | 165         |



LIST OF TABLES

|  | <u>Page</u> |
|--|-------------|
| 1.1 Stations with Wind Data in the Great Lakes Region and Peripheral Area Screened in Assessment . . . . . | 2           |
| 1.2 Land-Surface Form Terrain Features Representative of Exposed Locations . . . . .                       | 8           |
| 1.3 Classes of Wind Power Density at 10 m and 50 m . . . . .   | 9           |
| 1.4 Scheme of Classification . . . . .   | 9           |
| 2.1 Land Area and Population of the Great Lakes Region . . . . .   | 11          |
| 2.2 Areal Distribution of Wind Power Classes in the Great Lakes Region . . . . .                           | 21          |
| 3.1 Maps, Tables and Graphs Used to Depict the Wind Resource . . . . .                                     | 23          |
| 4.1 Areal Distribution (km <sup>2</sup> ) of Wind Power Classes in Illinois . . . . .                      | 39          |
| 4.2 Illinois Stations with Graphs of the Wind Characteristics . . . . .                                    | 46          |
| 5.1 Areal Distribution (km <sup>2</sup> ) of Wind Power Classes in Indiana . . . . .                       | 67          |
| 5.2 Indiana Stations with Graphs of the Wind Characteristics . . . . .                                     | 74          |
| 6.1 Areal Distribution (km <sup>2</sup> ) of Wind Power Classes in Michigan . . . . .                      | 95          |
| 6.2 Michigan Stations with Graphs of the Wind Characteristics . . . . .                                    | 102         |
| 7.1 Areal Distribution (km <sup>2</sup> ) of Wind Power Classes in Ohio . . . . .                          | 123         |
| 7.2 Ohio Stations with Graphs of the Wind Characteristics. . . . .   | 130         |
| 8.1 Areal Distribution (km <sup>2</sup> ) of Wind Power Classes in Wisconsin . . . . .                     | 151         |
| 8.2 Wisconsin Stations with Graphs of the Wind Characteristics. . . . .                                    | 158         |



## CHAPTER 1: REGIONAL WIND ENERGY RESOURCE ASSESSMENT

Rapid development of wind as a source of commercial electric power is the principal goal of the Federal Wind Energy Program. Utility planning, wind turbine manufacturing and marketing of wind energy conversion systems all depend on detailed wind resource assessments. This atlas of the wind resource of the Great Lakes Region, a product of the Wind Characteristics Program Element of the Federal Wind Energy Program, represents a major source of information for meeting these various needs.

This wind energy resource atlas is one of twelve such regional atlases being assembled to describe the potential wind resource in the United States (see Figure 1.1). The spatial and temporal resolution of the wind resource in these regional assessments will be depicted in considerably greater detail than that in existing national assessments (Reed 1975, Coty 1976, Garate 1977, Elliott 1977). To produce the Great Lakes Region atlas in a timely fashion, only existing

relevant data are used. The other atlases will use comparable data sets, analysis techniques, and presentations to ensure the comparability of the wind resource assessments.

The Great Lakes Region atlas assimilates six collections of wind resource data, one for the region and one for each of the five states that compose the Great Lakes region: Illinois, Indiana, Michigan, Ohio, Wisconsin. At the state level, features of the climate, topography, and wind resource are discussed in greater detail than in the regional discussion and the data locations on which the assessment is based are mapped. Variations over several time scales in the wind resource at selected stations in each state are shown on graphs of monthly average and interannual wind speed and power, and of hourly average wind speed for each season. Other graphs present speed, direction, and duration frequencies of the wind at these locations.

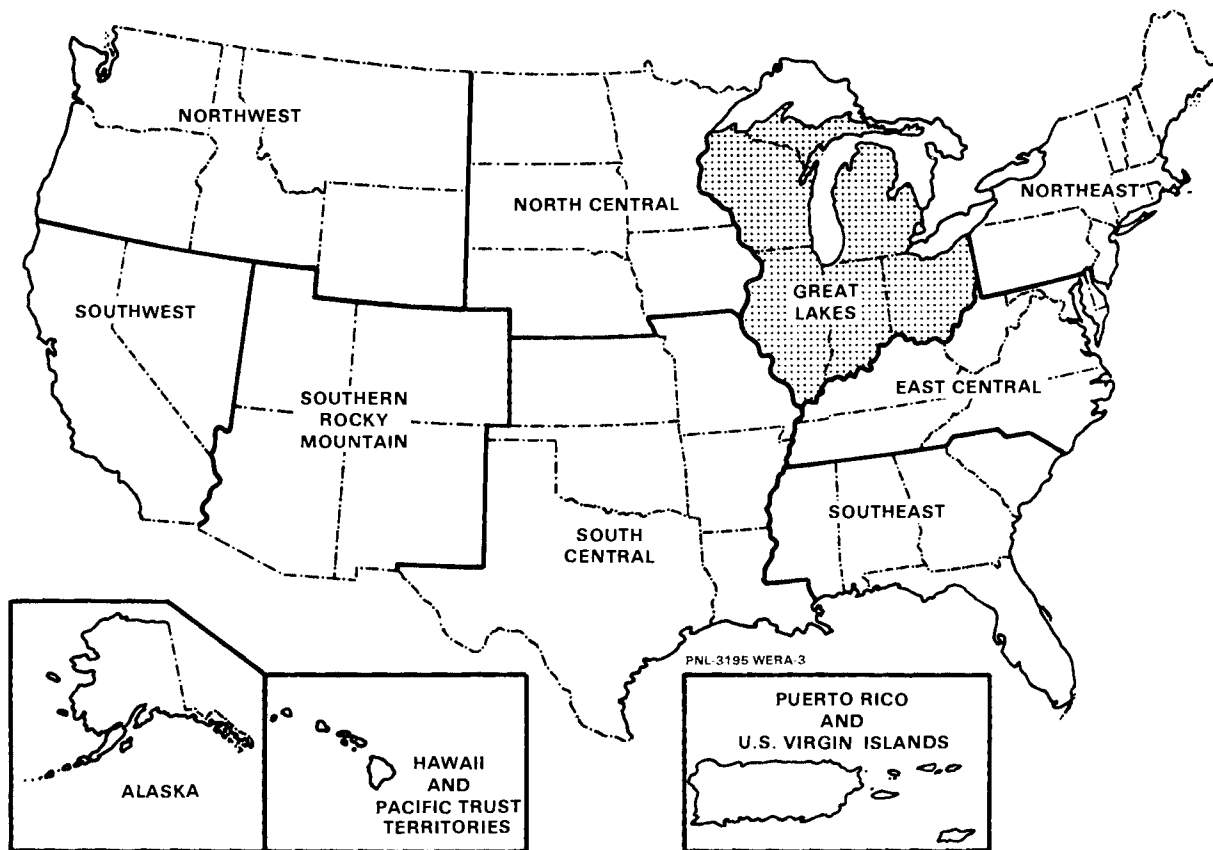


FIGURE 1.1. Geographic Divisions for Regional Wind Energy Assessments

The methods used to identify, screen, evaluate, and analyze the various types of data, and to produce the wind energy resource maps and graphs will only be described briefly. For more detail, see Elliott and Barchet (1980). However, this discussion will provide the reader with useful background information for interpreting the wind energy resource maps for the Great Lakes Region.

### 1.1 IDENTIFICATION OF WIND DATA SOURCES

The surface wind data on which this atlas has been based were obtained from several sources: the National Climatic Center (NCC), the U.S. Forest Service, university research projects, nuclear and fossil-fuel power plants and their proposed sites, DOE candidate wind turbine sites, the Atmospheric Environment Service of Canada, and other government and private organizations. The National Climatic Center offers the largest collection of wind data. Surveys and indices of wind data archived at the NCC (Changery 1975, 1978; Changery et al. 1977) are extremely helpful in locating available wind data. The Index of Original Surface Weather Records, published for each individual state by the NCC, provides additional information about stations at which wind data have been taken.

The wind data available from the NCC may be in one or more of three formats: summarized, digitized, and unsummarized. Initially, all wind data are in the unsummarized format consisting of the original station weather records. For many stations, the collections of individual observations have been condensed into wind summaries. Changery et al. (1977) present examples of the various summary formats used and indices of the stations for which wind summaries are available. For fewer stations (primarily airport stations) the NCC has put the original one- or three-hourly weather observations on magnetic tape to create a digitized time series of weather (and wind) observations. TDF-14 (NCC 1975) describes the data on these tapes. Table 1.1 indicates the number of stations with wind data in these various formats in the Great Lakes Region.

U.S. Forest Service data in the National Fire Weather Data Library (Furman and Brink 1975) are from remote sites in mountainous and forested areas under the jurisdiction of the Federal government (i.e., national forests, national parks, Indian reservations, or Bureau of Land Management areas). However, only one afternoon observation,

at about 2:00 p.m., is digitized per day during the local fire weather season. Although 30 of the 50 fire weather stations were retained, none of this data was actually used in the assessment because of its questionable quality and unknown exposure and representativeness.

Wind data from nuclear or fossil-fuel power plants or potential plant sites were examined (Verholek 1977). Other wind data sets collected by university research projects, state and local air pollution control agencies, or in support of environmental impact statements were also identified.

### 1.2 WIND DATA SCREENING

Table 1.1 indicates the quantity of wind data available in the Great Lakes Region. Not all of these data are needed in a wind resource assessment. Screening procedures were developed to identify stations with the most useful data and to eliminate stations that would not significantly contribute information on the distribution of the wind resources.

TABLE 1.1. Stations with Wind Data in the Great Lakes Region and Peripheral Area Screened in Assessment

| Source and Type                     | Screened | Retained |
|-------------------------------------|----------|----------|
| National Climatic Center            |          |          |
| Digitized                           | 147      | 72       |
| Summarized                          | 40       | 35       |
| Unsummarized                        | 142      | 75       |
| National Fire Weather Data Library  | 50       | 30       |
| Nuclear and Fossil-Fuel Power Plant | 23       | 23       |
| University Research Other           | 33       | 13       |
| Canadian                            | 23       | 23       |
| ERT AIRMAP                          | 86       | 63       |

Wind data in summarized or digitized format were preferred to unsummarized data. When stations had both summarized and digitized data, the digitized data were used for selected stations to prepare a more extensive characterization of the wind resource. Unsummarized data were used only when no summarized or digitized data were available.

In an area with a high density of stations with wind summaries, those stations appearing to have the best exposure to the wind, the greatest numbers of daily observations, the

longest periods of record, and the longest periods of unchanged anemometer height and location were usually selected over other nearby stations. When more than one type of summary was available for a given station (see Changery et al. 1977), the summary chosen covered the longest period of record with constant anemometer height and location, with the greatest number of wind speed and direction classes, and with the highest frequency of daily observations.

The screening of the National Fire Weather Data Library involved the determination of anemometer exposure and period of record. Elimination of those stations with poor wind exposure and short periods of record significantly reduced the number of U.S. Forest Service sites to be considered in the assessment. Table 1.1 shows the effect of screening on the number of sites analyzed. Only sites for which there was quality information pertaining to the wind resource were retained. The quality of the data, however, was so uncertain, that none of the stations were actually used in the final analysis.

### 1.3 TIME SCALES IN REGIONAL ASSESSMENTS

Several time scales are encountered in the following discussions of the wind resource: annual, seasonal, monthly, and diurnal. Annual mean values are generally based on an average of the one- or three-hourly observations of wind speed or power in the period of record; however, a complete calendar year of data (January 1 to December 31) is used for calculating individual yearly means. At stations with less than 24 hourly observations or 8 three-hourly observations per day, the values are only representative of the times of day for which the data were taken.

The four seasons are defined as:

- winter - December, January, and February
- spring - March, April, and May
- summer - June, July, and August
- autumn - September, October, and November.

The term "seasonal trends" refers to the change in monthly mean values over the course of the four seasons.

Monthly mean values are based on as many hours of data as are available for that month in each year of the period of record.

The daily or diurnal cycles of variation in the hourly mean wind power or speed are referenced to local standard time on a 24-hour clock.

### 1.4 EVALUATION OF WIND DATA

For the purpose of mapping the geographical variation of the wind resource, wind power density was chosen in preference to wind speed because the power density combines in a single number the distribution of wind speeds and the dependence of the power density on air density and on (the cube of) the wind speed. Quantitative wind data in three formats (digitized, summarized, and unsummarized) were evaluated for mean wind power density. The average wind power density  $\bar{P}$  (watts/m<sup>2</sup>) in a vertical plane perpendicular to the wind direction for stations with one- or three-hourly digitized data was calculated from:

$$\bar{P} = \frac{1}{2n} \sum_{i=1}^n \rho_i V_i^3 \quad (1)$$

where

- $n$  = the number of observations in the averaging period
- $\rho_i$  = the density (in kg/m<sup>3</sup>) computed from the station pressure and temperature at the  $i^{\text{th}}$  observation time
- $V_i$  = the wind speed (in m/s) at the  $i^{\text{th}}$  observation time.

For stations with wind summaries,  $\bar{P}$  was calculated from:

$$\bar{P} = \frac{1}{2} \bar{\rho} \sum_{j=1}^c f_j V_j^3 \quad (2)$$

where

- $\bar{\rho}$  = the mean air density
- $c$  = the number of wind speed classes
- $f_j$  = frequency of occurrence of winds in the  $j^{\text{th}}$  class
- $V_j$  = the median wind speed of the  $j^{\text{th}}$  class.

In those cases for which unsummarized wind data were assessed, the seasonal and annual average speeds,  $\bar{V}$ , were estimated

from a visual examination of one year's original weather records. The wind power density,  $P$ , was then estimated by assuming that the speed frequency distribution followed a Rayleigh distribution (Cliff 1977):

$$\bar{P} = 0.955 \bar{\rho} \bar{V}^3 \quad (3)$$

#### 1.4.1 Vertical Adjustment

The anemometer height above the surface rarely was at either the 10-m or 50-m reference levels chosen for the presentation of the wind resource. A power law was used to adjust the long-term mean wind speed or power density to the reference level:

$$\left(\frac{\bar{V}_r}{\bar{V}_a}\right) = \left(\frac{Z_r}{Z_a}\right)^\alpha \quad \text{or} \quad \left(\frac{\bar{P}_r}{\bar{P}_a}\right) = \left(\frac{Z_r}{Z_a}\right)^{3\alpha} \quad (4)$$

where

$\bar{V}_{a,r}$  and  $\bar{P}_{a,r}$  = the mean wind speed or wind power density at heights  $Z_{a,r}$  (the anemometer and reference level, respectively)  
 $\alpha$  = the power law exponent.

An examination of long-term mean wind speeds at airport locations at which the anemometer height was changed and at tower sites with multiple levels of anemometry indicates an  $\alpha \sim 1/7$  to be widely applicable to low surface roughness and well exposed sites from which conventional NCC data are available (Elliott 1979b).

#### 1.5 QUALITATIVE WIND INDICATORS

Although more than 300 stations provided quantitative data for the wind resource assessment in the Great Lakes Region, these stations were not uniformly distributed. The station location figures for each state show that most NCC stations are located in populated areas and along transportation corridors. Some areas in the Great Lakes region, such as extreme northwestern Wisconsin interior sections of the Upper Peninsula of Michigan, are devoid of any quantitative wind data suitable for this assessment. Furthermore, in areas of complex terrain, such as southeastern Ohio, observation sites are mostly confined to valley locations. To

evaluate the distribution of the wind resource in data-sparse areas, three qualitative indicators of the wind speed or power were developed for, and employed in, the assessment.

The most widely used technique depended on certain combinations of topographical and meteorological features (Elliott 1979a) that were associated with high or low wind speeds. Those features indicative of high mean wind speeds are:

- gaps, passes, and gorges in areas of frequent strong pressure gradients (e.g., the Straits of Mackinac)
- long valleys extending down from mountain ranges (not applicable to this region)
- high-elevation plains and plateaus (not applicable to this region)
- plains and valleys with persistent strong downslope winds associated with strong pressure gradients (not applicable to this region)
- exposed ridges and mountain summits in areas of strong upper-air winds (not applicable to this region)
- exposed coastal sites in areas of
  - 1) strong upper-air winds, or
  - 2) strong thermal/pressure gradients (e.g., shores of Lake Superior).

Features that signal rather low mean wind speeds are:

- valleys perpendicular to the prevailing winds aloft (not applicable to this region)
- sheltered basins (not applicable to this region)
- short and/or narrow valleys and canyons (not applicable to this region)
- areas of high surface roughness, e.g., forested hilly terrain (such as the Upper Peninsula of Michigan, or southeastern Ohio).

Areas in which the appropriate features occur were identified from topographic contour and shaded relief maps and from synoptic and climatological maps of sea-level pressure patterns and air flow.

#### 1.6 WIND POWER MAPS

The production of mean wind power density maps, such as those presented for each state, depended on the coherent synthesis of several pieces of information. The goal of the synthesis process was to present wind power density values representative of sites well exposed to the prevailing strong winds. Hilltops, ridge crests, mountain summits, large clearings, and other locations free of local obstructions to the wind are expected to have good exposure to the wind (see Table 1.2). In contrast, locations in narrow valleys and canyons, or downwind of hills and obstructions, or in forested or urban areas, are likely to have poor exposures.

The wind power densities shown on the maps in this atlas will not be representative of poorly exposed locations. Estimates for ridge crests and summits (the shaded areas on the maps) are lower limits to the wind power expected at exposed sites. In such areas, local terrain features can enhance the wind power considerably (e.g., by a factor of 2 or 3). By specifying the type of wind exposure to which the map values of wind power pertain, we avoid the ambiguity that typical-location or average-for-the-terrain values might introduce. In this atlas, the terms wind energy, wind power, and wind power density are used synonymously.

To represent the wind resource at well-exposed sites, it was necessary to become extremely familiar with the land-surface form and topography in the vicinity of every data site. Maps were prepared showing the location of stations, the mean wind speed and mean wind power at the reference level, the character of anemometer exposure, and the land-surface form for each state. On these maps, areas with the appropriate combinations of topographical and meteorological features were identified. A great deal of attention was given to the orientation of topographic features with the prevailing wind directions. Only after all this information was assembled were the maps analyzed. The annual maps for each state were merged into a regional mosaic.

#### 1.7 WIND POWER DENSITY CLASSES

The analysis of wind power maps departs from conventional isopleth analyses by showing the boundaries of wind power density classes. Each wind power class represents the range of wind power densities likely to be encountered at exposed sites within an area designated as having that wind power class. Table 1.3 gives the power density limits for the wind power classes used in the atlas for the 10-m (33-ft) and 50-m (164-ft) reference levels. The definitions of the wind power density classes are repeated with the annual wind power map for the region and for each state as a convenience for the reader.

Wind power density is proportional to the third moment of the wind speed distribution and to air density; therefore, a unique correspondence between power density and mean wind speed (the first moment of the speed distribution) does not exist. However, by specifying a Rayleigh wind speed distribution and a standard sea-level air density ( $1.22 \text{ kg/m}^3$ ), a mean wind speed can be determined for each wind power class limit. The decrease of air density with elevation requires the mean Rayleigh speed to increase by about 3%/1,000 m elevation (1%/1,000 ft) to maintain the same power density. If the wind speed distribution is more sharply peaked than the Rayleigh distribution, the equivalent mean speed will be slightly higher than the value in Table 1.3. Conversely, a broader distribution of wind speeds will slightly reduce the equivalent mean speed.

#### 1.8 CLASSES OF LAND-SURFACE FORM

The physical characteristics of the land-surface form affect the number of wind turbines that can be sited in exposed places. For example, over 90% of the land area in a flat plain may be favorably exposed to the wind; whereas in mountainous terrain only the ridge crests and passes, which may be only a small percentage (<5%) of the land area, may represent exposed sites. The map of classes of land-surface form by Hammond (1964) provided information on the distribution of plains, tablelands, hills, and mountains in the Great Lakes region. Several characteristics are coded on this map:

- percentage of land area occupied by surface of gentle inclination (less than 8% slope)

- local relief, the maximum difference in elevation within a unit square six miles across
- percentage of gently inclined surfaces that lie in the lower half of the local relief
- land area covered by sand, ice, and standing water
- pattern of major crests, peaks, and escarpments.
- the abundance and quality of wind data
- the complexity of the terrain
- the geographical variability of the resource.

The first three characteristics are used in the classification scheme (see Table 1.4); the latter two have been omitted from the maps presented here. A three-character code, for example B3a, designates each class of land-surface form. In this example, the "B" indicates that 50% to 80% of the area is occupied by gentle slopes; the "3" that the maximum local difference in elevation is 1100 to 150 m (300 to 500 ft); and the "a" that more than 75% of the gently sloping land is in the lowland. In areas of very little gentle slope (D) or very low relief and great smoothness (A1), the third designator is omitted.

For each land-surface form, the percentage of land area that is representative of well-exposed, moderately exposed, and poorly exposed sites has been estimated. These percentages were determined subjectively as a function of the slope, local relief, and profile type. Table 1.2 gives the average percentage of land area that is designated as exposed terrain for the different classes of land-surface form. For simplicity, the percentages shown for each class of land-surface form have been averaged over the range of categories in local relief and profile type found in the Great Lakes region. The average percentage of land area that is designated as exposed terrain ranges from 91% in smooth plains to 6% in hilly areas where the exposed areas are usually the hilltops.

### 1.9 CERTAINTY RATING

The analyses of wind power density at exposed sites shown on the wind power maps depend on the subjective integration of several factors: quantitative wind data, qualitative indicators of wind speed or power, characteristics of exposed sites in various terrain, and familiarity with the meteorology, climatology, and topography of the region. As a result, the degree of certainty with which the wind power class can be specified depends on

A certainty rating from 1 (low) to 4 (high) of the wind energy resource estimate has been made for each cell of a one-quarter degree latitude by one-third degree longitude grid on a state-by-state basis, by considering the influence of the above three factors on the certainty of the estimate of the wind power class for each cell. The definitions for the certainty ratings are adopted from those used by Voelker et al. (1979) in a resource assessment of U.S. Forest Service tracts. The certainty ratings for the wind resource assessment are defined as follows:

| Rating | Definition   |
|--------|--|
| 1      | The lowest degree of certainty. A combination of the following conditions exist: <ol style="list-style-type: none"> <li>1) No data exist in the vicinity of the cell.</li> <li>2) The terrain is highly complex.</li> <li>3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.</li> </ol>   |
| 2      | A low-intermediate degree of certainty. One of the following conditions exists: <ol style="list-style-type: none"> <li>1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data.</li> <li>2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.</li> </ol> |
| 3      | A high-intermediate degree of certainty. One of the following conditions exists:   |

- 1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data.
  - 2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.
- 4 The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.

The assignment of a certainty rating requires subjective evaluation of the interaction of the factors involved.

#### 1.10 AREAL DISTRIBUTION OF THE WIND RESOURCE

As noted above, the wind power density class values shown on the maps apply only to sites well exposed to the wind. Therefore, the map area designated as having a particular wind power class does not indicate the true land area experiencing this wind power. Instead, there is a complicated and difficult-to-quantify relationship among the class of land-surface form, the land-surface area and the map value of wind power density. For each land-surface form, the fraction of land area that would be favorably exposed to the winds, i.e., that would have the wind power density indicated on the map, was estimated. (See Table 1.2 for averages in various land-surface forms.) Furthermore, to be able to establish a wind power density for the remaining area, it was also necessary to specify a factor by which the wind power shown on the map is reduced in the less-exposed areas. As an additional complication, some land-surface forms, isolated hills, and ridges that rise above a nearly flat landscape may even experience a higher power density than the map indicates.

To accommodate these various situations, the land area represented by a given land-surface form was divided into four exposure categories:  
 (1) better exposure than typical for the

terrain, (2) exposure typical for the land-surface form, (3) partially sheltered exposure, and (4) very sheltered exposure. The partitioning of the land-surface forms into the four categories was based on the parameters used to classify the land-surface form and on familiarity with the terrain represented by the land-surface forms.

In order to adjust the wind power density from the map value to the various exposure categories, the power density was scaled to be (1) greater than, (2) equal to, (3) slightly less than, or (4) much less than the map value power density. The factor by which the map value was adjusted to represent the wind power density in each category was determined by the magnitude of elevation relief given by the middle character of the land-surface form code. (The minimum power density allowed for a category was the median value of wind power density class 1). The scaling factors for the wind power density were based on a conservative application of a power law type vertical adjustment with the height change specified by the terrain relief code.

In each cell of a grid one-third degree longitude by one-quarter degree latitude, the land-surface form was specified and the wind power class associated with a typically exposed site in that land-surface form was determined. By partitioning the area of the cell into the four exposure categories, and by scaling the wind power class to each category, the contribution of that cell to the areal distribution was determined.

A cell-by-cell representation of the areal distribution is given in a map that indicates the percentage land area in a cell over which the wind power class equals or exceeds a threshold value. Four maps are shown in the chapters on the state wind resources for threshold values of classes 2, 3, 4, and 5.

Summary tables of the areal distribution that combine the contributions by each cell are provided for the region and for each state. For each power class, the sum of the area contributed by each exposure category is determined for each state and the region. Summing the area associated with each power class in each cell gives the area of the state or region over which the power class exceeds a given value. The table gives the estimated land area (km<sup>2</sup>) and the percentage of land area associated with each power class.

Both of these presentations of the areal distribution of the wind resource are highly dependent on the estimates used to partition the land area into the four exposure categories and on the scaling of the power density for each category of exposure. Therefore, the areal distribution derived from the wind power and land-surface form maps must be considered only an approximation. The quantity and quality of wind data and

topographic information required to make a highly accurate cell-by-cell appraisal of the wind resource goes far beyond the scope of this regional wind resource assessment. However, as wind information becomes available through new measurement programs or through the discovery and processing of existing data sets, the evaluation of the areal distribution of the wind resource can be improved on a cell-by-cell basis.

TABLE 1.2. Land-Surface Form Terrain Features Representative of Exposed Locations

| Land-Surface Form           | Exposed Feature (Map Value) | Percentage Area <sup>(a)</sup> |
|-----------------------------|-----------------------------|--------------------------------|
| Plains: A1, 2, B2           | Plains                      | 91                             |
| Open Hills: C2, 3           | Hilltops and uplands        | 35                             |
| Hills: D3, 4                | Hilltops and uplands        | 6                              |
| Plains with Hills: B3b      | Open plains                 | 80                             |
| Tableland: B3c, B4c         | Tablelands, uplands         | 80                             |
| Plains with High Hills: B4d | Plains with relief          | 68                             |

<sup>(a)</sup>Percentage represents an average over the land-surface forms found in the Great Lakes Region.

TABLE 1.3. Classes of Wind Power Density at 10 m and 50 m<sup>(a)</sup>

| Wind Power Class | 10 m (33 ft)                             |                                 | 50 m (164 ft)                            |                                 |
|------------------|--|---------------------------------|--|---------------------------------|
|                  | Wind Power Density, watts/m <sup>2</sup> | Speed, <sup>(b)</sup> m/s (mph) | Wind Power Density, watts/m <sup>2</sup> | Speed, <sup>(b)</sup> m/s (mph) |
| 0                | 0  | 0                               | 0  | 0                               |
| 1                | 100                                      | 4.4 (9.8)                       | 200                                      | 5.6 (12.5)                      |
| 2                | 150                                      | 5.1 (11.5)                      | 300                                      | 6.4 (14.3)                      |
| 3                | 200                                      | 5.6 (12.5)                      | 400                                      | 7.0 (15.7)                      |
| 4                | 250                                      | 6.0 (13.4)                      | 500                                      | 7.5 (16.8)                      |
| 5                | 300                                      | 6.4 (14.3)                      | 600                                      | 8.0 (17.9)                      |
| 6                | 400                                      | 7.0 (15.7)                      | 800                                      | 8.8 (19.7)                      |
| 7                | 1000                                     | 9.4 (21.1)                      | 2000                                     | 11.9 (26.6)                     |

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 1.4. Scheme of Classification

**Slope (1st item)**

- A >80% of area gently sloping
- B 50 to 80% of area gently sloping
- C 20 to 50% of area gently sloping
- D <20% of area gently sloping

**Local Relief (2nd item)**

- 1 0 to 30 m (0 to 100 ft)
- 2 30 to 90 m (100 to 300 ft)
- 3 90 to 150 m (300 to 500 ft)
- 4 150 to 300 m (500 to 1000 ft)
- 5 300 to 900 m (1000 to 3000 ft)
- 6 900 to 1500 m (3000 to 5000 ft)

**Profile Type (3rd item)**

- a >75% of gentle slope is in lowland
- b 50 to 75% of gentle slope is in lowland
- c 50 to 75% of gentle slope is on upland
- d >75% of gentle slope is on upland



## CHAPTER 2: REGIONAL FEATURES

In this chapter, the geography, climate, annual average wind power, and seasonal variations in the wind power are described for the Great Lakes region. Assessments of the wind resource for each state in the Great Lakes region were performed using the methods described in Chapter 1. These assessments were then combined to depict the wind energy potential for the region. Major areas in the Great Lakes region that are estimated to have the greatest wind resource are also described in this chapter.

### 2.1 GEOGRAPHY AND TOPOGRAPHY

The Great Lakes Region, consisting of Illinois, Indiana, Michigan, Ohio, and Wisconsin, covers more than 643,000 km<sup>2</sup> (248,000 mi<sup>2</sup>) and has a total population of 40,252,678. Most of the region's inhabitants live in Illinois, Michigan, and Ohio. The major cities, rivers, mountain ranges, and national parks are shown in Figure 2.1.

**TABLE 2.1.** Land Area and Population of the Great Lakes Region

| State                 | Area            |                    | Population<br>In 1970 | Population<br>Per km <sup>2</sup> (mi <sup>2</sup> ) |
|-----------------------|-----------------|--------------------|-----------------------|--|
|                       | km <sup>2</sup> | (mi <sup>2</sup> ) |                       |  |
| Illinois              | 146,076         | (56,400)           | 11,113,976            | 76.1 (197.0)   |
| Indiana               | 93,993          | (36,291)           | 5,193,669             | 55.2 (143.1)   |
| Michigan              | 150,779         | (58,216)           | 8,875,083             | 58.8 (152.4)   |
| Ohio                  | 106,765         | (41,222)           | 10,652,017            | 99.7 (258.4)   |
| Wisconsin             | 145,465         | (56,164)           | 4,417,933             | 30.3 (78.6)  |
| Great Lakes<br>Region | 643,079         | (248,293)          | 40,252,678            | 62.6 (162.1)   |

The topography of the region, relative to western sections of the United States, is not complex. The entire area is almost all glaciated with terrain ranging from flat in Indiana and Illinois to gently rolling in central and northern Wisconsin. The two exceptions are southeastern Ohio and extreme southwestern Wisconsin where terrain is rugged and unglaciated. Proximity to the Great Lakes results in sandy bluffs and marshes. Glacial lakes are prevalent in Wisconsin and Michigan where the terrain is more hilly (see Figures 2.2 and 2.3). The flat plains found in most of Illinois, Indiana, and parts of central Michigan represent a region most favorably exposed to prevailing winds.

### 2.2 CLIMATE

The climate experienced by the Great Lakes states is generally continental or

modified-continental, where the degree of maritime modification depends on a location's proximity to a lake's shore. The climate in coastal sections of Wisconsin, Michigan, Ohio, and Illinois is typically continental, modified by the maritime influences of the Great Lakes; summers are not as hot and winters not as cold as central regions. Topographical relief is not significant (with the exception of southeastern Ohio), and as such, topography plays less of a role in affecting the climate than, say, in the northwestern United States.

Winters tend to be coldest in northern Wisconsin and along the Upper Peninsula of Michigan. In contrast, the southern coastal cities such as Chicago, Detroit, Cleveland, and Milwaukee have comparatively milder winters because of the tempering influence of the warmer lakes. Even though coastal regions experience warmer winters than the inland sections, the amount of precipitation in the form of snowfall is quite substantial. Heavy snow storms may result when cold, dry polar air intrudes over the warmer water.

Conversely, summers along the lake shores are generally cooler, with the exception of northeastern Illinois and Wisconsin where prevailing westerlies subdue the influences of Lake Michigan. Lake breezes develop from land-water temperature gradients, making summer afternoons somewhat cooler. This lake effect is best seen by comparing the temperatures at two locations (one inland, one coastal) in the same latitude. The mean temperature in July at Madison, Wisconsin, is 22°C (71°F) and 21°C (70°F) at Muskegan, Michigan; the mean January temperatures are -8°C (18°F) and -3°C (26°F), respectively.

There is a moderate meridional variance in precipitation over the Great Lakes region; the annual average precipitation in southern Indiana is 117 cm (46 in.), while in northern Michigan, it is 79 cm (31 in.). The distribution of precipitation reflects latitudinal position, the seasonal storm tracks, and the influence of the Great Lakes. In southeastern Ohio, orographic lifting has some effect on local precipitation.

Michigan experiences one of the largest net snowfalls east of the Rockies. The maximum average annual snowfall is 432 cm (170 in.) in the western region of the Upper Peninsula. The maximum for the Lower Peninsula is

305 cm (120 in.) along the western coast line. Here, prevailing westerlies have a long fetch across the relatively warmer Lake Michigan and arrive over land with much moisture.

### 2.3 WIND POWER IN THE GREAT LAKES REGION

The annual average available wind power density in the Great Lakes region is shown in Figure 2.4. The analyses of mean wind power apply to terrain features that are favorably exposed to the wind, such as hilltops, uplands, and open plains (see Section 1.6). However, nearby terrain features may interact with the wind field to cause the wind power at some exposed sites to vary as much as  $\pm 50$  to 100% from the assessment value. (See Wegley et al. 1980 for information on terrain features that may increase or reduce wind energy.) In forested or wooded areas, the assessment values are representative of large clearings such as airports with good exposure to the prevailing strong winds. The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (Section 1.8).

The high wind resource areas (class 4 or higher) of the Great Lakes region may be distributed over large areas (such as the coastal areas bordering Lakes Michigan, Superior, or Erie), or they can be confined to particular topographic features which enhance the wind speeds (such as the exposed, high hilltops in northern Michigan).

A brief description of the major (class 4 and higher) wind resource areas follows in Section 2.5. For more complete discussion of these wind resource areas, refer to the pertinent state chapter.

#### 2.3.1 Certainty Rating of the Wind Resource

Certainty ratings of the wind power resource were assigned to each grid cell as described in Section 1.9. Maps of the certainty rating in each state accompany the descriptions of that state's wind resource.

The geographical distribution of the certainty ratings ranges from low (1) to high (4). The areas in the Great Lakes region that are assigned high certainty ratings are generally in the flat interior sections, away from the shorelines. These areas include central and north central Illinois, central Indiana, interior sections of the Lower

Peninsula of Michigan, west central Ohio, and south central Wisconsin. A high certainty rating is assigned to these areas because of availability of existing data, low complexity of terrain, and low spatial variability of the wind resource. Most other areas in the Great Lakes region are given certainty ratings of 2 and 3.

#### 2.3.2 Areal Distribution

By superposition of a grid one-third degree longitude by one-quarter degree latitude over the region, the areal distribution of wind power can be computed as described in Section 1.10. Of the 958 grid cells that encompass the Great Lakes region, only 31 have exposed areas with class 4 or higher wind power and these are assigned predominantly to coastal regions along the lake shores.

Table 2.2 summarizes the areal distribution results for the states in the Great Lakes area. The subjectivity underlying the assignment of exposure partitioning and power scaling warrants reporting the area and percentages to only two significant digits (see Section 1.10). Thus, individual areas and percentages may not sum to their stated totals.

Of the four wind power classes, classes 1 and 2 give the highest area contribution. This results, in part, because of the geographic position of Illinois, Indiana, and Ohio relative to the Bermuda High, a semi-permanent weather system characterized by light winds which is typically centered near the southeastern United States. Areas of northern Wisconsin and central Michigan located away from the lake shores have characteristically low wind power because of the generally flat terrain combined with heavy forest cover. In contrast, class 3 and higher areas appear to be confined to coastal regions. The actual area covered by these high wind power classes is small, since the average wind power diminishes rapidly with distance from the shore. This is demonstrated in Figure 2.4 by indicating wind power class 4 over the water. This class designation means that only the immediate coastline is assigned a class 4 wind power and that wind power quickly decreases to class 3 within a few miles inland. The actual breadth of the class 4 region along the coast is difficult to quantify, as it depends largely on local topography and meteorological environment, making it impossible to accurately define a class 4 isopleth.

The class 4 regions in Figure 2.4 occurring along Lake Erie in Ohio, and Lake Michigan on the western coast of the Lower Peninsula, and Lake Superior on the northern coast of Michigan and Wisconsin, reflect not only the data but also the assumption that westerly and north-westerly winds have a long, smooth fetch across the water. The wind speeds recorded at well-exposed coastal stations located on sand bluffs are evidence of the high winds associated with long, smooth fetches.

## 2.4 SEASONAL VARIATIONS IN THE WIND RESOURCE

Throughout the Great Lakes region, winter and spring are the seasons of maximum wind power (see Figure 2.5). Areas with winter maxima include the coast of Lake Erie in northern Ohio, the east coast of Michigan along Lake Huron, and the western shores of the Lower Peninsula bordering Lake Michigan. Although the western shores of Lake Michigan in Wisconsin and Illinois have a winter maximum, there is little difference in wind power between winter and spring. This is probably because the lake breezes are most frequent and well developed during the spring months. This same characteristic is found along the western shoreline of Lake Huron in Michigan with the exception of the northern shores near 45° latitude where a winter maximum is clearly evident. The coastal winter maxima are largely the result of prevailing northwesterlies. In the cases of Lake Superior, Lake Huron, Lake Erie, and the western shores of Lake Michigan, however, eastward-moving storm systems are often associated with strong northeasterly winds.

In spring (March, April, May) the air flow remains quite strong over most of the Great Lakes region, although its strength decreases as spring progresses from March to May. The western half of the Lake Superior shoreline from northern Wisconsin to the Keweenaw Peninsula (Michigan) apparently experiences maximum wind power during this season. This may be due to the increased frequency and intensity of the Alberta track cyclonic storms which affect the northwestern portion of the Great Lakes region. Furthermore, near the lake shores the land-water temperature gradient which peaks in late April or May may contribute to the observed wind power density. The lag between land and water temperature changes results in pressure differentials that in turn sponsor an increase in wind speeds.

In summer (June, July, August) all sections of the Great Lakes experience low wind power. The lake-breeze effect influences coastal areas but is not an important source of wind power.

During the late summer and early autumn cyclonic activity is minimal over the Great Lakes region. Polar airmasses propagating southeastward from central Canada tend to drift more slowly over the east central United States than at other times of the year. These systems can frequently stagnate near the mid-Atlantic coast and/or eventually reinforce the Bermuda High. An area of high pollution potential, centered near southeastern Ohio (as delineated by Holzworth 1972), is a manifestation of the light ventilation winds and subsidence inversions characteristic of these weather systems. Consequently, wind power in southeastern sections of the Great Lakes would be at a minimum during this time.

As autumn progresses, wind speeds increase from September to November as the prevailing winds shift to westerlies. Autumn wind power along the shores is thus higher than summer wind power. In late autumn the middle/upper air wind speeds are not significantly different from those in early spring, and thus, the average wind power on exposed high hilltops is estimated to be in about the same power class in autumn as in the spring.

## 2.5 MAJOR WIND RESOURCE AREAS

Major areas in the Great Lakes region with high annual average wind power (class 4 and above) are briefly described in this section. For additional detail on these areas refer to chapters on the state assessments. For the locations of place names mentioned in this section, refer to the individual state maps (such as Figures 4.1 and 4.4 for Illinois).

### 2.5.1 The Shores of Lake Michigan

The annual average wind power for exposed coastal and offshore areas of western Michigan is estimated to be at least class 4. The abrupt increase in surface roughness just inland from the coastline, because of vegetation and topography, rapidly attenuates the wind resource landward. During winter, the season of maximum wind power for this region, high wind speeds are usually associated with prevailing northwesterlies.

The lake waters, warmer in winter than the surrounding land, can also

contribute to higher wind speeds. As a heat source, the warmer water can intensify cyclones that move out over the lakes; as a destabilizing medium, the warmer water can promote more efficient vertical mixing, resulting in downward transfer of higher momentum.

The western shore of Lake Michigan forms the eastern edge of Wisconsin and has an annual average wind power of class 3. This reduced wind power on the western shore reflects the prevailing westerly winds. Eastward-moving storm systems during the winter and late autumn are responsible for the easterly winds that flow off the lake. Thus, on the annual average, the wind power here is less than on the opposite shore, but still reflects the influence of Lake Michigan. Lake breezes, which are maximized in the spring, also enhance the wind power potential along this shoreline.

#### 2.5.2 Michigan Coastline of Lake Huron

Like the Wisconsin shore of Lake Michigan, the Lake Huron shoreline was assigned a wind power of class 3. Again the average prevailing winds are westerly. In addition to lake breeze effects in spring, during the storm season (late fall through early spring) northeasterly and easterly winds blow off the water. Because the low surface friction of the lake surface does not reduce the wind velocity, the annual average wind speeds along the coast are higher than those in central (inland) sections.

#### 2.5.3 Shoreline of Lake Erie

The coastal region of extreme northern Ohio has an estimated annual wind power of class 4. Northerly winds have a long, smooth fetch across Lake Erie, resulting in powerful winter and spring wind speeds. Exceptions to this are those areas in and around Sandusky Bay where even exposed sites are protected from northwesterly winds by the peninsula to the north. The geometry of the coastline, especially the eastern half, is such that exposed coastal and offshore sites can experience winds from both the northwestern and northeastern quadrants. As a result, high winds are experienced not only when the winds are northwesterly, but also when storms cause northeasterly winds to prevail.

#### 2.5.4 Shoreline of Lake Superior

The shape of the coastline and its exposure to the water are similar in some ways to the situation on the Ohio coast of Lake Erie. The main difference is that the winds impacting the shores of Lake Superior have a much longer fetch across the water. The western half of the coastline and Isle Royale have been assigned an annual average wind power of class 4, while the eastern half is estimated at class 3. The season of maximum wind power for the region from northern Wisconsin eastward to the Keweenaw Peninsula is spring, when the wind power is estimated as class 5. It is important to note that these wind powers are only for exposed sites along the coast and in the Gogebic and Porcupine mountains. The Huron Mountains, southeast of the Keweenaw Peninsula, represent a transition zone between the unsheltered region to the west, and the more-protected, less-exposed area to the east. The annual average class 3 wind power assigned to the Huron Mountains is representative only of the well-exposed sites on the higher elevations and should not be assumed to be indicative of the wind power in sheltered valley locations.

Class 3 wind power is extended east of the Huron Mountains to include offshore sections while the area immediately inland has been assigned class 2 wind power. This lower wind power for the eastern half of the coastline is indicative of the low (and flatter) terrain and extensive forestation. The wind resource of class 3 and higher is rapidly diminished inland because of the increased surface roughness. The difference in wind power between the western and eastern half is a result of the fact that the terrain in the eastern half is much flatter, heavily forested, and poorly exposed to prevailing winds. The western half of the coastline includes the Huron Mountains and part of the Gogebic Range; hilltop sites in these areas will be optimally exposed.



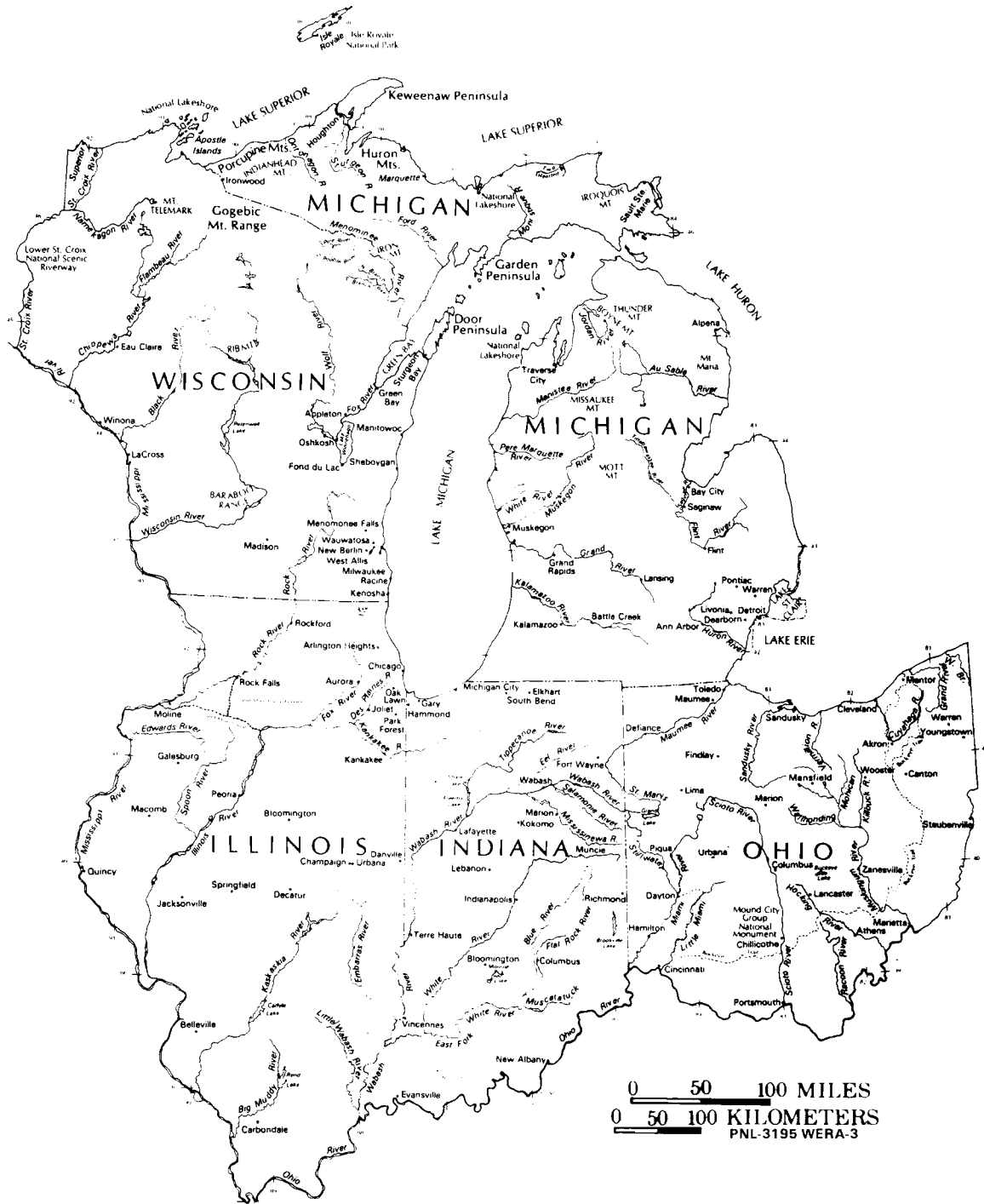


FIGURE 2.1. Geographic Map of the Great Lakes Region



FIGURE 2.2. Topographic Map of the Great Lakes Region

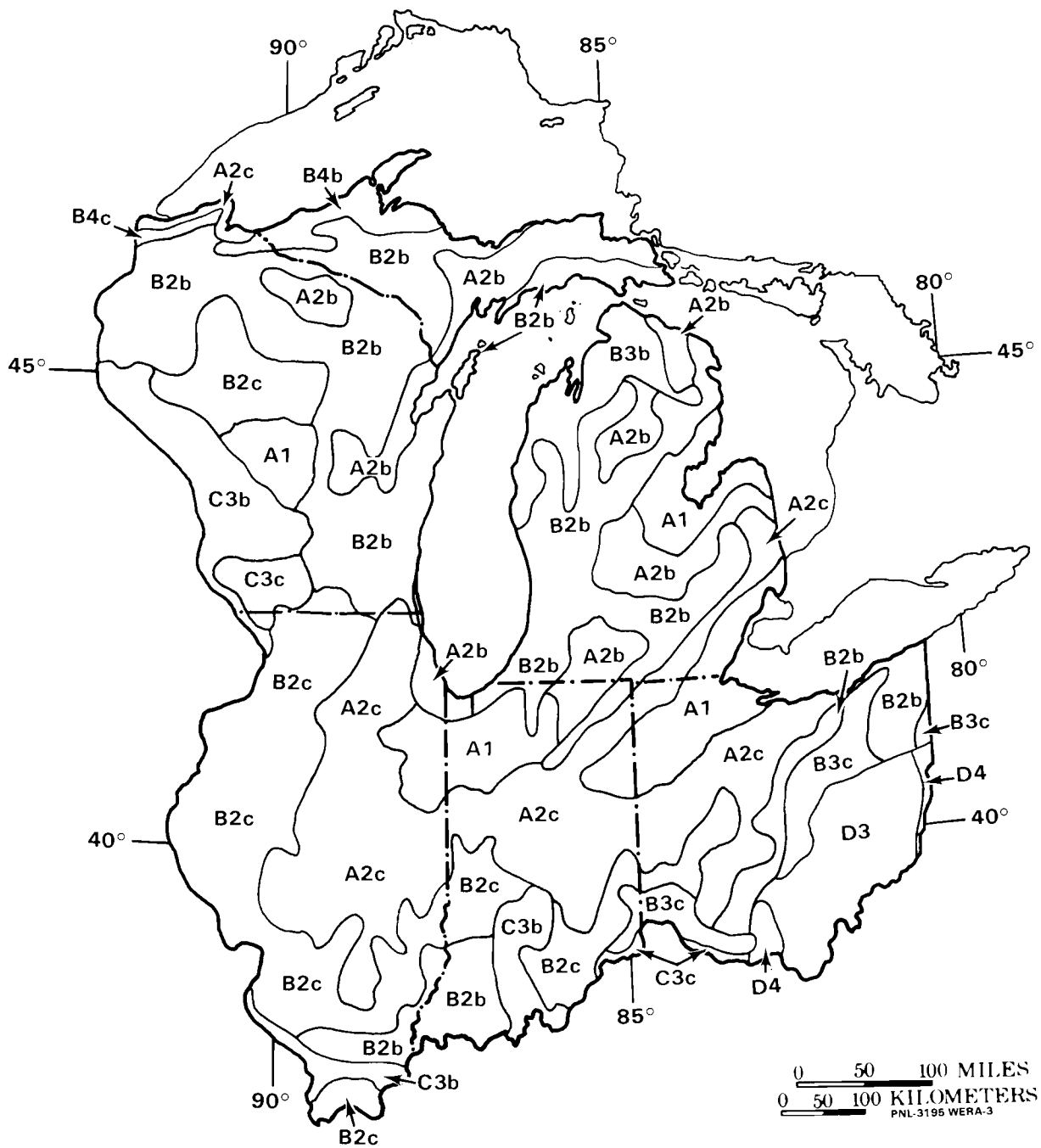


FIGURE 2.3. Classes of Land-Surface Form in the Great Lakes Region

## LAND-SURFACE FORM LEGEND

### PLAINS

|    |                                 |
|----|---------------------------------|
| A1 | FLAT PLAINS                     |
| A2 | SMOOTH PLAINS                   |
| B1 | IRREGULAR PLAINS, SLIGHT RELIEF |
| B2 | IRREGULAR PLAINS                |

### TABLELANDS

|       |                                 |
|-------|---------------------------------|
| B3c,d | TABLELANDS, MODERATE RELIEF     |
| B4c,d | TABLELANDS, CONSIDERABLE RELIEF |
| B5c,d | TABLELANDS, HIGH RELIEF         |
| B6c,d | TABLELANDS, VERY HIGH RELIEF    |

### PLAINS WITH HILLS OR MOUNTAINS

|         |                            |
|---------|----------------------------|
| A,B3a,b | PLAINS WITH HILLS          |
| B4,a,b  | PLAINS WITH HIGH HILLS     |
| B5a,b   | PLAINS WITH LOW MOUNTAINS  |
| B6a,b   | PLAINS WITH HIGH MOUNTAINS |

### SCHEME OF CLASSIFICATION

#### SLOPE (1st LETTER)

|   |                               |
|---|-------------------------------|
| A | >80% OF AREA GENTLY SLOPING   |
| B | 50-80% OF AREA GENTLY SLOPING |
| C | 20-50% OF AREA GENTLY SLOPING |
| D | <20% OF AREA GENTLY SLOPING   |

### OPEN HILLS AND MOUNTAINS

|    |                     |
|----|---------------------|
| C2 | OPEN LOW HILLS      |
| C3 | OPEN HILLS          |
| C4 | OPEN HIGH HILLS     |
| C5 | OPEN LOW MOUNTAINS  |
| C6 | OPEN HIGH MOUNTAINS |

#### LOCAL RELIEF (2nd LETTER)

|   |                                |
|---|--------------------------------|
| 1 | 0 TO 30m (1 TO 100 ft)         |
| 2 | 30 TO 90m (100 TO 300 ft)      |
| 3 | 90 TO 150m (300 TO 500 ft)     |
| 4 | 150 TO 300m (500 TO 1000 ft)   |
| 5 | 300 TO 900m (1000 TO 3000 ft)  |
| 6 | 900 TO 1500m (3000 TO 5000 ft) |

### HILLS AND MOUNTAINS

|    |                |
|----|----------------|
| D3 | HILLS          |
| D4 | HIGH HILLS     |
| D5 | LOW MOUNTAINS  |
| D6 | HIGH MOUNTAINS |

#### PROFILE TYPE (3rd LETTER)

|   |                                      |
|---|--------------------------------------|
| a | >75% OF GENTLE SLOPE IS IN LOWLAND   |
| b | 50-75% OF GENTLE SLOPE IS IN LOWLAND |
| c | 50-75% OF GENTLE SLOPE IS ON UPLAND  |
| d | >75% OF GENTLE SLOPE IS ON UPLAND    |

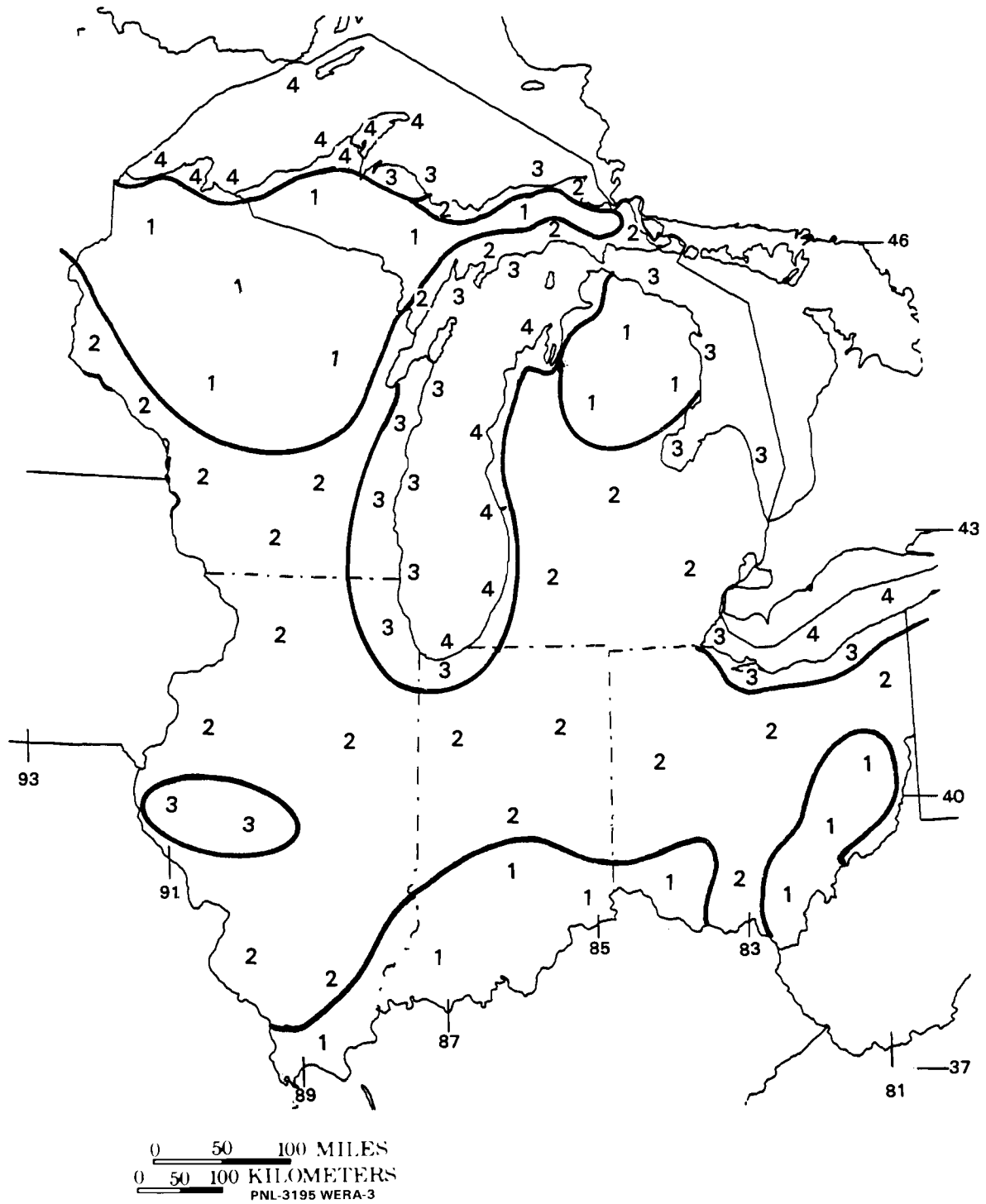


FIGURE 2.4. Annual Average Wind Power in the Great Lakes Region

Classes of Wind Power Density at 10 m and 50 m<sup>(a)</sup>

| Wind Power Class | 10 m (33 ft)                             |                                 | 50 m (164 ft)                            |                                 |
|------------------|--|---------------------------------|--|---------------------------------|
|                  | Wind Power Density, watts/m <sup>2</sup> | Speed, <sup>(b)</sup> m/s (mph) | Wind Power Density, watts/m <sup>2</sup> | Speed, <sup>(b)</sup> m/s (mph) |
| 0                | 0  | 0                               | 0  | 0                               |
| 1                | 100                                      | 4.4 (9.8)                       | 200                                      | 5.6 (12.5)                      |
| 2                | 150                                      | 5.1 (11.5)                      | 300                                      | 6.4 (14.3)                      |
| 3                | 200                                      | 5.6 (12.5)                      | 400                                      | 7.0 (15.7)                      |
| 4                | 250                                      | 6.0 (13.4)                      | 500                                      | 7.5 (16.8)                      |
| 5                | 300                                      | 6.4 (14.3)                      | 600                                      | 8.0 (17.9)                      |
| 6                | 400                                      | 7.0 (15.7)                      | 800                                      | 8.8 (19.7)                      |
| 7                | 1000                                     | 9.4 (21.1)                      | 2000                                     | 11.9 (26.6)                     |

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 2.2. Areal Distribution of Wind Power Classes in the Great Lakes Region

| Power Class | Land Area (km <sup>2</sup> ) Equal to or Exceeding Power Class |          |         |          |        |           |
|-------------|--|----------|---------|----------|--------|-----------|
|             | Great Lakes  | Illinois | Indiana | Michigan | Ohio   | Wisconsin |
| 1           | 593,712  | 137,395  | 86,472  | 135,502  | 99,804 | 134,599   |
| 2           | 318,057  | 106,062  | 42,727  | 88,031   | 50,052 | 31,201    |
| 3           | 62,456   | 16,973   | 2,442   | 24,356   | 7,879  | 10,805    |
| 4           | 8,542  | 0        | 0       | 4,504    | 1,003  | 3,025     |
| 5           | 281  | 0        | 0       | 281      | 0      | 1         |
| 6           | 114  | 0        | 0       | 113      | 0      | 1         |
| 7           | 0  | 0        | 0       | 0        | 0      | 0         |

| Power Class | Percentage Land Area Equal or Exceeding Power Class |          |         |          |      |           |
|-------------|---|----------|---------|----------|------|-----------|
|             | Great Lakes   | Illinois | Indiana | Michigan | Ohio | Wisconsin |
| 1           | 100.  | 100.     | 100.    | 100.     | 100. | 100.      |
| 2           | 53.   | 77.      | 49.     | 65.      | 50.  | 23.       |
| 3           | 10.   | 12.      | 2.8     | 18.      | 8.   | 8.        |
| 4           | 1.4   | 0.0      | 0.0     | 3.3      | 1.   | 2.        |
| 5           | .05   | 0.0      | 0.0     | .21      | 0.0  | 0.0       |
| 6           | .02   | 0.0      | 0.0     | .08      | 0.0  | 0.0       |
| 7           | 0.0   | 0.0      | 0.0     | 0.0      | 0.0  | 0.0       |

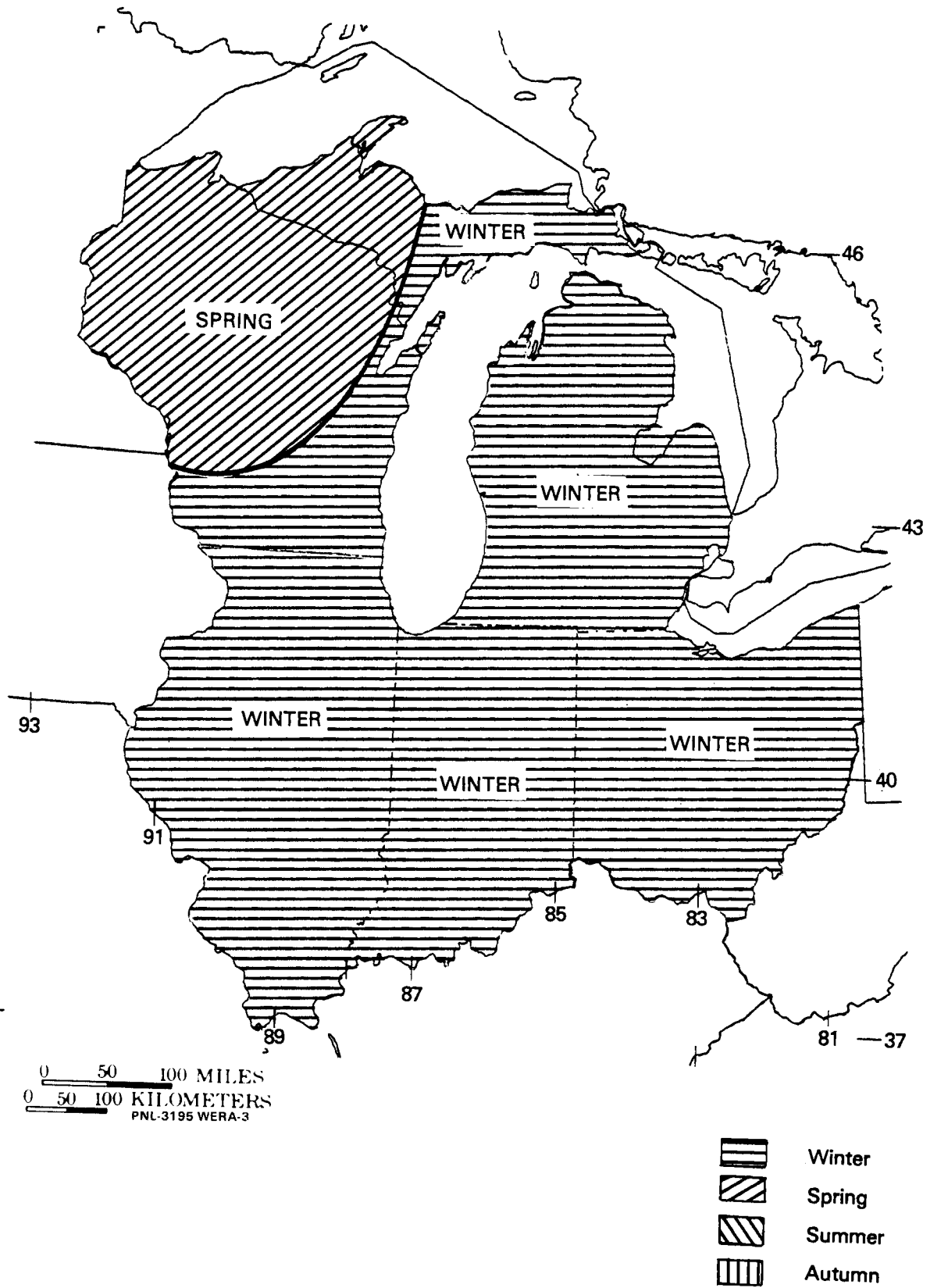


FIGURE 2.5. Seasonal Maximum Wind Power in the Great Lakes Region

CHAPTER 3: STATE FEATURES

The wind resource for each state is described in Chapters 4 through 8. The state descriptions are presented in a consistent format. The text of each description is followed by maps, graphs, and tables that identify features of the geography and the wind energy resource, and that summarize the data collected from the observation stations. The sequence of maps, tables, and graphs used to depict these features is presented in Table 3.1. In the state descriptions, these illustrations are presented so that related information is on facing pages and can be reviewed simultaneously.

To avoid repetition in the following chapters, the general format and content of the various maps, tables, and graphs used to describe the wind resource for each state are summarized here.

3.1 MAPS OF STATE FEATURES

The maps of cultural geography show the locations of major cities, rivers and terrain features for each state. The maps of shaded topographic relief of Ohio and Wisconsin are reproductions of the 1:500,000 scale U.S. Geological Survey maps, whereas the relief maps of Illinois, Indiana, and Michigan are reproductions from plates in the National Atlas of the United States of America. The land-surface form maps are constructed from Hammond's map of land-surface form classes (Hammond, 1964). This is also shown at a scale of 1:17,000,000 on Plate 62 in the National Atlas of the United States. The use of the land-surface form map was described in Section 1.8.

Two maps are used to show the locations of stations with wind data. The first map gives the locations and names of the NCC stations with wind data in any form. The other map shows the location of NCC and other data stations that were used in this assessment of the wind resource.

The maps of annual average wind power are accompanied by maps of the certainty ratings by grid cell for the annual average wind power estimates, and by maps of the areal distribution by grid cell of the wind resource. The certainty rating, which ranges from 1 (low) to 4 (high), indicates the level of confidence in the estimates of the wind resource in each cell of the grid. The certainty rating is based on the availability of wind data, the complexity of the terrain, and the inherent geographical variability of the wind resource (see Section 1.9). The maps of areal distribution give the percentages of land area in each cell estimated to experience annual average wind power equal to or greater than wind power classes 2, 3, 4, and 5 (see Section 1.10).

Maps of the average wind power are presented for each season: winter (December, January, February); spring (March, April, May); summer (June, July, August); and autumn (September, October, November). The legend for the power classes is found on the annual average wind power map.

TABLE 3.1. Maps, Tables and Graphs Used to Depict the Wind Resource

| <b>Maps</b>  |  |
|--|--|
| Left Hand  | Right Hand   |
| Cultural Geography<br>Land-Surface Form<br>NCC Station Locations<br>Annual Average Wind Power<br><br>Certainty Rating<br>Areal Distribution (Power Classes 2 & 3)<br>Seasonal Average Wind Power<br>(Winter, Summer) | Topographic Shaded Relief<br>Legend to Land-Surface Form<br>Location of Stations Used in Wind Assessment<br>Legend to Wind Power Classes and Table on Areal Distribution<br>Legend for Certainty Rating<br>Areal Distribution (Power Classes 4 & 5)<br>Seasonal Average Wind Power<br>(Spring, Autumn) |
| <b>Graphs</b>  |  |
| Summary Table of Selected Stations<br>Monthly Speed and Power<br>Directional Frequency<br>Speed Duration   | Interannual Speed and Power<br>Diurnal Speed<br>Speed Frequency<br>Power Duration  |

### 3.2 FEATURES OF SELECTED STATIONS

The analysis of the wind resource by state and by region depends on information from individual stations. For those stations with one- or three-hourly data on NCC magnetic tapes, a detailed analysis of the temporal variation and character of the wind resource can be obtained. Graphs portraying various features of the wind resource have been printed for selected stations in each state and are presented in the state chapters. For each station presented, a brief description of the station's topographical setting and unique features is given in the text preceding the maps and graphs. The geographical area represented by a station varies, depending on the complexity of the local terrain and the variability of the wind resource.

A table listing the stations for which graphs and summaries of the features of the wind resource are presented precedes the series of graphs. Height adjustments were made only to obtain estimates of the average wind speed and power at 10 m and 50 m. None of the other wind characteristics (e.g., diurnal wind speed, wind direction, speed and power duration, etc.) presented in the graphs for selected stations were adjusted to reference height. Caution should therefore be used in comparing and interpreting station graphs.

In the plots of interannual wind power and speed, the first line of each graph contains the station name and state. The second line contains the WBAN number. In all other plots, the first line on each station graph contains the station identification that corresponds to the name and location listed in the table and the month and year of the selected period of record. Only one period of record with constant anemometer height was plotted for most stations, even though some stations had several periods of record. However, if there was uncertainty as to which period had better anemometer exposure or if two periods with similar exposure indicated substantially different wind characteristics, two periods of record were plotted. Usually, periods when the anemometer was located on a mast directly on the ground were preferred to periods when the anemometer was located on the roof of a building.

The second line of each station graph contains the WBAN number, the anemometer height (Z) in m and location, and the annual average wind speed (V) in

m/s and wind power (P) in watts/m<sup>2</sup>. V and P are adjusted to 10 m for the graphs of interannual and monthly average wind power and speed and are at anemometer height, Z, for all other graphs.

The coded information listed with the anemometer height is one of the following (Changery 1978):

- R - indicates the anemometer was located on the roof of a control tower, operations building, hangar or other similar structure. Mast heights were normally 2 to 4 m (6 to 12 ft) above roof line; however, at many inner-city locations, masts were considerably taller. The listed height is elevation above ground level, not roof level; the "R" indicates a rooftop exposure.
- G - indicates the anemometer was located on a mast attached directly to the ground. Most anemometers at airport locations were changed from roof to ground exposure by the early 1960s.
- B - indicates a beacon tower exposure. For these locations, neither R nor G was considered satisfactory.
- UNK - indicates that documentation on instrument heights was not available.

If information on exposure was unavailable, no exposure code is given.

On a few station plots, an E follows the annual average wind power. If a pressure or temperature observation is missing, the wind power for that observation is computed using an air density based on station elevation. If the number of missing observations exceeds 25% of the total, then an E is used to designate that the wind power is an estimated value.

To allow for station-to-station comparisons, as many as 18 graphs of the same type may appear on one page. The scale of each set of plots was determined by the maximum range of values found for all stations in the region.

#### 3.2.1 Interannual Wind Power and Speed

The plots of interannual wind speed and power portray the variations of the yearly average over all periods of record. The beginning and ending of each period of record with constant anemometer height and location are designated by a

"plus" symbol on the wind power curve and by a "diamond" symbol on the wind speed curve. If the anemometer height was unknown, a height of 10 m was assumed. Only yearly mean wind speeds based on 12 months' data (January through December) were plotted.

Year-to-year deviations from the long-term annual average may not be a reliable indicator of the deviations at nearby sites or areas (Elliott 1979b).

### 3.2.2 Monthly Average Wind Power and Speed

Graphs of the monthly average wind power and wind speed portray the monthly and seasonal trends of the wind. Stations with less than five years of observations may not show reliable seasonal trends. Also, stations in complex terrain may not represent the trends in nearby areas because of the influence of nearby terrain. Most of the wind power station curves are less than or equal to 400 watts/m<sup>2</sup>.

### 3.2.3 Diurnal Wind Speed by Season

The diurnal variation in seasonal wind speed is plotted in four curves, one for each season. Local standard time (LST) is used (hour 24 = midnight). For National Weather Service and Federal Aviation Administration stations, the diurnal curves are based on 24 observations daily for periods ending before 1965, and on 8 observations daily for periods ending after 1964. For Air Force stations the diurnal curves are usually based on 24 observations daily regardless of the period. The diurnal curves for Navy stations are based on 24 observations daily for periods ending before March 1972 and on 8 observations daily for periods ending after February 1972.

### 3.2.4 Directional Frequency and Average Speed

Graphs of the annual average frequency of occurrence show the percentage of time that the observed winds were directed from each of the 16-point sectors of the compass and the average wind speed of all observations in

each sector. Some stations show a definite bias toward 8-point compass observations. The coincidence of peaks in the two curves indicates that the highest wind speeds occur from the prevailing directions. Caution should be used in applying these data to other sites, because nearby terrain and obstructions strongly influence the wind directions. Some of the directional data presented may not be reliable or representative because of the anemometer location.

### 3.2.5 Annual Average Wind Speed Frequency

Graphs of the annual average frequency of observed wind speeds are shown in 1 m/s intervals about each whole m/s wind speed. Together with the observed distribution. These peaks reflect observer bias toward certain wind mean speed is also shown. Some of the stations show pronounced peaks in the observed distribution; these peaks reflect observer bias toward certain wind speeds, such as 2, 5, and 8 m/s (5, 10, and 15 knots). This bias occurs more frequently in records prior to 1960. Because many of the wind instruments used had a threshold velocity of about 1.5 m/s (3 knots), the frequency of observations in the 1 m/s class is often lower than the frequencies of the 'calm' and the 2 m/s wind classes.

### 3.2.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in two sets of graphs. Abrupt changes in the slope of the duration curves for speed and power usually correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity. Points are plotted at 1 m/s intervals for the speed duration curves. Points are plotted every 50 watts/m<sup>2</sup> up to 500 watts/m<sup>2</sup> and every 100 watts/m<sup>2</sup> up to 1,000 watts/m<sup>2</sup> in the power duration curves.



**ILLINOIS**

Illinois covers an area of 146,076 km<sup>2</sup> (56,400 mi<sup>2</sup>) and had, in 1970, a population of 11,113,976. Approximately one-half of its residents live in the Chicago area or surrounding communities in the extreme northeast of the state (see Figure 4.1).

Almost the entire state is flat with little significant relief (Figure 4.2). Some low hills can be found in extreme southern Illinois, and a small unglaciated area exists in the northwestern part of the state (Figure 4.3). These regions are not considered to have any important influence on the local climate of the state. Overall, Illinois is characterized by a typically continental climate except for the small region bordering Lake Michigan where the climate is slightly modified to maritime-continental. Prevailing westerlies and eastward-moving storm systems are the dominant influence on the weather; the influence of Lake Michigan is not extensive.

Sources of wind data are generally abundant throughout the state, especially in the Chicago area (Figure 4.4), but somewhat sparse in the central western sections. The presence of six nuclear power plants in the northern half of the state provided wind data in areas where no National Climatic Center (NCC) data were recorded. Most of the NCC data in southern sections are unsummarized (see Figure 4.5).

#### 4.1 ANNUAL AVERAGE WIND POWER

The annual average available wind power density in Illinois is shown in Figure 4.6. The analyses of mean wind power apply to terrain features that are favorably exposed to the wind, such as hilltops, uplands and open plains (see Section 1.6). However, nearby terrain features may interact with the wind field to cause the wind power at some exposed sites to vary as much as  $\pm 50$  to 100% from the assessment value. (See Wegley et al. 1980 for information on terrain features that may increase or reduce wind energy.) In forested or wooded areas, the estimates are representative of large clearings with good exposure to the prevailing strong winds, such as airports, where runways are generally aligned parallel to the prevailing wind direction(s). The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (Section 1.8).

The annual average wind power is almost uniform over the entire state, except for a region of wind power class 3 along the coast of Lake Michigan and another in the central western part of Illinois. Most of the state is flat and thus well exposed to the prevailing strong winds. However, in areas of rolling terrain or low hills, some wind sheltering may occur. Because of the low relief, there is little possibility of enhancement of wind speeds by topography. Prevailing winds are southerly at most of the stations examined, although westerly and northerly winds also occur quite frequently. Figure 4.13 shows southerly as the prevailing direction at most stations in both northern and southern Illinois.

The west-central region in Illinois apparently experiences higher wind power than the surrounding area of the same landform. The origin of this anomaly in the wind power distribution is undetermined. High values of wind speed and power are probably the result of exceptionally good exposure at the data stations. This area of potentially high wind power is denoted in Figure 4.6 by an isopleth of class 3 wind power.

The band of class 3 wind power in the northeastern part of Illinois reflects the strong winds blowing off Lake Michigan when eastward-moving storm systems cause the winds to shift to the northeast and east. Such winds have a long, smooth fetch across the water and arrive at the coast with substantial speeds. The inland intrusion of class 3 wind power in northeast Illinois also reflects the very smooth terrain. Air passing over areas of such low roughness experiences less of a frictional drag than it would over rougher terrain. The actual area covered by this power class is not assumed to be accurately delineated by the isopleth in Figure 4.6; rather, it serves to indicate, in a general manner only, the higher wind power potential that results from strong winds blowing off Lake Michigan. Exposed coastal and offshore sites, e.g., open shorelines that are not sheltered from the prevailing winds, are estimated to have at least class 3 wind power. The abrupt increase of surface roughness (because of vegetation and buildings inland from the coastline) rapidly attenuates the wind resource landward of the coastline. However, class 3 wind power may extend inland 16 to 24 km (10 to 15 mi) especially at 50 m and greater heights where the attenuation due to roughness is less.

The small area of class 1 wind power in extreme southern Illinois is largely due to the climatology of the area: eastward-moving storm systems in winter and early spring pass more frequently across northern and central sections than across southern sections.

#### 4.1.1 Certainty Rating of the Wind Resource

The wind power estimates for much of Illinois have been assigned certainty ratings of 3 or 4 (see Figure 4.7) because of the availability of existing data and the low complexity of terrain (smooth or irregular plains). However, the coastal area in northwestern Illinois has a certainty rating of only 2, because the wind power resource along the immediate coastline is highly variable and few well-exposed data stations are found along the coast.

Other areas of the state have certainty ratings of 2, largely due to the absence of data. In some cases, data stations were present but had unknown or undetermined exposures.

#### 4.1.2 Areal Distribution

The areal distribution of wind power in Illinois is illustrated in Figure 4.8. The numbers identify the percentage area in each cell of the grid in which the wind power equals or exceeds some threshold value. Table 4.1 illustrates that only a small percentage (<20%) of Illinois has a wind power class of 3 or higher. Thus, the maps of areal distribution are rather featureless for wind power class 4 or higher. In the area of class 3 wind power along the coast of Lake Michigan in the northeastern corner of the state, the grid boxes have a high percentage area of class 3 wind power. Except for the extreme southern section, almost every grid cell in the state has a significant fraction of area with class 2 wind power.

### 4.2 SEASONAL WIND POWER

Wind power maps for each season are shown in Figure 4.9. Over most of Illinois, the season of maximum wind power is generally the winter. Winter storms tend to be more intense because the temperature and pressure gradients are stronger during this season. However, spring wind power is almost as great as winter wind power throughout most of the state and is generally of the same power class. Summer is the season of lowest wind power everywhere in the state. Eastward-moving storm systems frequently occur during winter and spring and give rise to strong westerly winds.

In the summer, the storm tracks tend to be further north, and the winds are much weaker.

#### 4.2.1 Winter

During the winter, wind power throughout most of Illinois is at its highest. Winds are principally controlled by eastwardly and northeastwardly moving storm systems. The coastal band of class 3 wind power seen in the annual average is larger in winter and covers more than half the state. In Figure 4.9, wind power class 4 is shown offshore in Lake Michigan; this indicates a very narrow area within which an exposed coastal or offshore site could experience wind power of 200 to 250 watts/m<sup>2</sup> at 10 m. Sites a few miles inland have been estimated to experience lower wind power (class 3) due to increased surface roughness. Additionally, during the winter, winds are off the lake for only about 12% to 15% of the time, so that the winds over the Chicago area are mostly from the west-northwest. The area in west-central Illinois with anomalously high wind power, discussed in Section 4.1, is denoted by an isopleth of class 4.

#### 4.2.2 Spring

The distribution of spring wind power classes is almost identical to that in the winter. Prevailing winds are generally westerly and southerly. Class 3 wind power occurs over most of the state, except for the southern part. As in winter, class 4 wind power is estimated for the exposed coastal areas along Lake Michigan. Northeasterlies occur approximately 25% of the time during the spring, making the influence of Lake Michigan more important in this season.

#### 4.2.3 Summer

In summer, wind power is only class 1 and 2 over the entire state. The band of class 2 wind power indicates the lake-breeze effect. Even near Lake Michigan, none of the stations indicate over 100 W/m<sup>2</sup> (class 1) during summer.

#### 4.2.4 Autumn

In autumn, wind power in Illinois increases over the whole state from September to November, as the storm tracks move southward and upper-air wind speeds intensify. The shifting of storm paths is reflected in the class 2 region of wind power in northern and central sections. Exposed coastal areas along Lake Michigan are estimated to have class 3 wind power.

### 4.3 FEATURES OF SELECTED STATIONS

Table 4.2 gives the location and annual wind speed and power density of 14 stations in Illinois. Other features of the wind resource at these stations are graphed in Figures 4.10 to 4.16. All of these stations are in northern and central sections; none are below 38.5° lat. For Moline, Springfield, and Chicago/Midway, two periods of record are presented.

Scott Air Force Base (AFB), at Belleville in the southern third of the state, is located in an area of plains with small hills. The relatively low wind speeds that are recorded appear to indicate questionable exposure. This site experiences significantly lower wind power than nearby St. Louis WBAS and Vandalia.

Bradford/Rinkenberger Airport is situated in the north central part of Illinois. The surrounding terrain is characterized by rolling hills and exposure appears to be good.

Chicago/Midway Airport is located approximately 13 km (8 mi) from Lake Michigan and is within the urban Chicago area. From one period of record to the other, the anemometer was moved from a rooftop location to a ground mast. The ground mast location, although lower, is usually better exposed than the rooftop. Generally, exposure seems quite good.

Chicago/O'Hare International Airport like Midway Airport is situated inland from Lake Michigan in the Chicago metropolitan area. Exposure is apparently good, but it is likely that observed wind speeds are lower here than those at a site directly on the coast or offshore.

Effingham is in the south central part of Illinois. Tributaries of the Little Wabash River dissect the plains, producing gently rolling terrain to the south and flatter terrain to the north. Only one year of data exists for this site. However the exposure seems good, and the year of data is assumed representative.

Glenview is situated north of Chicago within 8 km (5 mi) of Lake Michigan. Terrain is flat and the surrounding area is urban. This site experiences lower wind power than Midway and O'Hare airports, suggesting questionable anemometer exposure.

Joliet Municipal Airport in the northern third of the state is about 56 km (36 mi) south-southwest of Chicago. The terrain is smooth. This site appears to be representative of the area although the frequency distribution indicates strong observer bias in the wind measurements.

Moline/Quad-City Airport is located on the banks of the Rock River, in a valley some 10 to 13 km (6 to 8 mi) upstream from the Mississippi River. Several miles to the south, small hills exist, defining the limits to the valley floor. Exposure is estimated to be good.

Greater Peoria Airport in the north central part of the state is situated in the broad Illinois River valley. The terrain is mostly plains, and the exposure (especially to southerly winds) is quite good.

Quincy/Baldwin Field is located on a flat plain in the extreme western part of the state. It appears to be well exposed and was considered well representative of the northwestern area in Illinois.

Rantoul/Chanute AFB is located in the east central part of Illinois. Terrain is characterized by plains with gently rolling hills. The low wind speeds observed indicate questionable anemometer exposure.

Rockford Airport is situated near the Wisconsin border on the north side of the Rock River valley. The terrain is rolling plains, and the site is very well exposed to southwesterly and northeasterly winds.

Springfield/Capitol Airport is in the central part of the state. The terrain is flat plains, and from the data, exposure appears to be excellent.

Vandalia is on a smooth plain in the south-central part of Illinois. It appears to be very well exposed to prevailing winds and is representative of the area in which it is situated.

#### 4.3.1 Interannual Wind Power and Speed

As Figure 4.10 shows there is little interannual variation in wind power or speed. The two Chicago airport stations do not show much similarity (although they are both about the same distance from the coast), probably because of differences in exposure. It is surprising that the

Glenview station, situated very close to the shoreline, experiences lower wind power over the period of record than either of the Chicago stations. Of the eight stations with 10 or more continuous years of record with constant anemometer height, the smallest interannual variation occurs at Belleville - a 1.7 ratio of highest to lowest wind power. The largest variation appears to be that for O'Hare International Airport, with a ratio of about 2.0.

#### 4.3.2 Monthly Average Wind Power and Speed

Except for Effingham, Moline, and Rockford, most of the stations show maximum wind power in March (see Figure 4.11). Chicago/Midway, O'Hare, and Glenview display a very slight increase in wind power in April, as do all other stations in northern Illinois, except for Bradford. Although the peak monthly average wind power generally occurs during the spring season in Illinois, the rapid decrease in power from April to May reduces the seasonal average to below that of winter. The high values of wind power in winter for stations closer to the coast are partially attributable to northeasterly winds which sweep inland after passing over the lake.

In all cases, summer is the season of minimum wind power. The autumnal increase in wind speed seen for each station reflects the building land-water temperature gradient and the intensifying storm systems which cross the state.

#### 4.3.3 Diurnal Wind Speed by Season

Stations in Illinois generally have the highest wind speeds from mid-morning to mid-afternoon, 1100 to 1700 local standard time (LST) (Figure 4.12). Peak winds occur around 1500 during spring and summer and around 1400 in the winter. The greatest diurnal variations generally occur in summer and the least in winter. This mid-day increase in wind speeds is due to the destabilizing effect of solar radiation as the sun rises in the sky.

#### 4.3.4 Directional Frequency and Average Speed

In the absence of any significant topography, the directional frequency of the prevailing winds is largely determined by the synoptic weather

patterns (Figure 4.13). Located along the western edge of the Bermuda High, Illinois is open to southerly winds that are a climatological response to the anticyclonic (clockwise) circulation around that system. During the winter and early spring months cyclonic storm development frequently occurs in the lee of the Rocky Mountains. This phenomenon acts to reinforce the southerly component of the winds over Illinois.

Whereas the most frequent winds are generally from the south, they are not necessarily the strongest prevailing winds. Figure 4.13 shows that the strongest winds are from the northwest quadrant. This northwesterly flow is attributable to the intensification of winter storms as they track northeastward through the Midwest. The relatively warm water of the Great Lakes area can contribute to the intensification process of these storms. As a consequence, winter storms reach peak maturity just east of Illinois, and the northern sections of the state are positioned in a post-frontal orientation. This type of configuration results in winds originating from the northwest quadrant. Glenview and the two Chicago stations are sites where the strongest winds flow from the northeast. This is to be expected since the winds off the lake have a long fetch across the smoother lake surface. The reduced frictional surface drag results in more powerful winds.

#### 4.3.5 Annual Average Wind Speed Frequency

Because observer bias and low instrument threshold speeds may distort the observed frequency distribution (Figure 4.14), the representativeness of the Rayleigh speed distribution is hard to evaluate. Observer biases are apparent in the frequency distributions for Belleville, Effingham, Glenville, Joliet, Quincy, and Vandalia.

#### 4.3.6 Annual Average Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in Figure 4.15 and 4.16. Abrupt changes in the slope of duration curves correspond to peaks in the speed frequency distribution caused by observer bias and by instrument threshold velocity.





FIGURE 4.1. Geographic Map of Illinois

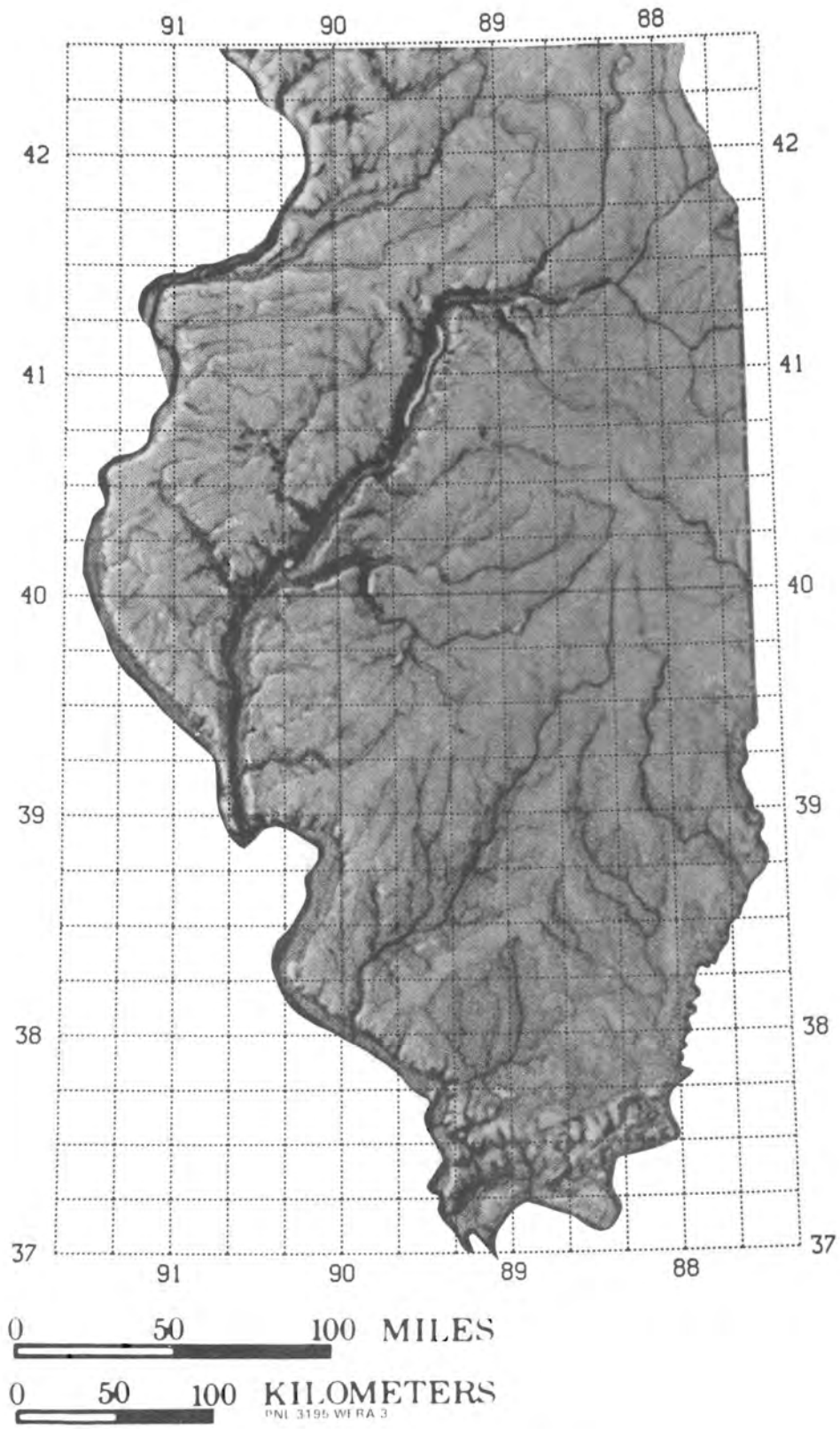


FIGURE 4.2. Topographic Map of Illinois

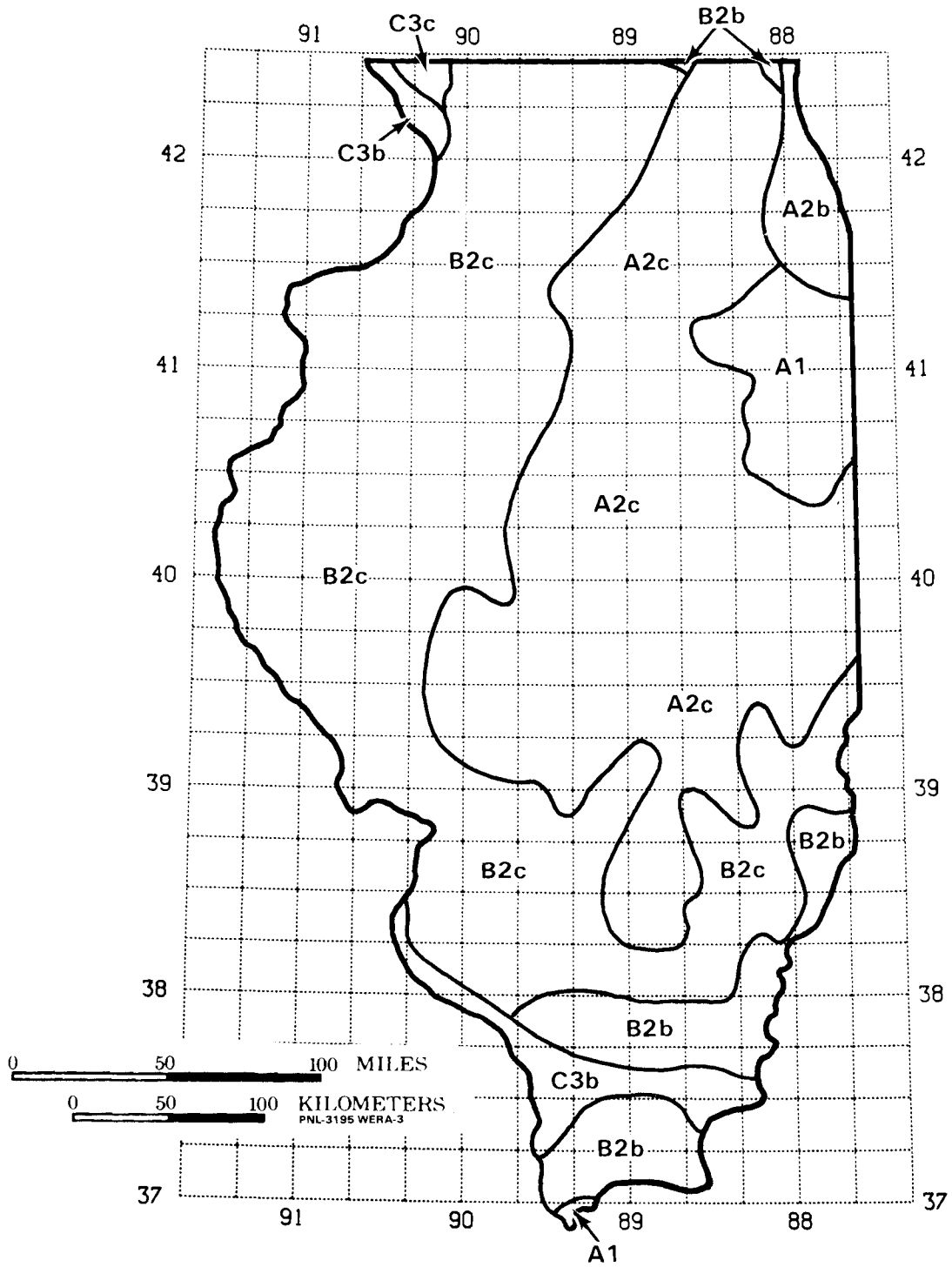


FIGURE 4.3. Classes of Land-Surface Form in Illinois

## LAND-SURFACE FORM LEGEND

### PLAINS

|    |                                 |
|----|---------------------------------|
| A1 | FLAT PLAINS                     |
| A2 | SMOOTH PLAINS                   |
| B1 | IRREGULAR PLAINS, SLIGHT RELIEF |
| B2 | IRREGULAR PLAINS                |

### TABLELANDS

|       |                                 |
|-------|---------------------------------|
| B3c,d | TABLELANDS, MODERATE RELIEF     |
| B4c,d | TABLELANDS, CONSIDERABLE RELIEF |
| B5c,d | TABLELANDS, HIGH RELIEF         |
| B6c,d | TABLELANDS, VERY HIGH RELIEF    |

### PLAINS WITH HILLS OR MOUNTAINS

|          |                            |
|----------|----------------------------|
| A, B3a,b | PLAINS WITH HILLS          |
| B4, a,b  | PLAINS WITH HIGH HILLS     |
| B5a,b    | PLAINS WITH LOW MOUNTAINS  |
| B6a,b    | PLAINS WITH HIGH MOUNTAINS |

### SCHEME OF CLASSIFICATION

#### SLOPE (1st LETTER)

|   |                               |
|---|-------------------------------|
| A | >80% OF AREA GENTLY SLOPING   |
| B | 50-80% OF AREA GENTLY SLOPING |
| C | 20-50% OF AREA GENTLY SLOPING |
| D | <20% OF AREA GENTLY SLOPING   |

### OPEN HILLS AND MOUNTAINS

|    |                     |
|----|---------------------|
| C2 | OPEN LOW HILLS      |
| C3 | OPEN HILLS          |
| C4 | OPEN HIGH HILLS     |
| C5 | OPEN LOW MOUNTAINS  |
| C6 | OPEN HIGH MOUNTAINS |

#### LOCAL RELIEF (2nd LETTER)

|   |                                |
|---|--------------------------------|
| 1 | 0 TO 30m (1 TO 100 ft)         |
| 2 | 30 TO 90m (100 TO 300 ft)      |
| 3 | 90 TO 150m (300 TO 500 ft)     |
| 4 | 150 TO 300m (500 TO 1000 ft)   |
| 5 | 300 TO 900m (1000 TO 3000 ft)  |
| 6 | 900 TO 1500m (3000 TO 5000 ft) |

### HILLS AND MOUNTAINS

|    |                |
|----|----------------|
| D3 | HILLS          |
| D4 | HIGH HILLS     |
| D5 | LOW MOUNTAINS  |
| D6 | HIGH MOUNTAINS |

#### PROFILE TYPE (3rd LETTER)

|   |                                      |
|---|--------------------------------------|
| a | >75% OF GENTLE SLOPE IS IN LOWLAND   |
| b | 50-75% OF GENTLE SLOPE IS IN LOWLAND |
| c | 50-75% OF GENTLE SLOPE IS ON UPLAND  |
| d | >75% OF GENTLE SLOPE IS ON UPLAND    |

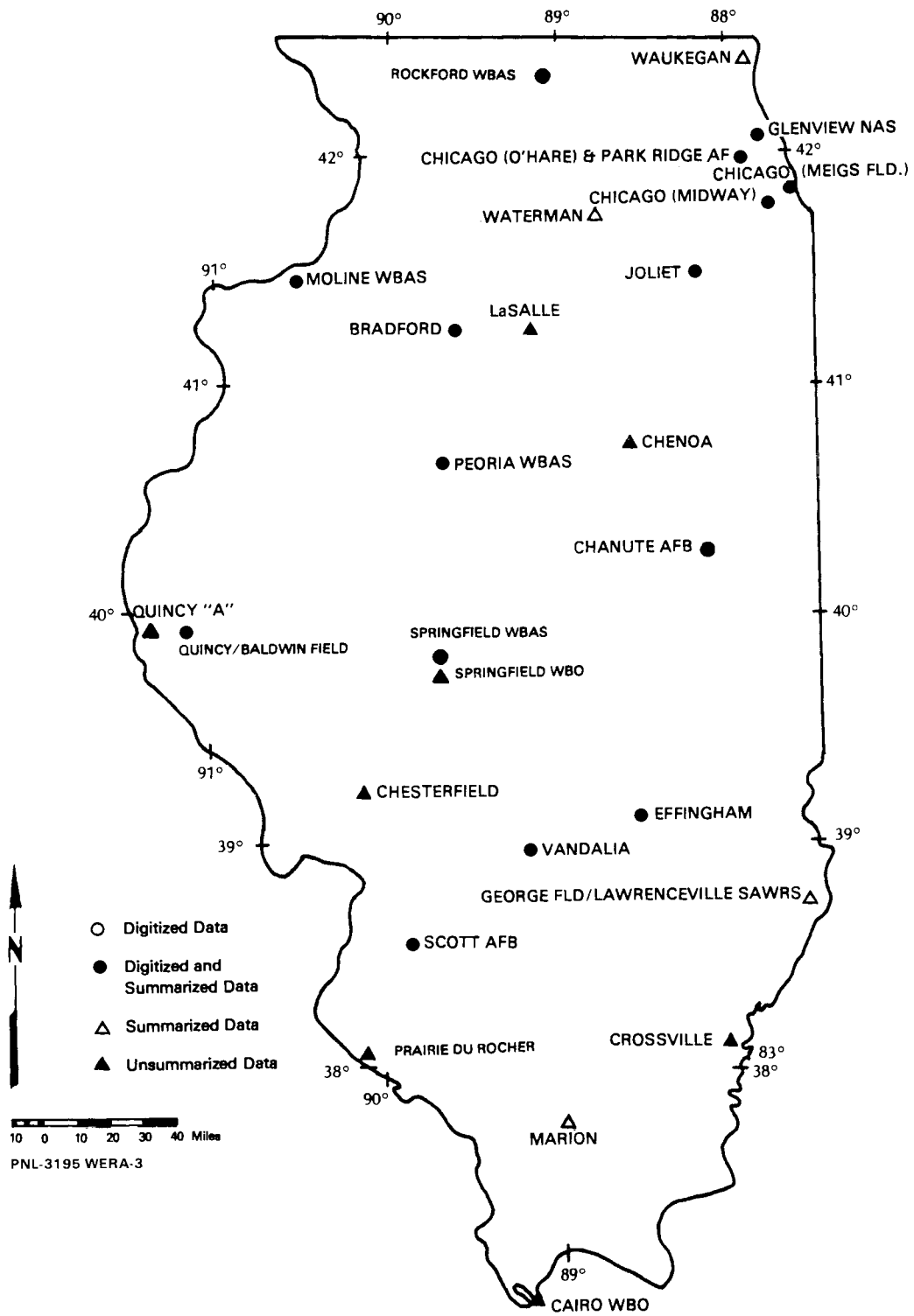


FIGURE 4.4. NCC Station Locations in Illinois

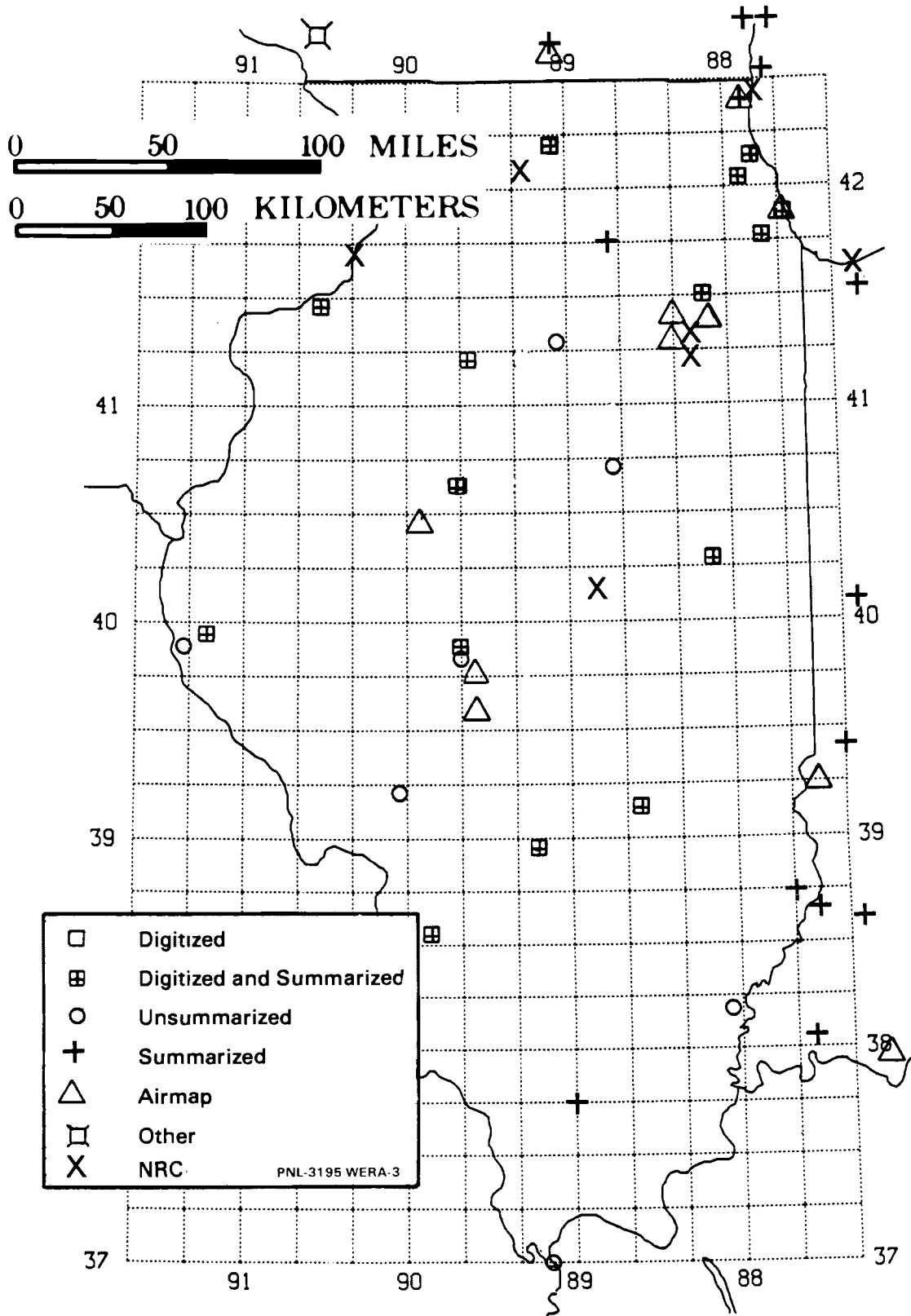


FIGURE 4.5. Location of Stations Used in Illinois Resource Assessment†

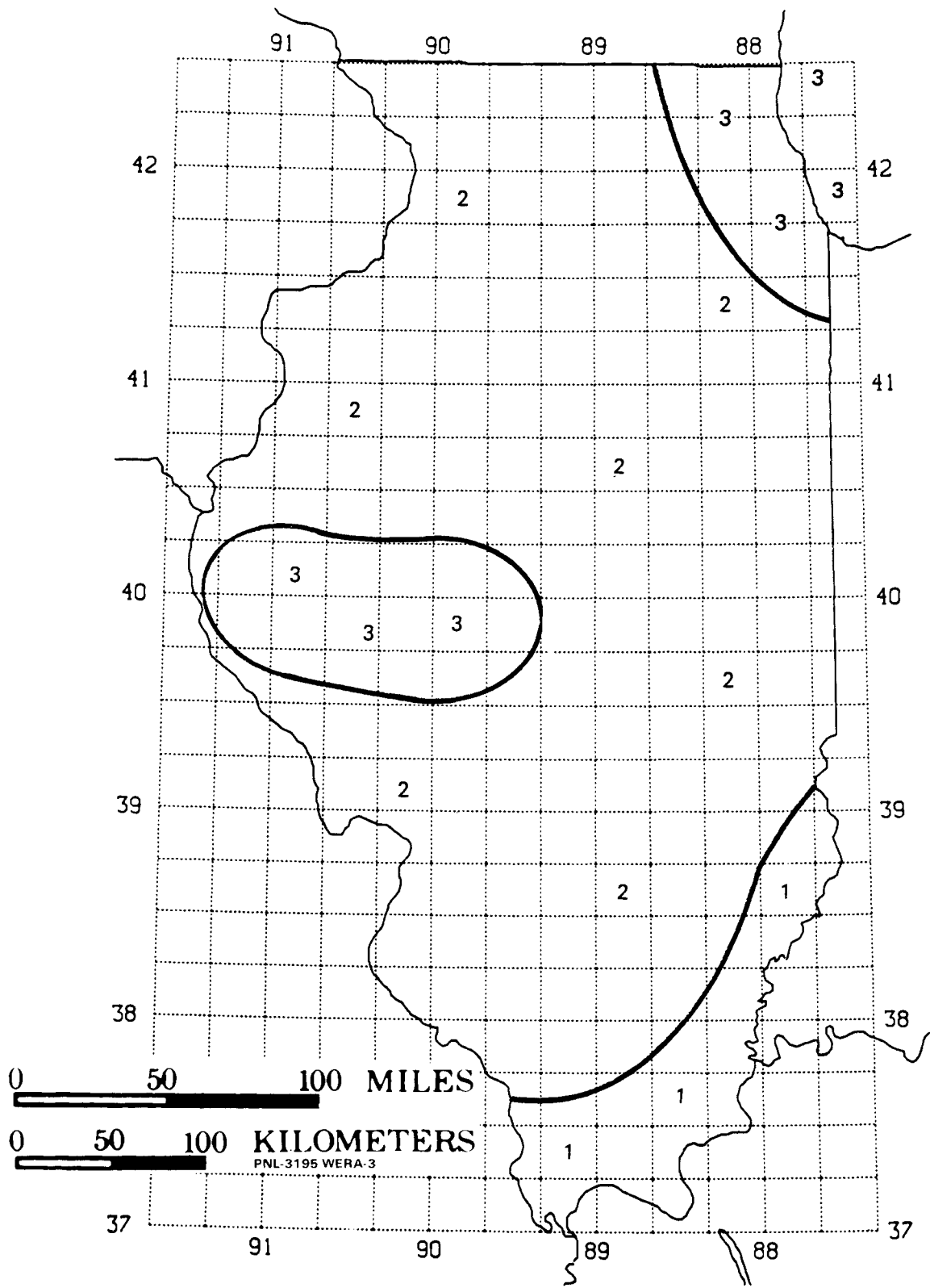


FIGURE 4.6. Illinois Annual Average Wind Power

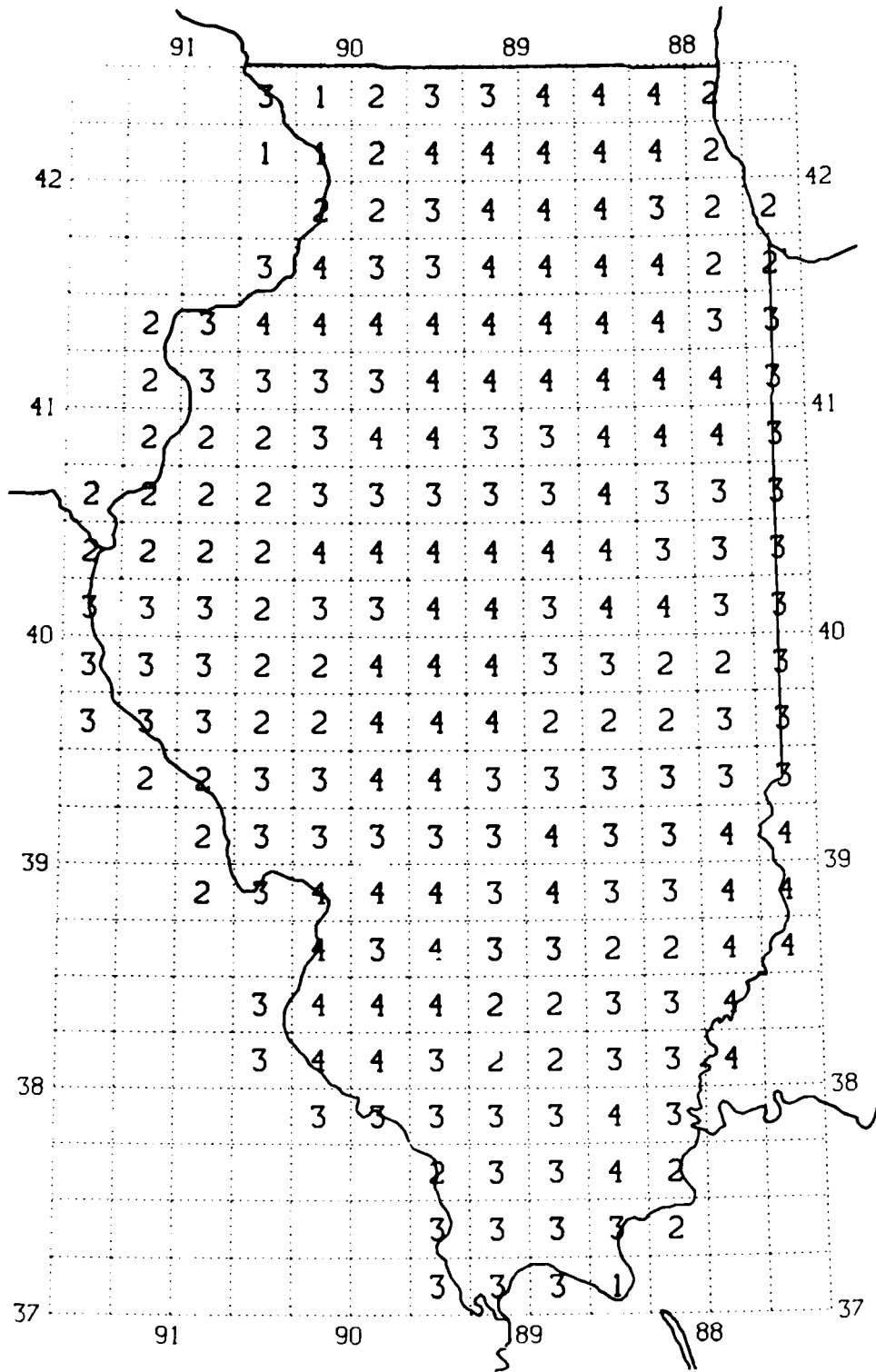
| Wind Power Class | 10 m (33 ft)                             |                                 | 50 m (164 ft)                            |                                 |
|------------------|--|---------------------------------|--|---------------------------------|
|                  | Wind Power Density, watts/m <sup>2</sup> | Speed, <sup>(b)</sup> m/s (mph) | Wind Power Density, watts/m <sup>2</sup> | Speed, <sup>(b)</sup> m/s (mph) |
| 0                | 0  | 0                               | 0  | 0                               |
| 1                | 100                                      | 4.4 (9.8)                       | 200                                      | 5.6 (12.5)                      |
| 2                | 150                                      | 5.1 (11.5)                      | 300                                      | 6.4 (14.3)                      |
| 3                | 200                                      | 5.6 (12.5)                      | 400                                      | 7.0 (15.7)                      |
| 4                | 250                                      | 6.0 (13.4)                      | 500                                      | 7.5 (16.8)                      |
| 5                | 300                                      | 6.4 (14.3)                      | 600                                      | 8.0 (17.9)                      |
| 6                | 400                                      | 7.0 (15.7)                      | 800                                      | 8.8 (19.7)                      |
| 7                | 1000                                     | 9.4 (21.1)                      | 2000                                     | 11.9 (26.6)                     |

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 4.1. Areal Distribution (km<sup>2</sup>) of Wind Power Classes in Illinois

| Power Class | Land Area | Percent Land Area | Cumulative Land Area | Percent Cumulative Land Area |
|-------------|-----------|-------------------|----------------------|------------------------------|
| 1           | 31,000    | 23.0              | 140,000              | 100.0                        |
| 2           | 89,000    | 65.0              | 100,000              | 77.0                         |
| 3           | 17,000    | 12.0              | 17,000               | 12.5                         |
| 4-7         | 0         | 0.00              | 0                    | 0.00                         |



0 50 100 MILES

0 50 100 KILOMETERS

PNL-3195 WERA-3

FIGURE 4.7. Certainty Rating of Illinois Wind Resource

### CERTAINTY RATING LEGEND

| Rating | Definition   |
|--------|--|
| 1      | <p>The lowest degree of certainty. A combination of the following conditions exists:</p> <ol style="list-style-type: none"><li>1) No data exist in the vicinity of the cell.</li><li>2) The terrain is highly complex.</li><li>3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.</li></ol>   |
| 2      | <p>A low-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"><li>1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data.</li><li>2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.</li></ol> |
| 3      | <p>A high-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"><li>1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data.</li><li>2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.</li></ol>       |
| 4      | <p>The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.</p>   |

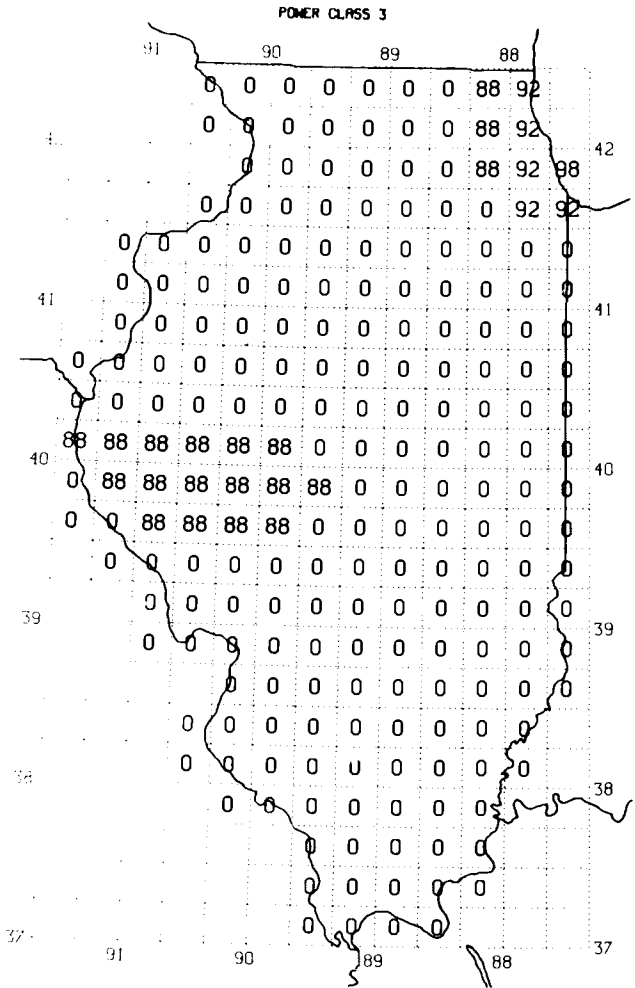
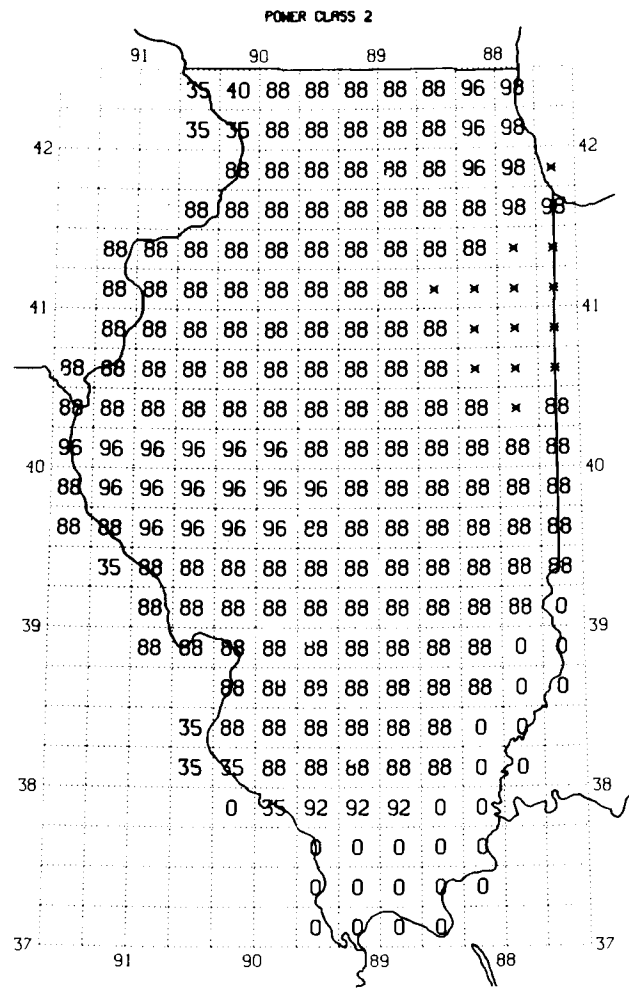


FIGURE 4.8. Areal Distribution of Wind Resource in Illinois (Power Classes 2 and 3); Percent of Land Area With or Exceeding Power Class Shown. An asterisk denotes 100%.

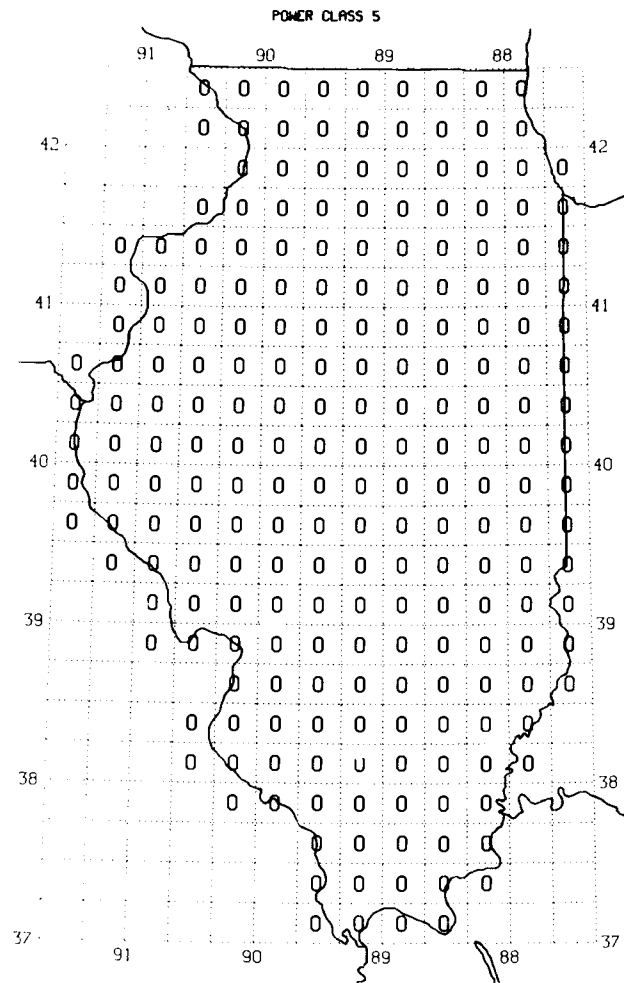
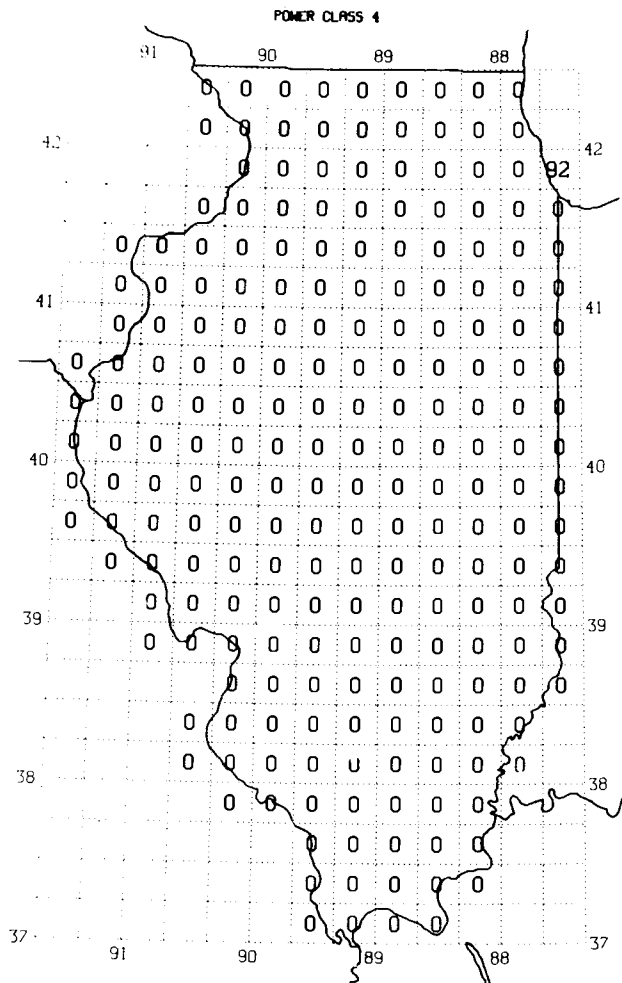


FIGURE 4.8 (Continued). Areal Distribution of Wind Resource in Illinois (Power Classes 4 and 5); Percent of Land Area With or Exceeding Power Class Shown.

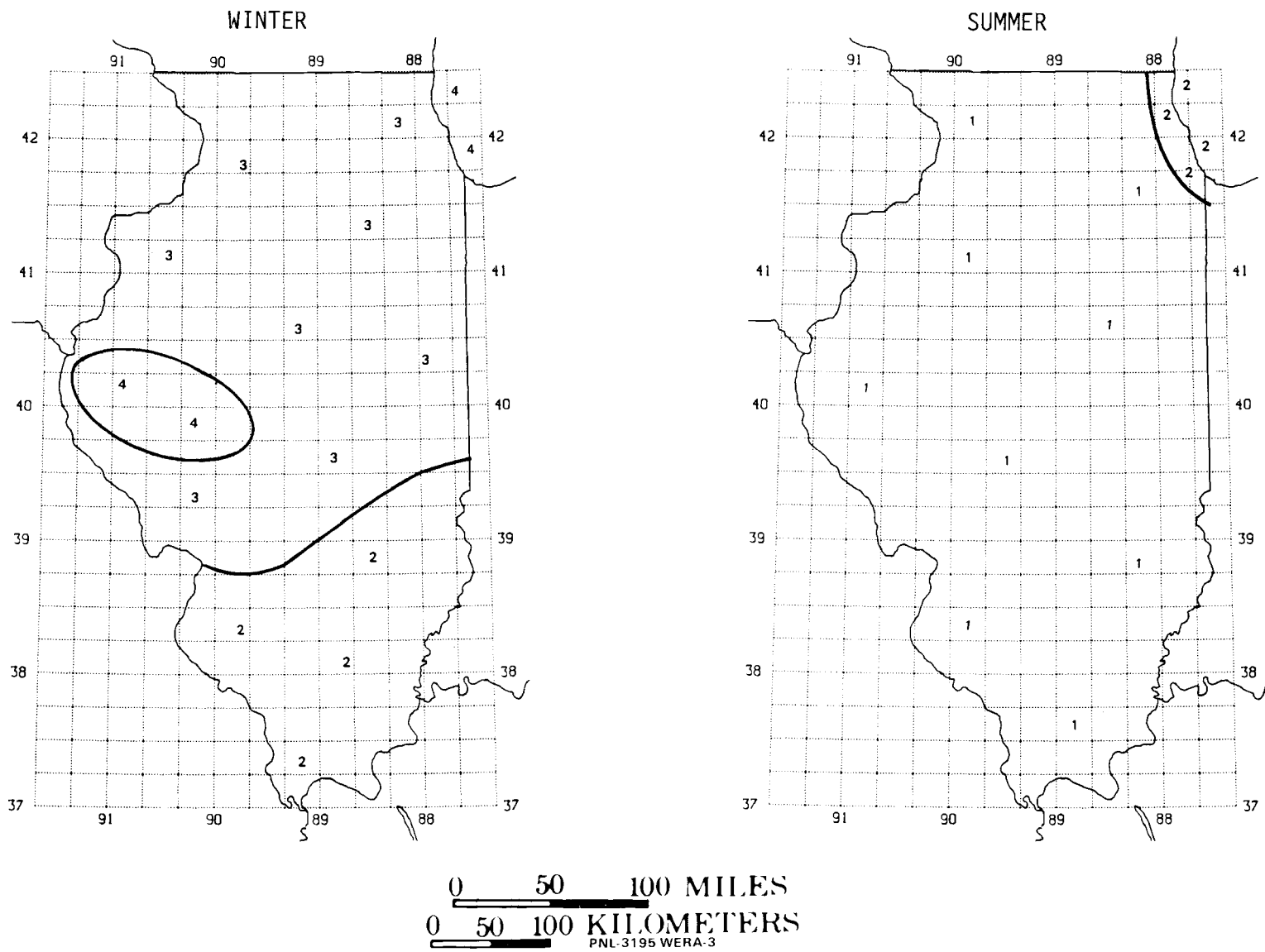


FIGURE 4.9. Seasonal Average Wind Power in Illinois

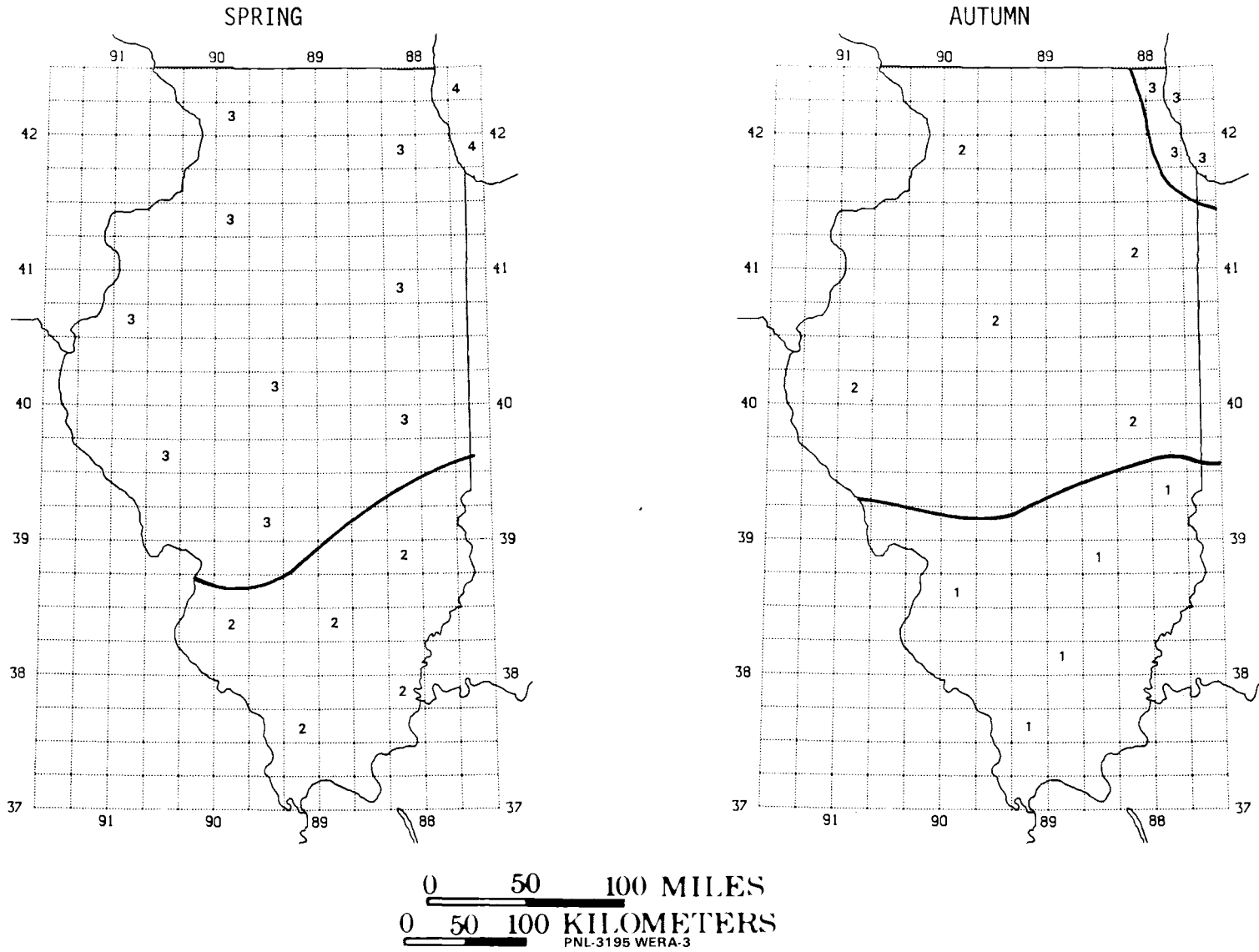


FIGURE 4.9 (Continued). Seasonal Average Wind Power in Illinois

TABLE 4.2. Illinois Stations with Graphs of the Wind Characteristics

| Station     | Station Name <sup>(a)</sup>  | Latitude,<br>Degrees North | Longitude,<br>Degrees West | Elevation of<br>Station, m | Period of<br>Record,<br>mm/yy | Anemometer<br>Height, m | Annual Average<br>Wind Speed, m/s |            |            | Annual Average<br>Wind Power<br>Watts/m <sup>2</sup> |            |            |
|-------------|------------------------------|----------------------------|----------------------------|----------------------------|-------------------------------|-------------------------|-----------------------------------|------------|------------|--|------------|------------|
|             |                              |                            |                            |                            |                               |                         | At<br>Anemometer<br>Height        | At<br>10 m | At<br>50 m | At<br>Anemometer<br>Height                           | At<br>10 m | At<br>50 m |
| Belleville  | Scott AFB                    | 38.54                      | 89.84                      | 135                        | 04/63-12/72                   | 6.1                     | 3.0                               | 3.2        | 4.0        | 58   | 72         | 143        |
| Bradford    | Rinkenberger                 | 41.23                      | 89.62                      | 224                        | 12/48-12/54                   | 17.1                    | 5.1                               | 4.7        | 6.0        | 154  | 122        | 244        |
| Chicago     | Midway Airport WBAS          | 41.78                      | 87.74                      | 187                        | 01/48-04/58                   | 11.6                    | 4.4                               | 4.3        | 5.4        | 101  | 95         | 189        |
| Chicago     | Midway Airport WBAS          | 41.78                      | 87.74                      | 187                        | 04/62-12/78                   | 6.1                     | 4.8                               | 5.1        | 6.5        | 118  | 146        | 291        |
| Chicago     | O'Hare Int'l<br>Airport WBAS | 41.98                      | 87.89                      | 211                        | 12/60-12/78                   | 6.1                     | 4.5                               | 4.8        | 6.1        | 103  | 127        | 254        |
| Effingham   | CAA                          | 39.15                      | 88.55                      | 185                        | 03/50-03/51                   | 8.8                     | 4.8                               | 4.9        | 6.2        | 113  | 118        | 236        |
| Glenview    | NAS                          | 42.08                      | 87.83                      | 199                        | 09/58-12/78                   | 5.5                     | 3.7                               | 4.0        | 5.0        | 79   | 102        | 204        |
| Joliet      | Municipal Airport<br>WBAS    | 41.50                      | 88.16                      | 181                        | 01/46-12/52                   | 13.4                    | 4.8                               | 4.6        | 5.8        | 161  | 142        | 283        |
| Moline      | Quad-City Airport<br>WBAS    | 41.44                      | 90.51                      | 184                        | 11/58-12/64                   | 7.6                     | 4.2                               | 4.3        | 5.5        | 96   | 108        | 215        |
| Moline      | Quad-City Airport<br>WBAS    | 41.44                      | 90.51                      | 184                        | 01/65-12/78                   | 7.6                     | 4.5                               | 4.7        | 5.9        | 117  | 131        | 262        |
| Peoria      | Greater Peoria<br>Airport    | 40.66                      | 89.68                      | 208                        | 10/59-12/78                   | 6.1                     | 4.4                               | 4.8        | 6.0        | 100  | 124        | 246        |
| Quincy      | Baldwin Field CAA            | 39.93                      | 91.19                      | 233                        | 12/48-12/54                   | 8.8                     | 4.8                               | 4.9        | 6.2        | 143  | 151        | 301        |
| Rantoul     | Chanute AFB                  | 40.29                      | 88.14                      | 228                        | 05/56-03/60                   | 4.0                     | 3.7                               | 4.3        | 5.4        | 76   | 113        | 225        |
| Rockford    | Greater Rockford<br>Airport  | 42.20                      | 89.10                      | 223                        | 12/62-12/78                   | 6.1                     | 4.5                               | 4.9        | 6.2        | 109  | 134        | 268        |
| Springfield | Capital Airport WBAS         | 39.83                      | 89.66                      | 183                        | 01/48-12/61                   | 15.1                    | 5.4                               | 5.1        | 6.4        | 199  | 166        | 331        |
| Springfield | Capital Airport WBAS         | 39.83                      | 89.66                      | 183                        | 12/61-12/78                   | 6.1                     | 4.9                               | 5.3        | 6.6        | 131  | 162        | 323        |
| Vandalia    |                              | 38.98                      | 89.16                      | 163                        | 04/51-12/54                   | 6.1                     | 4.3                               | 4.6        | 5.8        | 102  | 126        | 251        |

<sup>a</sup>AFB - Air Force Base; WBAS - Weather Bureau Airport Station; CAA - Civil Aeronautics Administration; NAS - Naval Air Station.

—+— WIND POWER  
 ◆---◆ WIND SPEED  
 PNL-3195 WERA-3

LEFT ORDINATE - WATTS/M<sup>2</sup>  
 RIGHT ORDINATE - M/S  
 ABSCISSA - YEAR

V AND P ADJUSTED FROM Z TO 10 M BY 1/7 POWER LAW

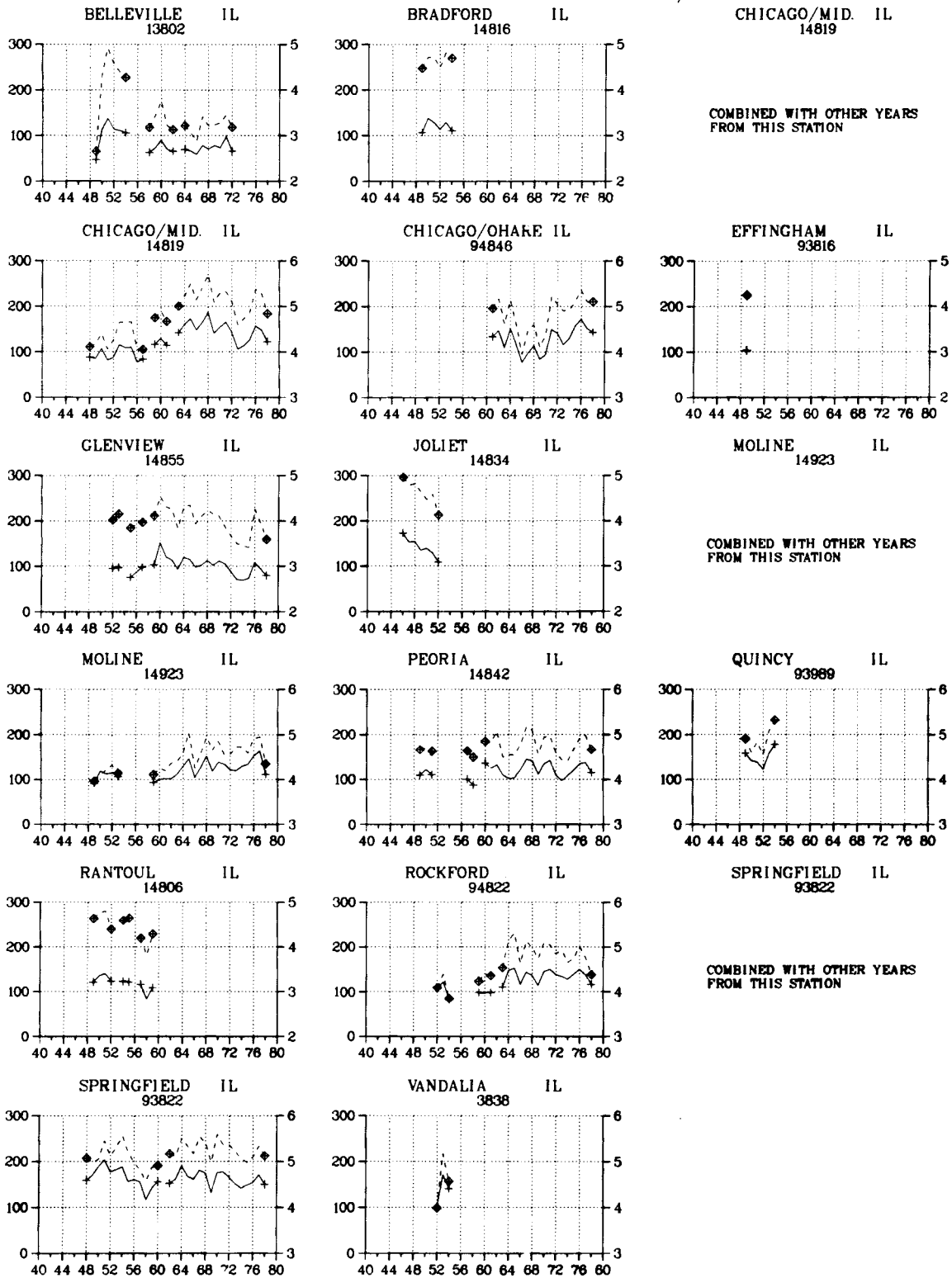


FIGURE 4.10. Interannual Wind Power and Speed for Illinois

— WIND POWER  
 - - - WIND SPEED  
 PNL-3195 WERA-3

LEFT ORDINATE - WATTS/M<sup>2</sup>  
 RIGHT ORDINATE - M/S  
 ABSCISSA - MONTH

V AND P ADJUSTED FROM Z TO 10 M BY 1/7 POWER LAW

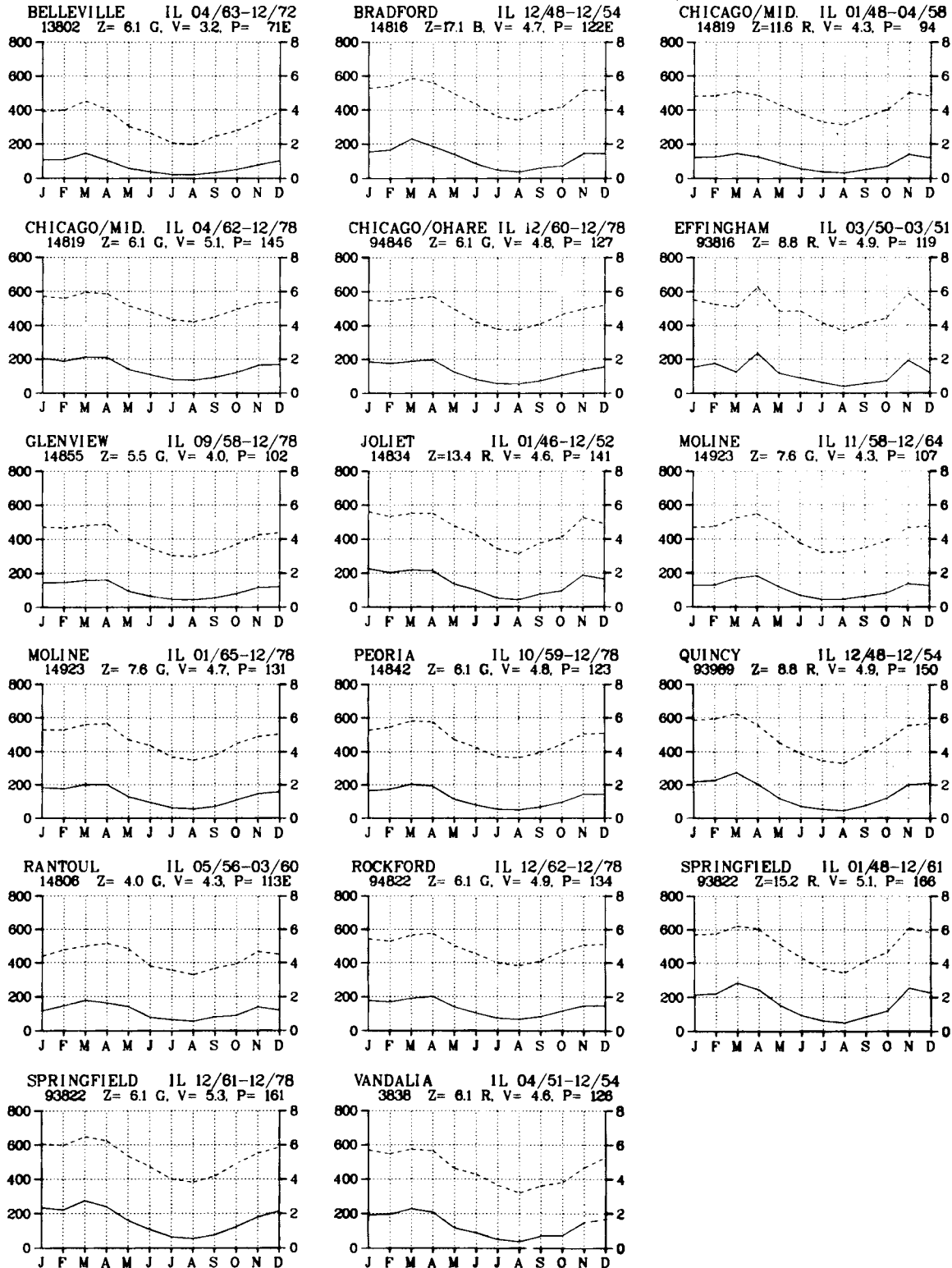


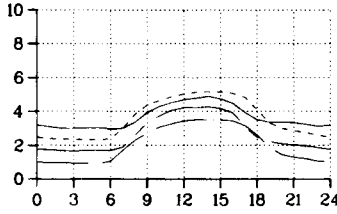
FIGURE 4.11. Monthly Average Wind Power and Speed for Illinois

— WINTER  
 ⊕ — ⊕ SUMMER  
 PNL-3195 WERA-3

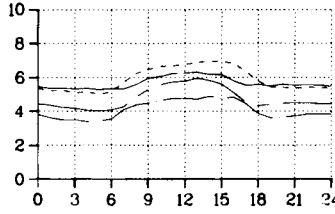
◆ — ◆ SPRING  
 ⊞ — ⊞ AUTUMN

ORDINATE - M/S  
 ABSCISSA - HOUR

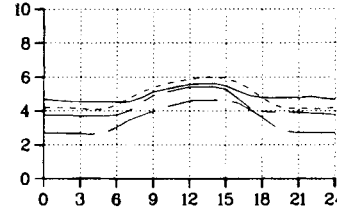
BELLEVILLE IL 04/63-12/72  
 13802 Z= 6.1 G, V= 3.0, P= 58E



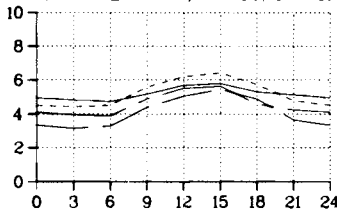
BRADFORD IL 12/48-12/54  
 14816 Z=17.1 B, V= 5.1, P= 154E



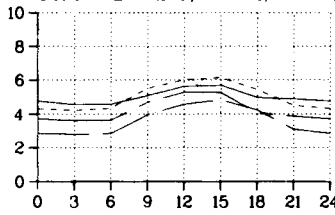
CHICAGO/MID. IL 01/48-04/58  
 14819 Z=11.6 R, V= 4.4, P= 101



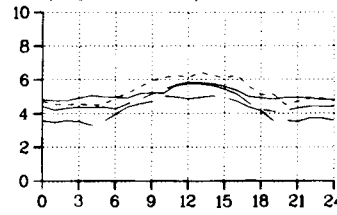
CHICAGO/MID. IL 04/62-12/78  
 14819 Z= 6.1 G, V= 4.8, P= 118



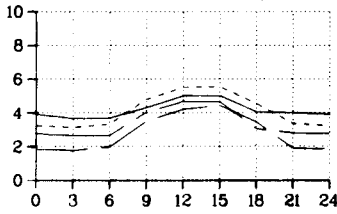
CHICAGO/OHARE IL 12/60-12/78  
 94846 Z= 6.1 G, V= 4.5, P= 103



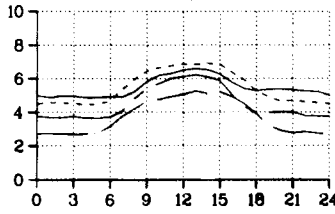
EFFINGHAM IL 03/50-03/51  
 93816 Z= 8.8 R, V= 4.8, P= 113



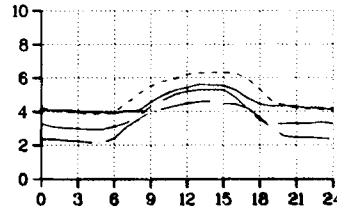
GLENVIEW IL 09/58-12/78  
 14855 Z= 5.5 G, V= 3.7, P= 79



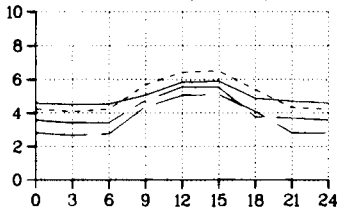
JOLIET IL 01/46-12/52  
 14834 Z=13.4 R, V= 4.8, P= 161



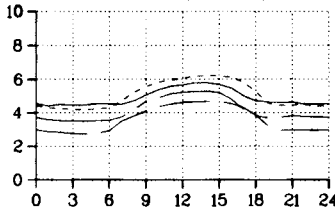
MOLINE IL 11/58-12/64  
 14923 Z= 7.6 G, V= 4.2, P= 96



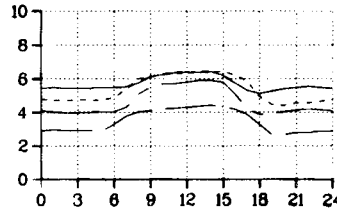
MOLINE IL 01/65-12/78  
 14923 Z= 7.6 G, V= 4.5, P= 117



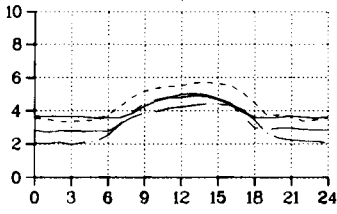
PEORIA IL 10/59-12/78  
 14842 Z= 6.1 G, V= 4.4, P= 100



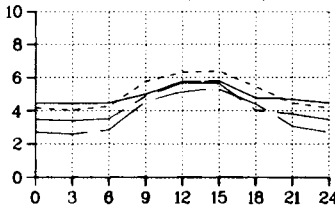
QUINCY IL 12/48-12/54  
 93969 Z= 8.8 R, V= 4.8, P= 143



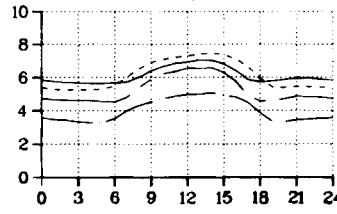
RANTOUL IL 05/56-03/60  
 14806 Z= 4.0 G, V= 3.7, P= 76E



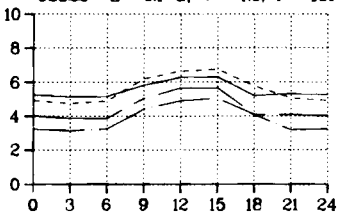
ROCKFORD IL 12/62-12/78  
 94822 Z= 6.1 G, V= 4.5, P= 109



SPRINGFIELD IL 01/48-12/61  
 93822 Z=15.2 R, V= 5.4, P= 199



SPRINGFIELD IL 12/61-12/78  
 93822 Z= 6.1 G, V= 4.9, P= 131



VANDALIA IL 04/51-12/54  
 3838 Z= 6.1 R, V= 4.3, P= 102

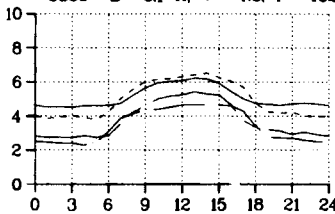


FIGURE 4.12. Diurnal Wind Speed by Season for Illinois

— PERCENT FREQUENCY LEFT ORDINATE - PERCENT  
 - - - - WIND SPEED RIGHT ORDINATE - M/S  
 PNL-3195 WERA-3  
 ABSCISSA - WIND DIRECTION

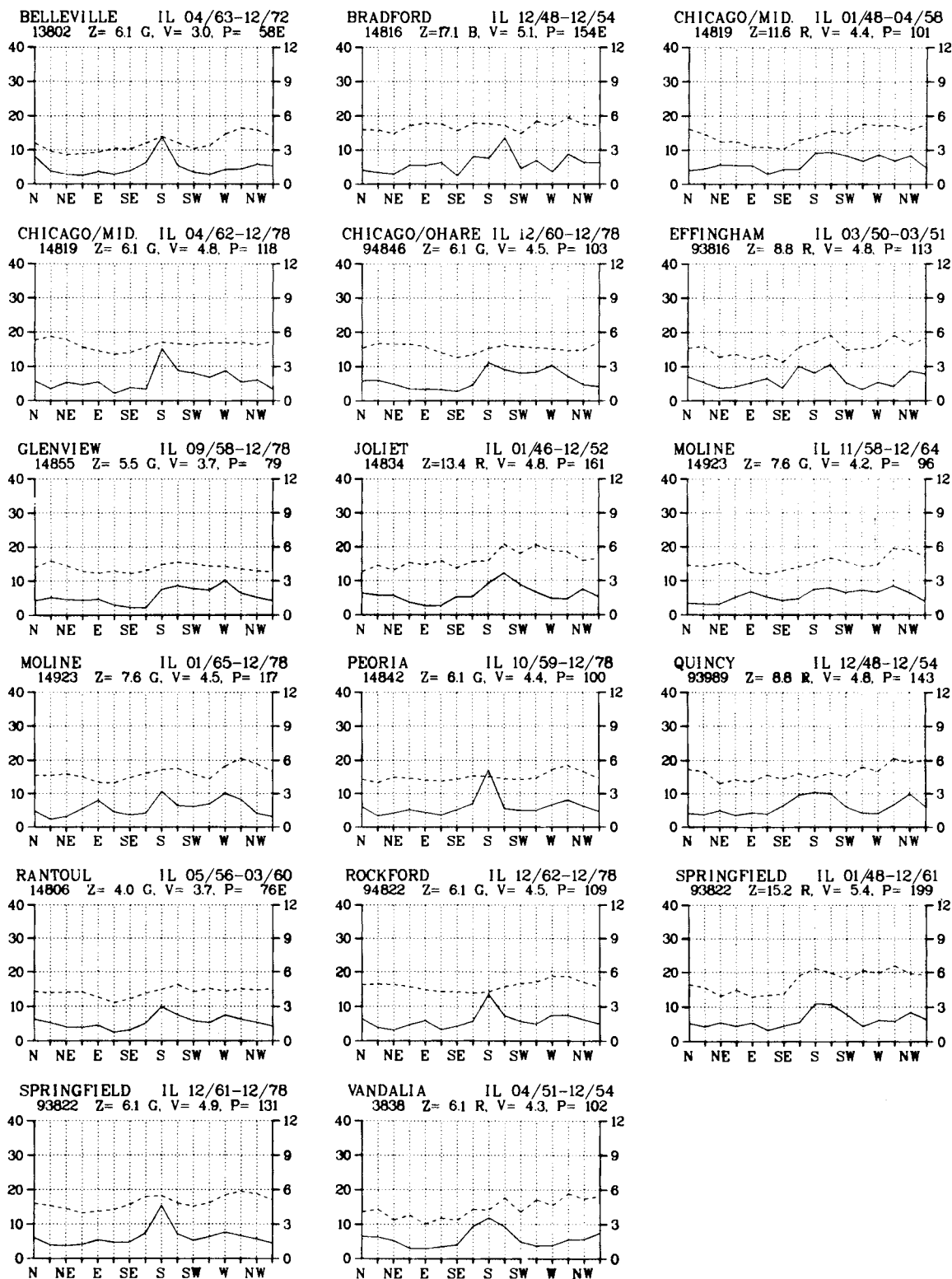


FIGURE 4.13. Directional Frequency and Average Wind Speed for Illinois

— ACTUAL DISTRIBUTION      ORDINATE - PERCENT  
 - - - RAYLEIGH DISTRIBUTION      ABSCISSA - M/S  
 PNL-3195 WERA-3

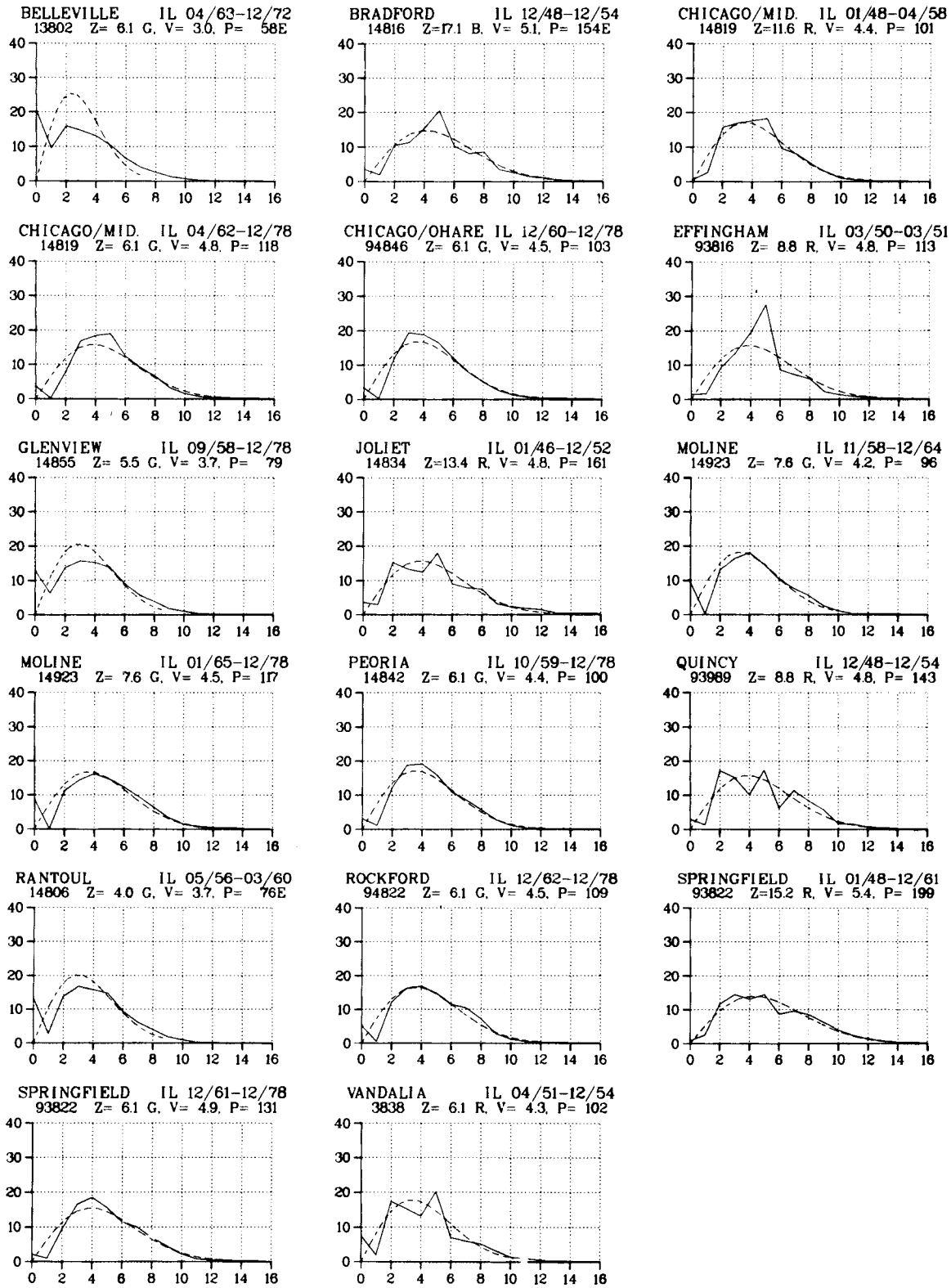


FIGURE 4.14. Annual Average Wind Speed Frequency for Illinois

ORDINATE - PERCENT  
 ABSCISSA - M/S  
 PNL-3195 WERA-3

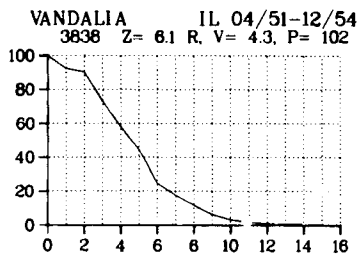
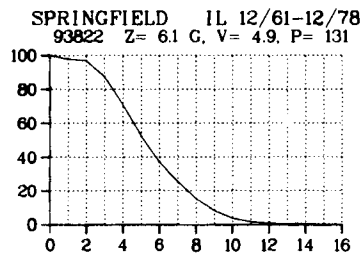
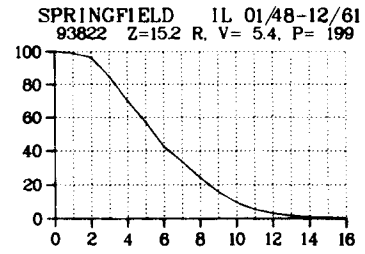
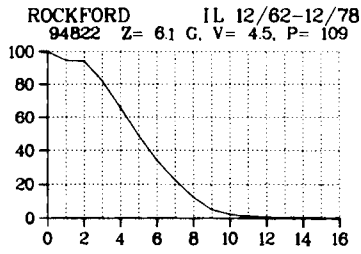
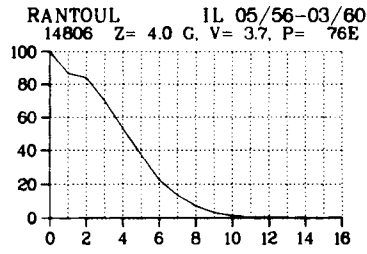
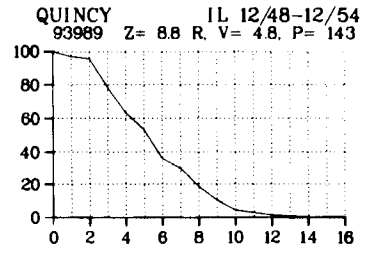
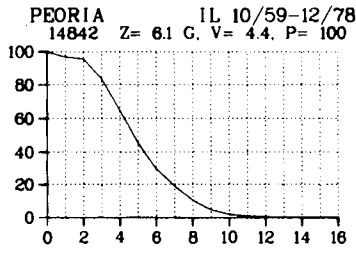
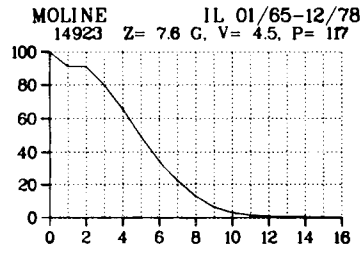
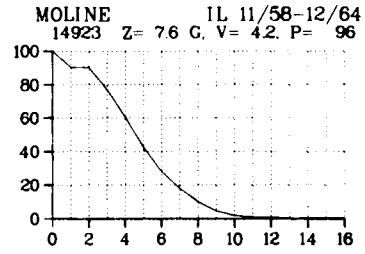
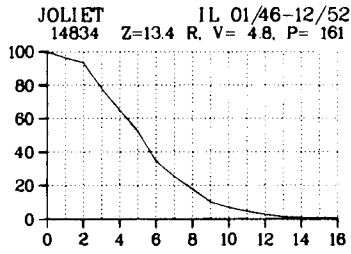
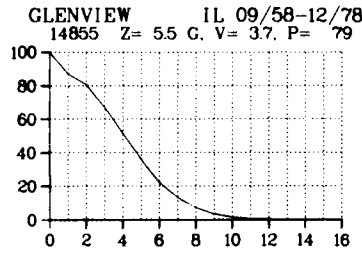
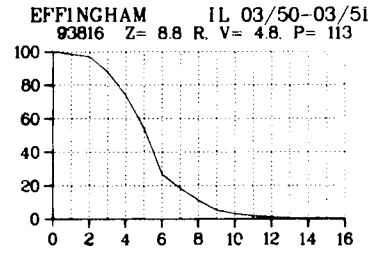
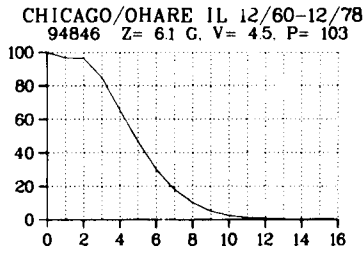
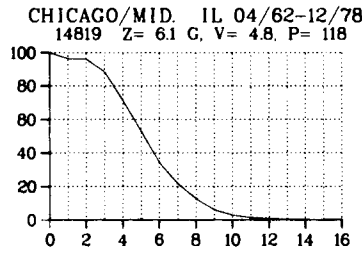
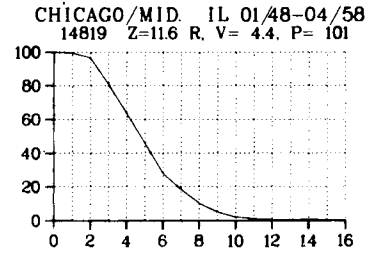
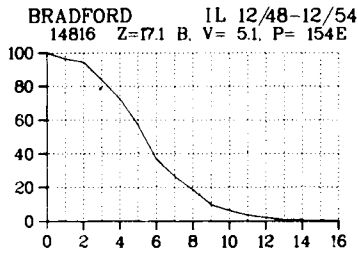
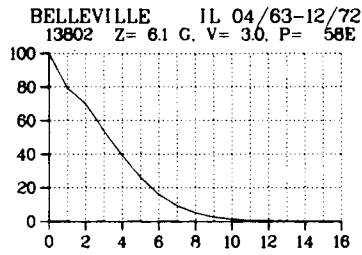


FIGURE 4.15. Annual Average Wind Speed Duration for Illinois

ORDINATE - PERCENT  
 ABSCISSA - WATTS/M<sup>2</sup>  
 PNL-3195 WERA-3

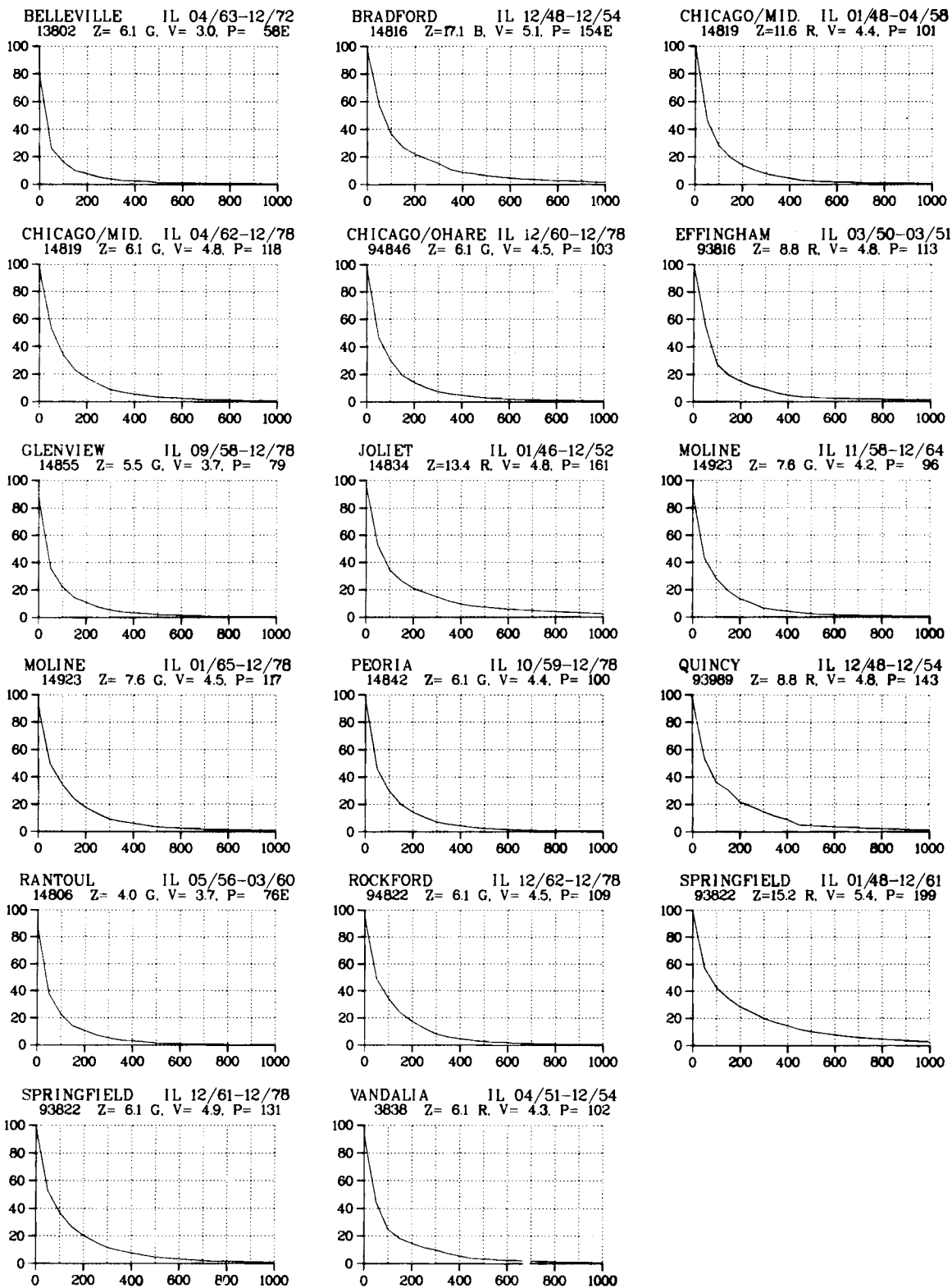


FIGURE 4.16. Annual Average Wind Power Duration for Illinois



**INDIANA**

Indiana covers an area of 93,944 km<sup>2</sup> (36,291 mi<sup>2</sup>) and had, in 1970, a population of 5,193,669. Most of the population lives in the major cities: Indianapolis, Fort Wayne, and Evansville (Figure 5.1).

Much of Indiana is smooth plains with little relief. Elevations range from 100 m (300 ft) in the southwestern corner of the state, to more than 400 m (1,200 ft) in the east central and northeastern sections. The most rugged terrain is found in the south central region where the land is unglaciated (Figures 5.2 and 5.3).

Available wind data from the National Climatic Center (NCC) is fairly well distributed throughout the state (Figure 5.4) except for extreme south central Indiana. Wind data were also obtained for the two nuclear facilities in the state. One is situated near Lake Michigan, the other on the Ohio River. The industrial plants providing wind data are generally situated along the Ohio River and the Wabash River (Figure 5.5).

### 5.1 ANNUAL AVERAGE WIND POWER

The annual average available wind power density in Indiana is shown in Figure 5.6. The analyses of mean wind power apply to terrain features that are favorably exposed to the wind, such as hilltops, uplands, and open plains (see Section 1.6). However, nearby terrain features may interact with the wind field to cause the wind power at some exposed sites to vary as much as +50 to 100% from the assessment value. (See Wegley et al. 1980 for information on terrain features that may increase or reduce wind energy.) In forested or wooded areas, the estimates are representative of large clearings with good exposure to prevailing strong winds, such as airports, where runways are generally aligned parallel to the prevailing wind direction(s). The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (Section 1.8).

The annual average wind power in Indiana is very similar to that in Illinois because both states experience much the same synoptic weather regimes and are both very flat; in fact, Indiana has only a small unglaciated area in the south central part of the state. Additionally, seasonal storm tracks generally associated with strong winds do not cross extreme southern sections of

Indiana as frequently as they cross the northern sections. The band of class 3 and 4 wind power near the coast of Lake Michigan indicates the presence of the winds sweeping from the lake. The eastern coast of Lake Michigan experiences higher wind speeds than the corresponding western coast in Illinois. This is due to the prevailing westerly winds. When the westerly winds pass across the lake surface, they meet less friction; off-lake winds have higher speeds than off-land winds.

The class 4 power estimates along the Lake Michigan shoreline represent offshore and exposed coastal areas, e.g., open shorelines that are not sheltered from the prevailing winds. The abrupt increase of surface roughness because of vegetation and topography inland from the shoreline rapidly attenuates the wind resource landward of the coastline.

#### 5.1.1 Certainty Rating of the Wind Resource

Certainty ratings of the wind power estimates for Indiana vary from 1 to 4 (Figure 5.7). The only substantial area with a certainty rating of 2 is the northeast corner bordering Lake Michigan. These grid cells are assigned a 2 rating because of the high variability of the wind resource along the coast and immediately inland, and because of undetermined exposure of some of the data stations. Throughout the rest of the state, most grid cells have a certainty rating of 3 or 4 since the terrain is not highly complex and the wind power variability is low. Data stations located on the expanse of flat or smooth plains appear representative of nearby exposed areas.

#### 5.1.2 Areal Distribution

The areal distribution of wind power in Indiana is illustrated in Figure 5.8. The numbers identify the percentage area in each cell of the grid in which the wind power equals or exceeds some threshold value. The uniformity of land surface and wind power regimes makes the areal distribution of wind power in Indiana easy to represent. The impact of the wide expanse of plains throughout the state with class 2 or higher wind power is immediately apparent in Table 5.1, which shows that about 46% of the state has class 2 or higher wind power. Figure 5.8 further reinforces the summary of Table 5.1 by indicating that about half of the grid boxes in the northern half of the state

have large fractions of area experiencing class 2 wind power. The large percentage area contribution of class 2 wind power occurs because about 50% of the state was estimated to have class 2 wind power. The prevalence of class 1 wind power in southern Indiana reflects weak prevailing winds (because of proximity to the Bermuda High), lack of topographical enhancement, and distance from storm tracks.

## 5.2 SEASONAL WIND POWER

Wind power maps for each season are shown on facing pages in Figure 5.9. In all cases, winter is the season of maximum wind power and summer the season of minimum wind power. Prevailing winds are generally from the southwest quadrant during most of the year. In winter, however, winds tend to blow from the northwest. In summer, northwestern Indiana near Lake Michigan often experiences a lake breeze, but this breeze does not significantly increase the mean summer wind power.

### 5.2.1 Winter

During the winter, wind power along the coast of Lake Michigan in northwestern Indiana is estimated as class 5. This reflects the prevailing strong northwesterly winds that have a long, smooth fetch across the water before they reach land. The narrowness of this band is indicated in Figure 5.9 by the appearance of the "5" offshore. The rapid decrease in wind power with distance from the shoreline, by increased surface roughness, is denoted by the band of class 4 wind power. Further inland, the wind power potential is reduced to class 3. This region is frequently in the path of eastward-moving winter storms and frequently experiences the strong winds associated with such disturbances.

Even though the winds aloft are strongest during the winter season and are predominantly westerly, the winter wind power is only class 2 in the southern plains because of the greater surface roughness of the area. This factor is most influential in the valleys and basins in the small unglaciated region in southern Indiana.

### 5.2.2 Spring

Although the springtime land-water temperature gradient is stronger than the corresponding winter temperature gradient, the prevailing winds are no

longer northwesterly in this season. Furthermore, as discussed in Chapter 4, including May in the spring season brings the seasonal average down so that the mean wind speeds are slightly lower than in winter and decrease from March to May. This change is indicated by the decrease to class 4 wind power along Lake Michigan and by the disappearance of the class 4 band just inland of the coast. Throughout the rest of Indiana, the wind power classes are generally the same as for winter, even though the mean spring wind speeds are usually slightly lower than mean winter wind speeds.

### 5.2.3 Summer

The highest wind power class in summer is found on the shoreline and probably reflects the lake-breeze effect and open-water fetch. The rest of the state has very little potential wind power in this season. The weakness of the winds is indicated by a wide expanse of wind power class 1 over the entire state, and by the small band of class 2 on the immediate coastline.

### 5.2.4 Autumn

Wind power generally increases from September to November as the upper-air wind speeds intensify. The autumn map shows evidence of the southward shifting of storm tracks and the redevelopment of the land-water temperature gradient. Prevailing winds are from the northwest quadrant so that the influence of Lake Michigan begins to be felt. This is reflected in the return of the bands of class 3 and 4 wind power along the coast, and the increase of wind power to class 2 in northern Indiana.

## 5.3 FEATURES OF SELECTED STATIONS

Graphs of detailed wind characteristics are presented for 9 stations in Indiana (Table 5.2). Three of these are in the northern part of the state, one in the southern region, and the remainder in the central sections of Indiana. Evansville, Fort Wayne, Indianapolis and South Bend each have two different periods of record presented; all other stations have one period of record.

Bunker Hill/Grissom Air Force Base is situated south of the Wabash River in an open plain in north central Indiana. This site seems to be representative of the area although the wind speeds recorded are low.

Columbus Air Force Base (AFB) is located on the southern extension of the White River. It appears to have good exposure from all directions, although wind speed and power at this station are lower than expected.

Evansville, located on the Ohio River in the extreme southwest corner of the state, is surrounded by hilly terrain. Although the anemometer was moved from a rooftop to a ground mast from one period of record to the next, the observed wind speeds are lower in the second period.

Fort Wayne AFB and Weather Bureau Airport Station (WBAS) are both located near St. Mary's River in northeastern Indiana. The anemometers were shifted to ground masts from rooftop locations between the first and second periods of record. Exposure was considered to be very good.

Goshen is situated on the Elkhart River in the northern part of the state. The area is relatively flat with terrain gently sloping upward to the northwest. The data indicate good exposure to prevailing winds.

Indianapolis WBAS is located near the White River in the White River plain. Absence of topography makes this site well exposed to prevailing winds. The anemometer location was changed from a roof top to a ground mast in 1961.

South Bend/St. Joseph County Airport is situated in extreme north central Indiana on an irregular plain. Terrain slopes gently to flat plains west and southwest of the airport. The site appears to be fairly well exposed to prevailing winds. The exposure is assumed to be better for the more recent period of record since the anemometer was moved to a ground mast location.

Terre Haute/Hulman Field is situated just west of the Indiana-Illinois border on the Wabash River. The station is on an irregular plain and seems moderately well exposed to prevailing winds.

West Lafayette, in west central Indiana, is located near the Wabash River. The terrain is generally smooth and judging from the data the site has very good exposure.

### 5.3.1 Interannual Wind Power and Speed

At most of the 9 stations, the interannual variability of wind power and speed is moderate. Fort Wayne appears to

have had the most frequent variations, while Evansville and South Bend showed the least frequent changes. The highest wind power occurred in Fort Wayne (in 1977) with a value of  $180 \text{ watts/m}^2$  (Figure 5.10). The area of lowest wind power in all the periods of record appears to be Evansville ( $50 \text{ watts/m}^2$ ). South Bend shows slightly less wind power than Fort Wayne but has less variation as well.

### 5.3.2 Monthly Average Wind Power and Speed

At all 9 stations, wind power and speed are lowest in the summer months (Figure 5.11). With the exception of Fort Wayne (1961-1978) and South Bend (1963-1978), the maximum wind power occurs in the spring, usually in March. At Fort Wayne and South Bend, the wind power in January is slightly higher than the value in March. At Fort Wayne, the average wind power is  $210 \text{ W/m}^2$  in January and  $202 \text{ W/m}^2$  in March, and at South Bend, about the same. However, in earlier years at both South Bend and Fort Wayne, the maximum wind power definitely occurred in March.

The highest monthly maxima are experienced at West Lafayette, Fort Wayne, South Bend, and Terre Haute. The winter maxima at Fort Wayne and South Bend are probably due to the excellent exposure to northwesterly winds. These four stations are typical of open, relatively smooth plains.

### 5.3.3 Diurnal Wind Speed by Season

Stations in Indiana generally have the highest wind speeds during the late-morning and afternoon hours, 900 to 1800 LST. The peak winds appear to occur between 1200 and 1500 LST year round. The greatest diurnal variations generally occur in summer, the least in winter. The diurnal variations at the 9 stations are very similar, regardless of location. This is typical for sites in the flat terrain prevalent in Indiana (Figure 5.12).

### 5.3.4 Directional Frequency and Average Speed

At most of the stations, prevailing winds are from the southwest (Figure 5.13). Winds are generally from the south in the southernmost part of the state and from the west at Fort Wayne (1961-1978) and Bunker Hill. As in Illinois the southerly winds over Indiana arise in response to the circulation around the Bermuda High and to the storms that develop in the lee of the Rockies. The higher frequency of southwest winds

in the northern tier of the state reflects its relative position with respect to the Bermuda High and Alberta track cyclones. The prevailing winds, however, are not necessarily the strongest winds. At Fort Wayne, Goshen, Terre Haute, West Lafayette, Bunker Hill, Columbus, Indianapolis, and South Bend, the strongest winds are from the west-northwest. These winds are most vigorous because of Indiana's geographic location (post-frontal) with respect to mature midwest cyclones.

#### 5.3.5 Annual Average Wind Speed Frequency

Because of possible observer bias and low instrument threshold speeds, the representativeness of the Rayleigh speed distribution is hard to determine. This bias is most readily observable at Columbus, Goshen, Terre Haute, and West Lafayette. The most obvious bias

occurred for stations with data periods during the 1940's and 1950's. The more recent records show an improved fit to the Rayleigh distribution (Figure 5.14).

#### 5.3.6 Annual Average Wind Speed and Power Duration

The tail of the observed wind speed distribution (e.g., frequency of winds greater than 8 m/s) is significant, because it contains much of the wind energy. From Figures 5.15 and 5.16, it is clear that the power-producing winds are sustained longest at Fort Wayne, Goshen, Indianapolis, South Bend, and West Lafayette. Of these stations, strongest winds are most persistent at West Lafayette. This could be partially due to the higher anemometer height; the curves in Figures 5.15 and 5.16 are not adjusted for anemometer height.





FIGURE 5.1. Geographic Map of Indiana

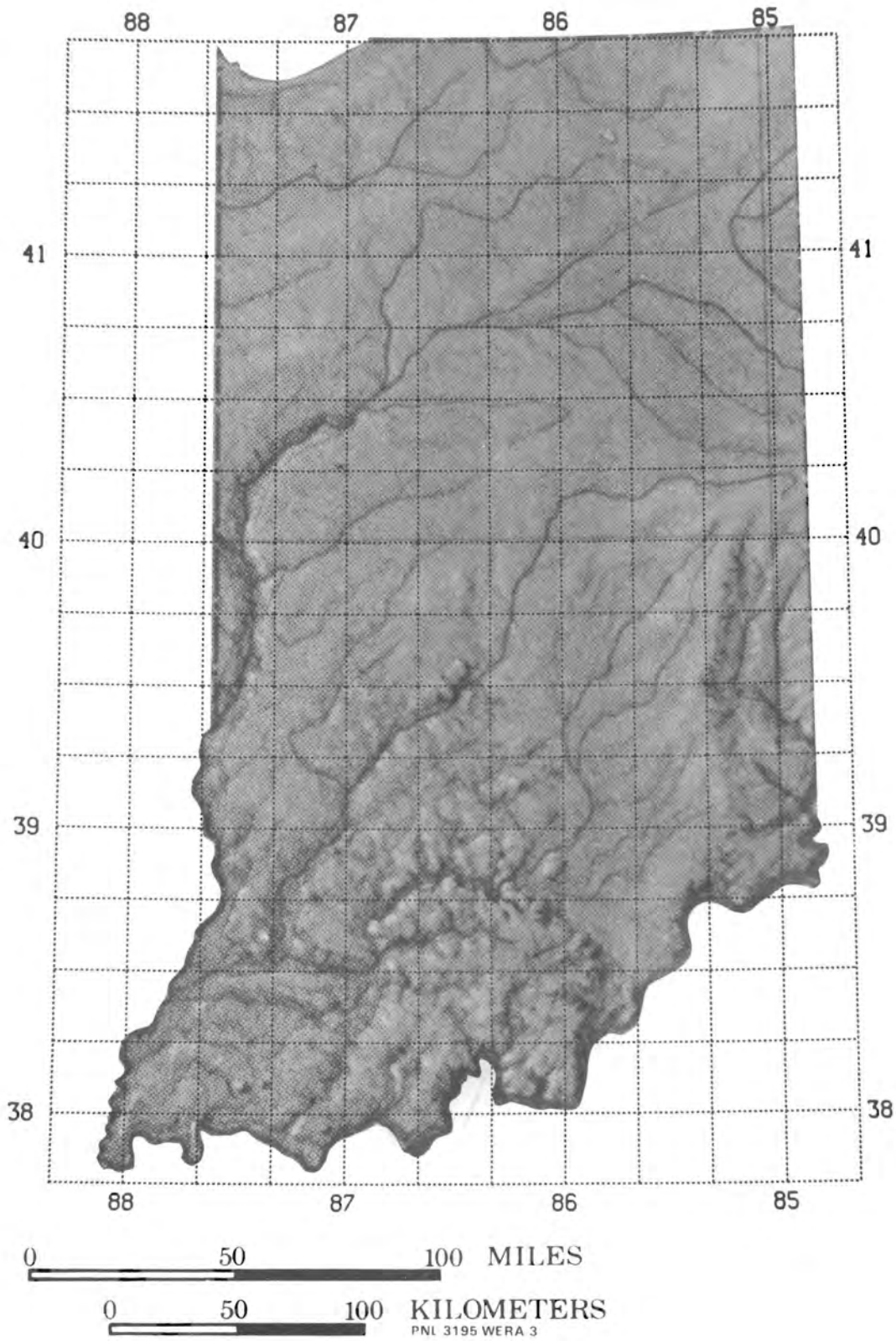


FIGURE 5.2. Topographical Map of Indiana

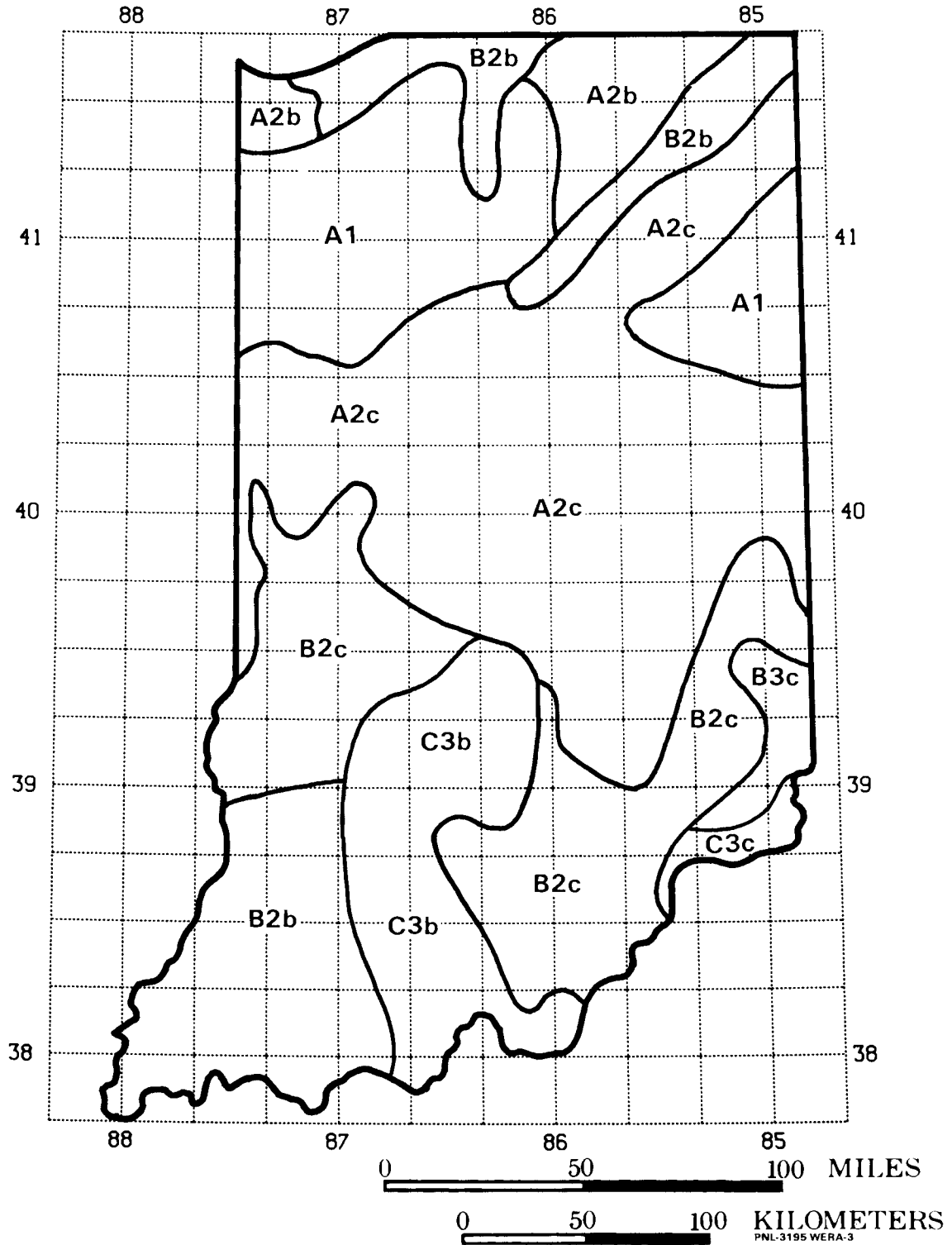


FIGURE 5.3. Classes of Land-Surface Form in Indiana

## LAND-SURFACE FORM LEGEND

### PLAINS

|    |                                 |
|----|---------------------------------|
| A1 | FLAT PLAINS                     |
| A2 | SMOOTH PLAINS                   |
| B1 | IRREGULAR PLAINS, SLIGHT RELIEF |
| B2 | IRREGULAR PLAINS                |

### PLAINS WITH HILLS OR MOUNTAINS

|         |                            |
|---------|----------------------------|
| A,B3a,b | PLAINS WITH HILLS          |
| B4,a,b  | PLAINS WITH HIGH HILLS     |
| B5a,b   | PLAINS WITH LOW MOUNTAINS  |
| B6a,b   | PLAINS WITH HIGH MOUNTAINS |

### OPEN HILLS AND MOUNTAINS

|    |                     |
|----|---------------------|
| C2 | OPEN LOW HILLS      |
| C3 | OPEN HILLS          |
| C4 | OPEN HIGH HILLS     |
| C5 | OPEN LOW MOUNTAINS  |
| C6 | OPEN HIGH MOUNTAINS |

### HILLS AND MOUNTAINS

|    |                |
|----|----------------|
| D3 | HILLS          |
| D4 | HIGH HILLS     |
| D5 | LOW MOUNTAINS  |
| D6 | HIGH MOUNTAINS |

### TABLELANDS

|       |                                 |
|-------|---------------------------------|
| B3c,d | TABLELANDS, MODERATE RELIEF     |
| B4c,d | TABLELANDS, CONSIDERABLE RELIEF |
| B5c,d | TABLELANDS, HIGH RELIEF         |
| B6c,d | TABLELANDS, VERY HIGH RELIEF    |

### SCHEME OF CLASSIFICATION

#### SLOPE (1st LETTER)

- A >80% OF AREA GENTLY SLOPING
- B 50-80% OF AREA GENTLY SLOPING
- C 20-50% OF AREA GENTLY SLOPING
- D <20% OF AREA GENTLY SLOPING

#### LOCAL RELIEF (2nd LETTER)

- 1 0 TO 30m (1 TO 100 ft)
- 2 30 TO 90m (100 TO 300 ft)
- 3 90 TO 150m (300 TO 500 ft)
- 4 150 TO 300m (500 TO 1000 ft)
- 5 300 TO 900m (1000 TO 3000 ft)
- 6 900 TO 1500m (3000 TO 5000 ft)

#### PROFILE TYPE (3rd LETTER)

- a >75% OF GENTLE SLOPE IS IN LOWLAND
- b 50-75% OF GENTLE SLOPE IS IN LOWLAND
- c 50-75% OF GENTLE SLOPE IS ON UPLAND
- d >75% OF GENTLE SLOPE IS ON UPLAND

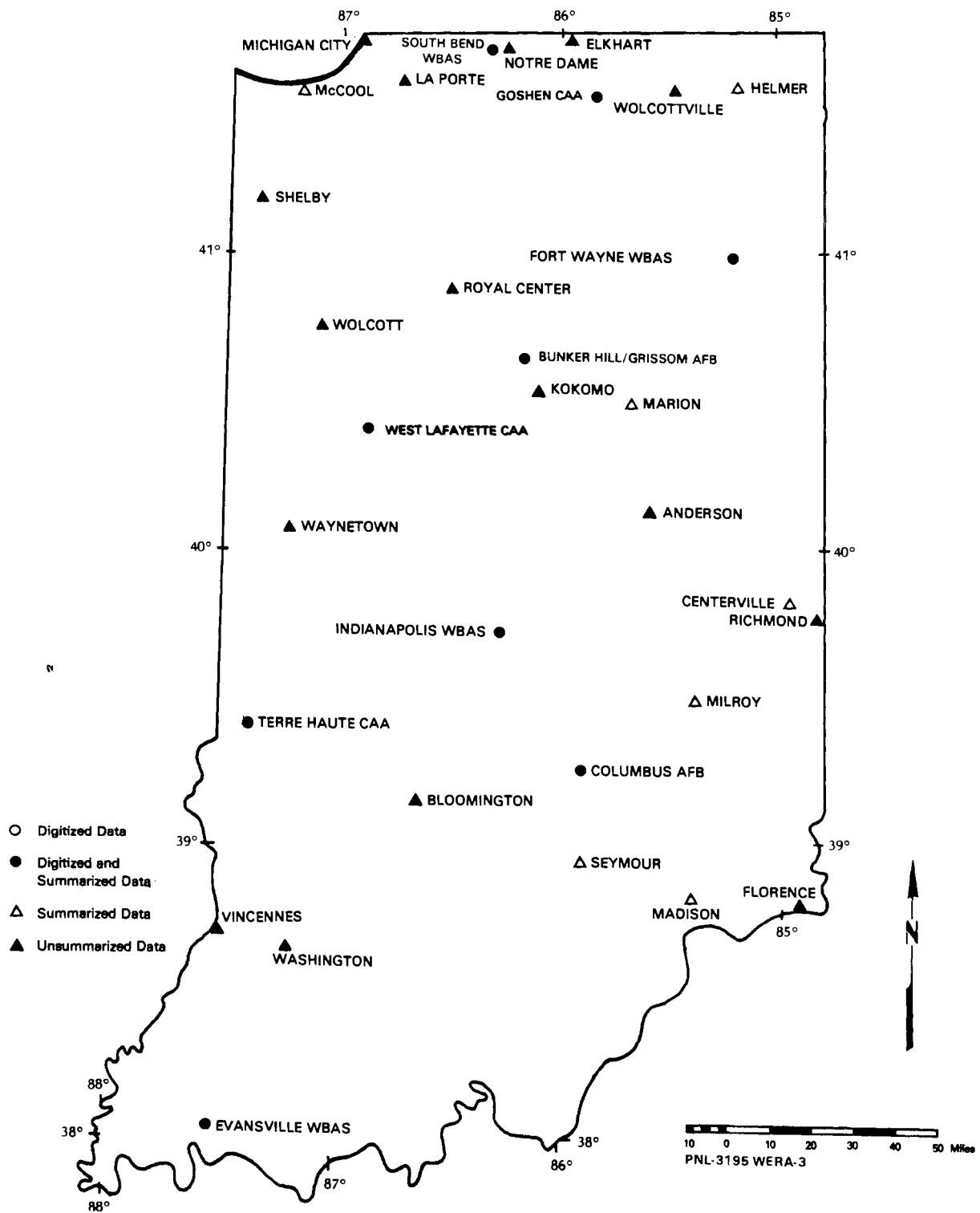


FIGURE 5.4. NCC Station Locations in Indiana

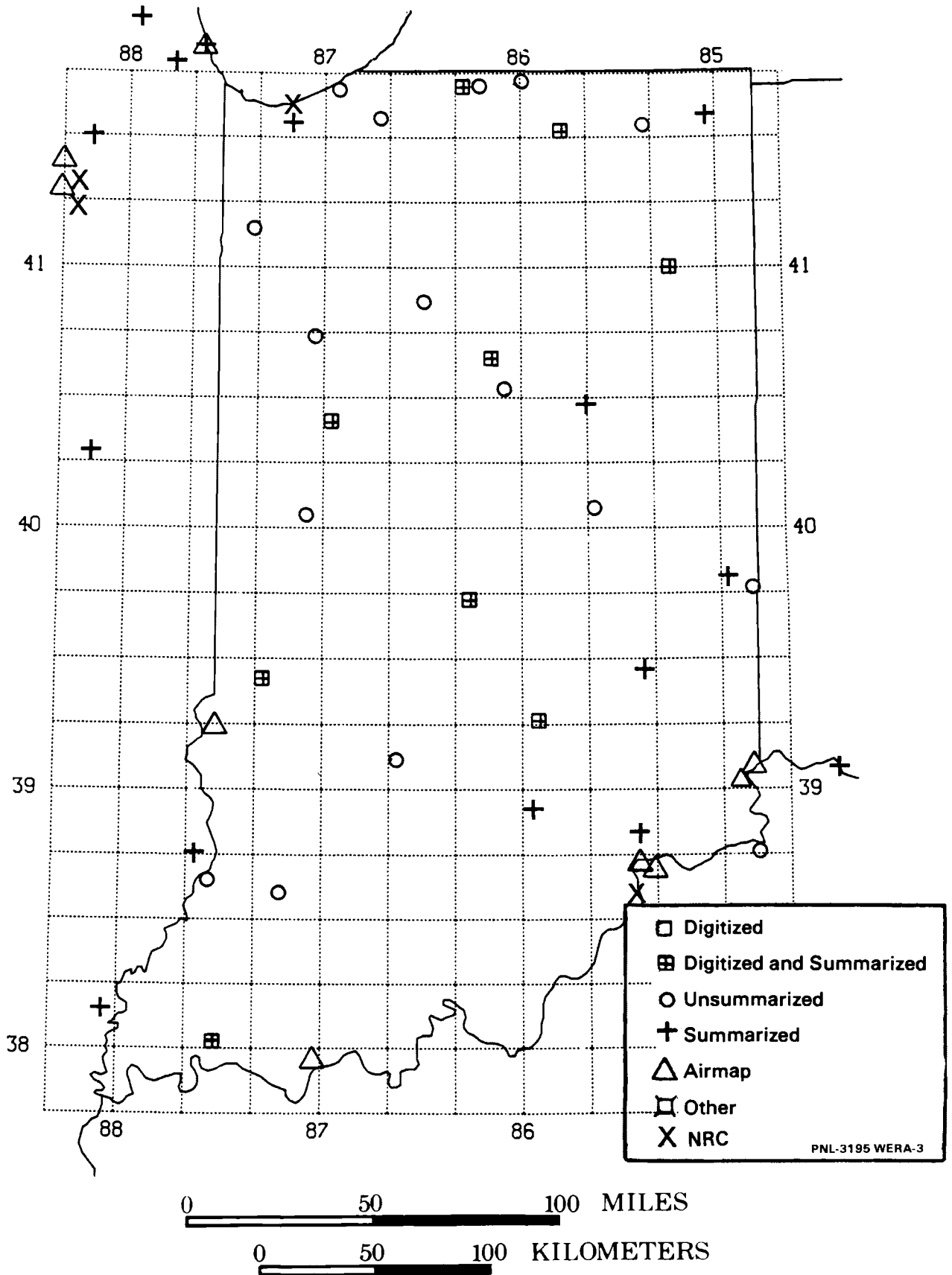


FIGURE 5.5. Location of Stations Used in Indiana Resource Assessment

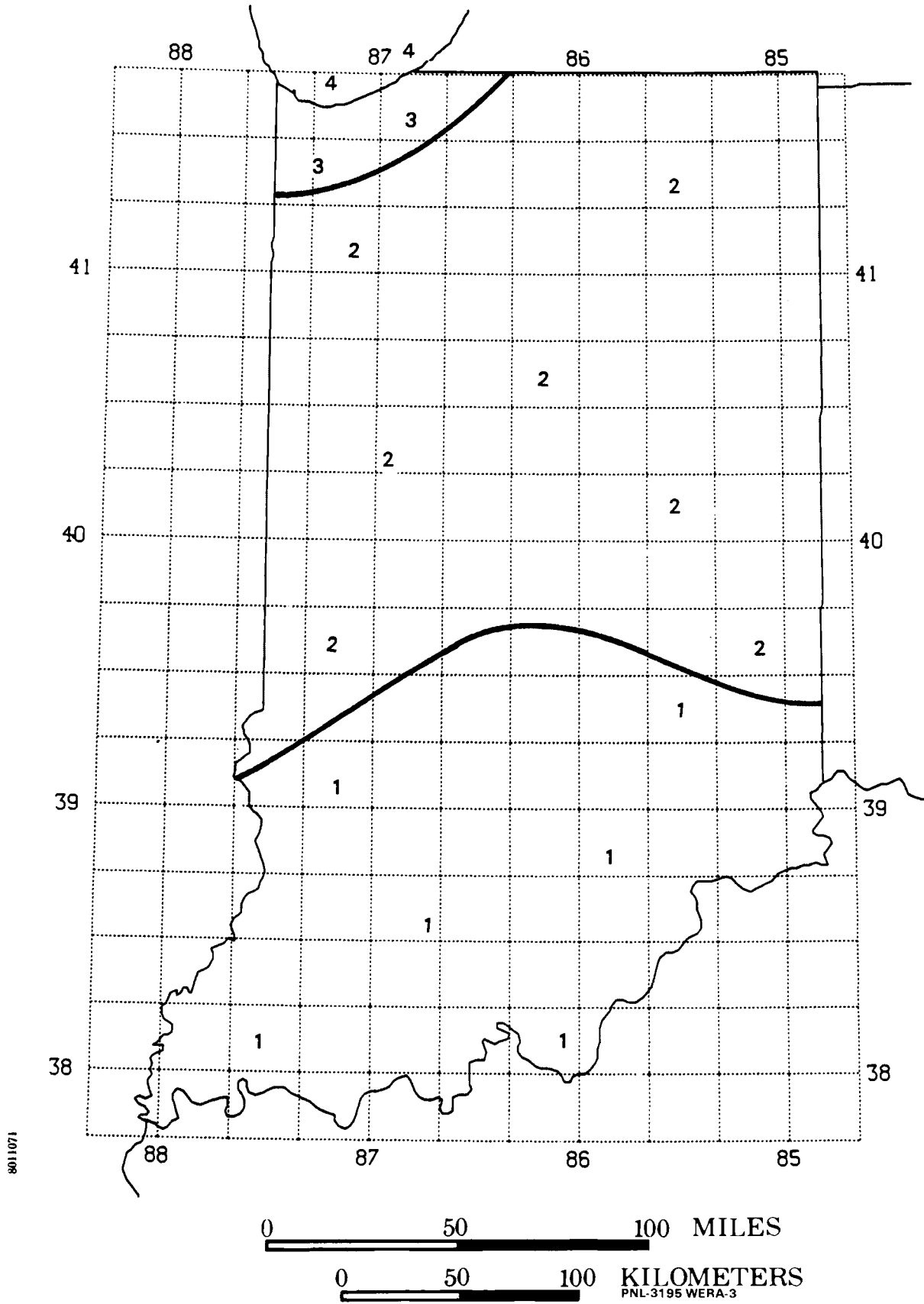


FIGURE 5.6. Indiana Annual Average Wind Power

Classes of Wind Power Density at 10 m and 50 m<sup>(a)</sup>

| Wind Power Class | 10 m (33 ft)                             |                                 | 50 m (164 ft)                            |                                 |
|------------------|--|---------------------------------|--|---------------------------------|
|                  | Wind Power Density, watts/m <sup>2</sup> | Speed, <sup>(b)</sup> m/s (mph) | Wind Power Density, watts/m <sup>2</sup> | Speed, <sup>(b)</sup> m/s (mph) |
| 1                | 0  | 0                               | 0  | 0                               |
| 2                | 100                                      | 4.4 (9.8)                       | 200                                      | 5.6 (12.5)                      |
| 3                | 150                                      | 5.1 (11.5)                      | 300                                      | 6.4 (14.3)                      |
| 4                | 200                                      | 5.6 (12.5)                      | 400                                      | 7.0 (15.7)                      |
| 5                | 250                                      | 6.0 (13.4)                      | 500                                      | 7.5 (16.8)                      |
| 6                | 300                                      | 6.4 (14.3)                      | 600                                      | 8.0 (17.9)                      |
| 7                | 400                                      | 7.0 (15.7)                      | 800                                      | 8.8 (19.7)                      |
|                  | 1000                                     | 9.4 (21.1)                      | 2000                                     | 11.9 (26.6)                     |

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 5.1. Areal Distribution (km<sup>2</sup>) of Wind Power Classes in Indiana

| Power Class | Land Area | Percent Land Area | Cumulative Land Area | Percent Cumulative Land Area |
|-------------|-----------|-------------------|----------------------|------------------------------|
| 1           | 44,000    | 50.0              | 86,000               | 100.0                        |
| 2           | 40,000    | 46.0              | 43,000               | 49.0                         |
| 3           | 2,400     | 2.8               | 2,400                | 2.8                          |
| 4-7         | 0         | 0.00              | 0                    | 0.00                         |

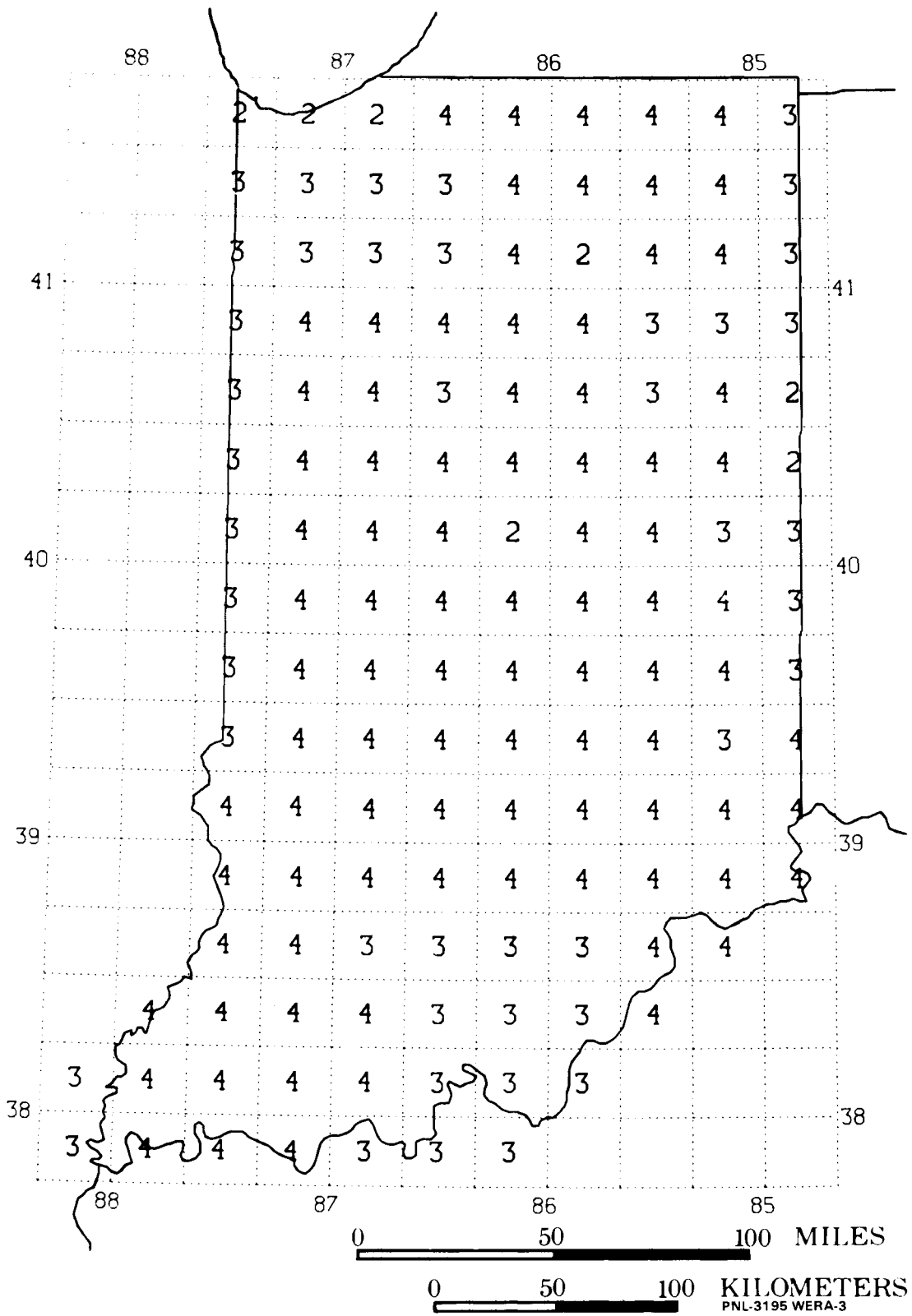


FIGURE 5.7. Certainty Rating of the Indiana Wind Resource

## CERTAINTY RATING LEGEND

| Rating | Definition   |
|--------|--|
| 1      | <p>The lowest degree of certainty. A combination of the following conditions exists:</p> <ol style="list-style-type: none"><li>1) No data exist in the vicinity of the cell.</li><li>2) The terrain is highly complex.</li><li>3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.</li></ol>   |
| 2      | <p>A low-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"><li>1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data.</li><li>2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.</li></ol> |
| 3      | <p>A high-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"><li>1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data.</li><li>2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.</li></ol>       |
| 4      | <p>The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.</p>   |

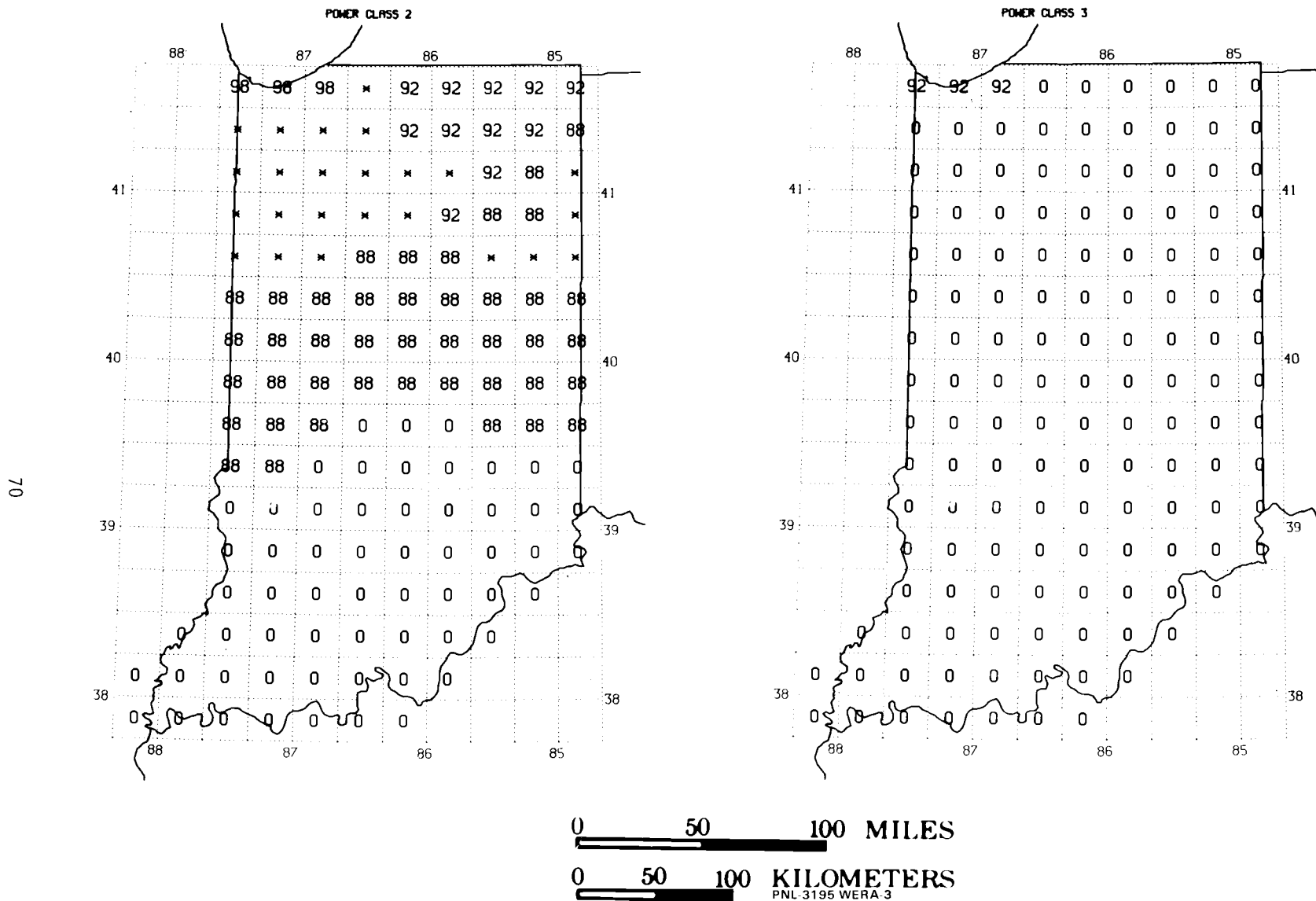


FIGURE 5.8. Areal Distribution of Wind Resource in Indiana (Power Classes 2 and 3); Percent of Land Area With or Exceeding Power Class Shown. An asterisk denotes 100%.

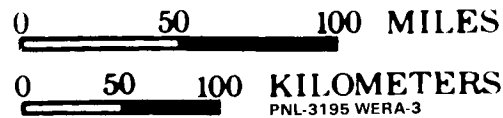
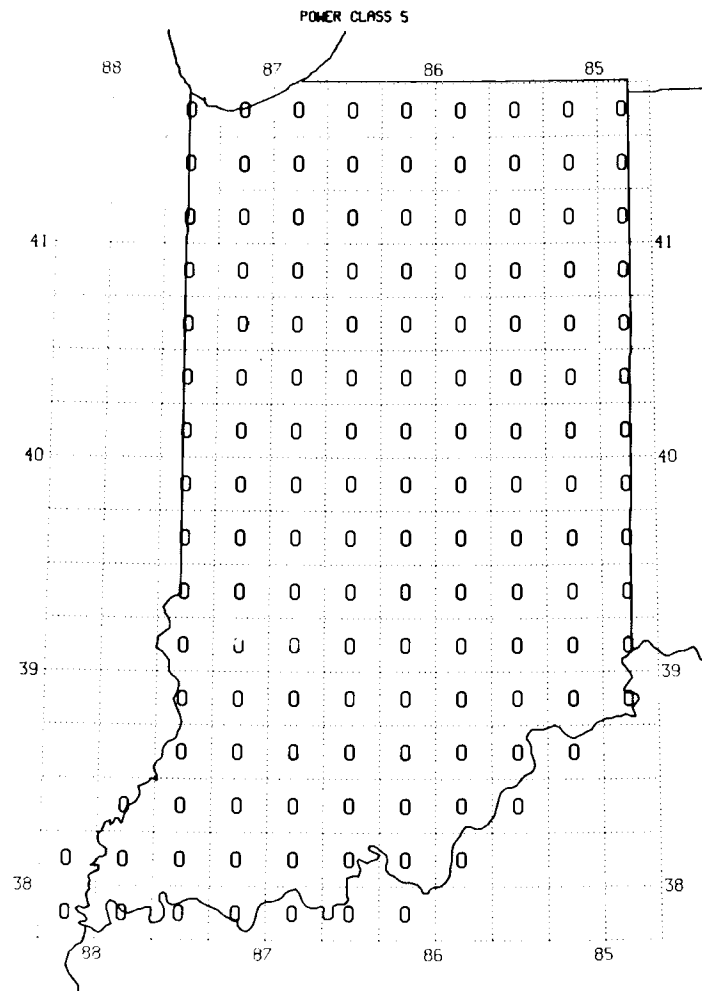
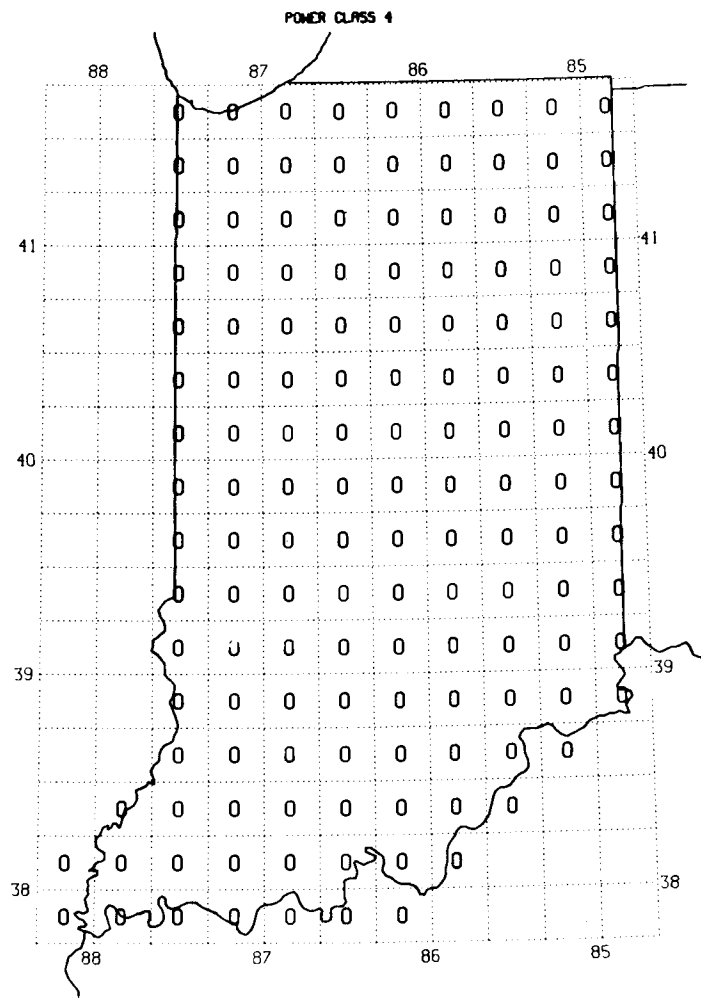


FIGURE 5.8.(Continued). Areal Distribution of Wind Resource in Indiana (Power Classes 4 and 5); Percent of Land Area With or Exceeding Power Class Shown.

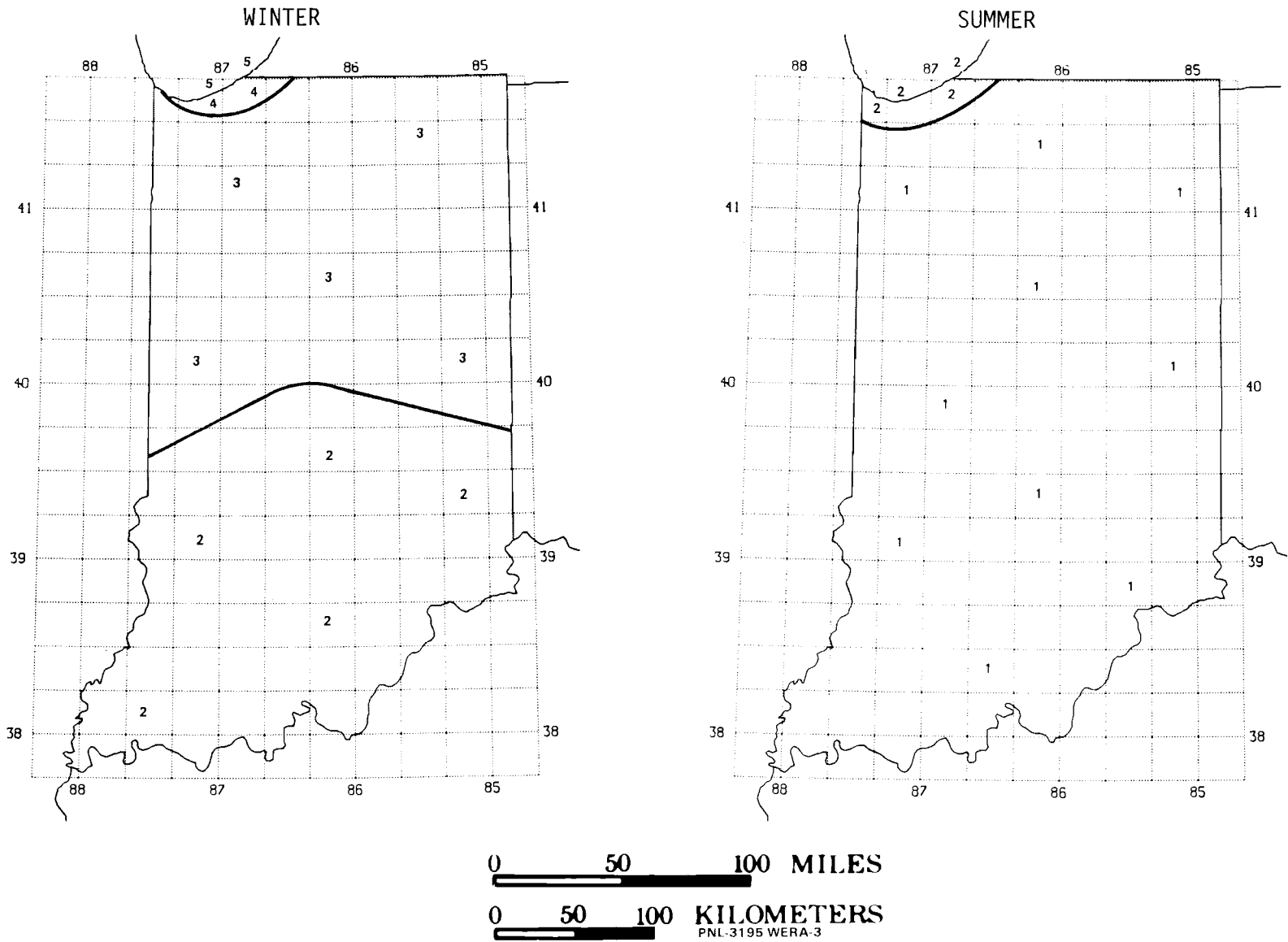


FIGURE 5.9. Seasonal Average Wind Power in Indiana

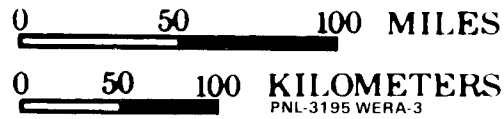
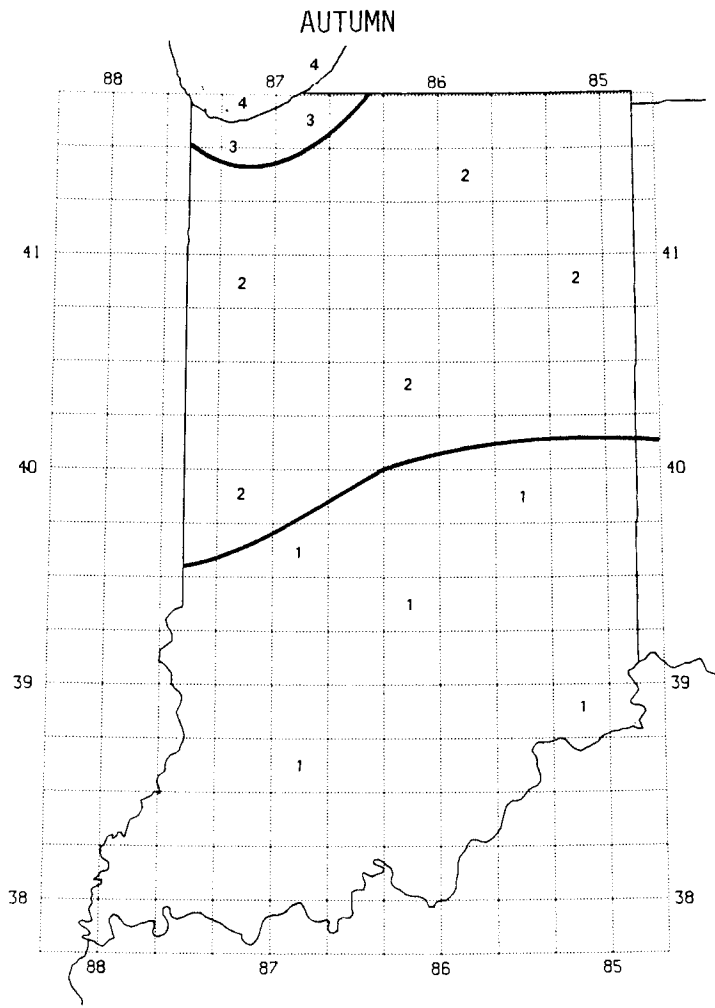
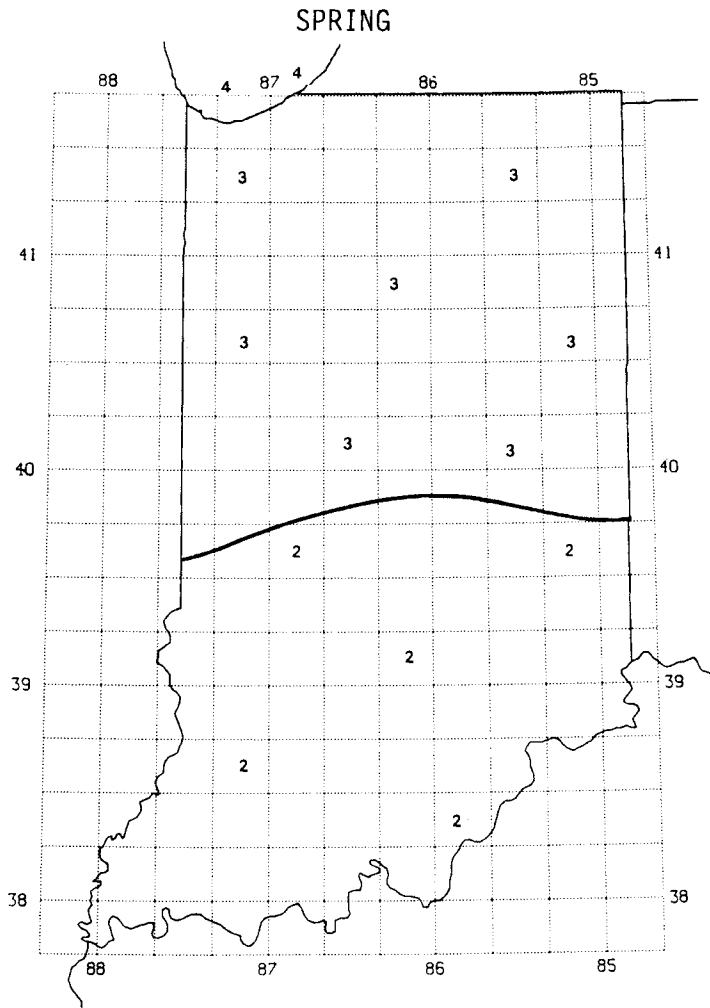


FIGURE 5.9 (Continued). Seasonal Average Wind Power in Indiana

TABLE 5.2. Indiana Stations with Graphs of the Wind Characteristics

| Station             | Station Name <sup>(a)</sup>    | Latitude,<br>Degrees North | Longitude,<br>Degrees West | Elevation of<br>Station, m | Period of<br>Record,<br>mm/yy | Anemometer<br>Height, m | Annual Average<br>Wind Speed, m/s |            |            | Annual Average<br>Wind Power<br>Watts/m <sup>2</sup> |            |            |
|---------------------|--------------------------------|----------------------------|----------------------------|----------------------------|-------------------------------|-------------------------|-----------------------------------|------------|------------|--|------------|------------|
|                     |                                |                            |                            |                            |                               |                         | At<br>Anemometer<br>Height        | At<br>10 m | At<br>50 m | At<br>Anemometer<br>Height                           | At<br>10 m | At<br>50 m |
| Bunker Hill         | NAS                            | 40.64                      | 86.14                      | 249                        | 04/59-11/68                   | 4.0                     | 3.6                               | 4.1        | 5.1        | 72   | 107        | 213        |
| Columbus            | Bakalar AFB                    | 39.26                      | 85.89                      | 199                        | 07/54-07/58                   | 22.9                    | 3.7                               | 3.3        | 4.1        | 77   | 54         | 108        |
| Evansville          | Dress Memorial<br>Airport      | 38.05                      | 87.53                      | 122                        | 01/52-09/61                   | 19.5                    | 4.1                               | 3.7        | 4.7        | 95   | 71         | 142        |
| Evansville          | Dress Memorial<br>Airport      | 38.05                      | 87.53                      | 122                        | 09/61-12/78                   | 6.1                     | 3.4                               | 3.7        | 4.6        | 58   | 72         | 142        |
| Ft. Wayne           | Baer Field                     | 41.00                      | 85.21                      | 249                        | 03/53-09/61                   | 19.8                    | 5.2                               | 4.7        | 5.9        | 158  | 118        | 235        |
| Ft. Wayne           | Baer Field                     | 41.00                      | 85.21                      | 249                        | 09/61-12/78                   | 6.1                     | 4.6                               | 4.9        | 6.2        | 117  | 145        | 288        |
| Goshen              | CAA                            | 41.53                      | 85.79                      | 252                        | 06/50-11/54                   | 17.7                    | 4.5                               | 4.2        | 5.3        | 126  | 99         | 197        |
| Indianapolis        | Weir Cook WBAS                 | 39.73                      | 86.26                      | 247                        | 07/50-09/59                   | 19.5                    | 5.0                               | 4.5        | 5.7        | 146  | 110        | 219        |
| Indianapolis        | Weir Cook WBAS                 | 39.73                      | 86.26                      | 247                        | 12/61-12/78                   | 6.1                     | 4.0                               | 4.3        | 5.4        | 76   | 94         | 187        |
| South Bend          | St. Joseph Co.<br>Airport WBAS | 41.69                      | 86.31                      | 238                        | 11/49-03/63                   | 17.7                    | 4.9                               | 4.5        | 5.7        | 132  | 103        | 206        |
| South Bend          | St. Joseph Co.<br>Airport WBAS | 41.69                      | 86.31                      | 238                        | 03/63-12/78                   | 6.4                     | 4.6                               | 4.9        | 6.1        | 110  | 133        | 265        |
| Terre Haute<br>West | Hulman Field CAA               | 39.44                      | 87.30                      | 181                        | 01/48-12/52                   | 7.6                     | 4.0                               | 4.1        | 5.2        | 94   | 106        | 211        |
|                     | Lafayette CAA                  | 40.41                      | 86.93                      | 190                        | 12/48-12/54                   | 16.2                    | 5.1                               | 4.8        | 6.0        | 166  | 135        | 269        |

<sup>a</sup>AFB - Air Force Base; WBAS - Weather Bureau Airport Station; CAA - Civil Aeronautics Administration; NAS - Naval Air Station.

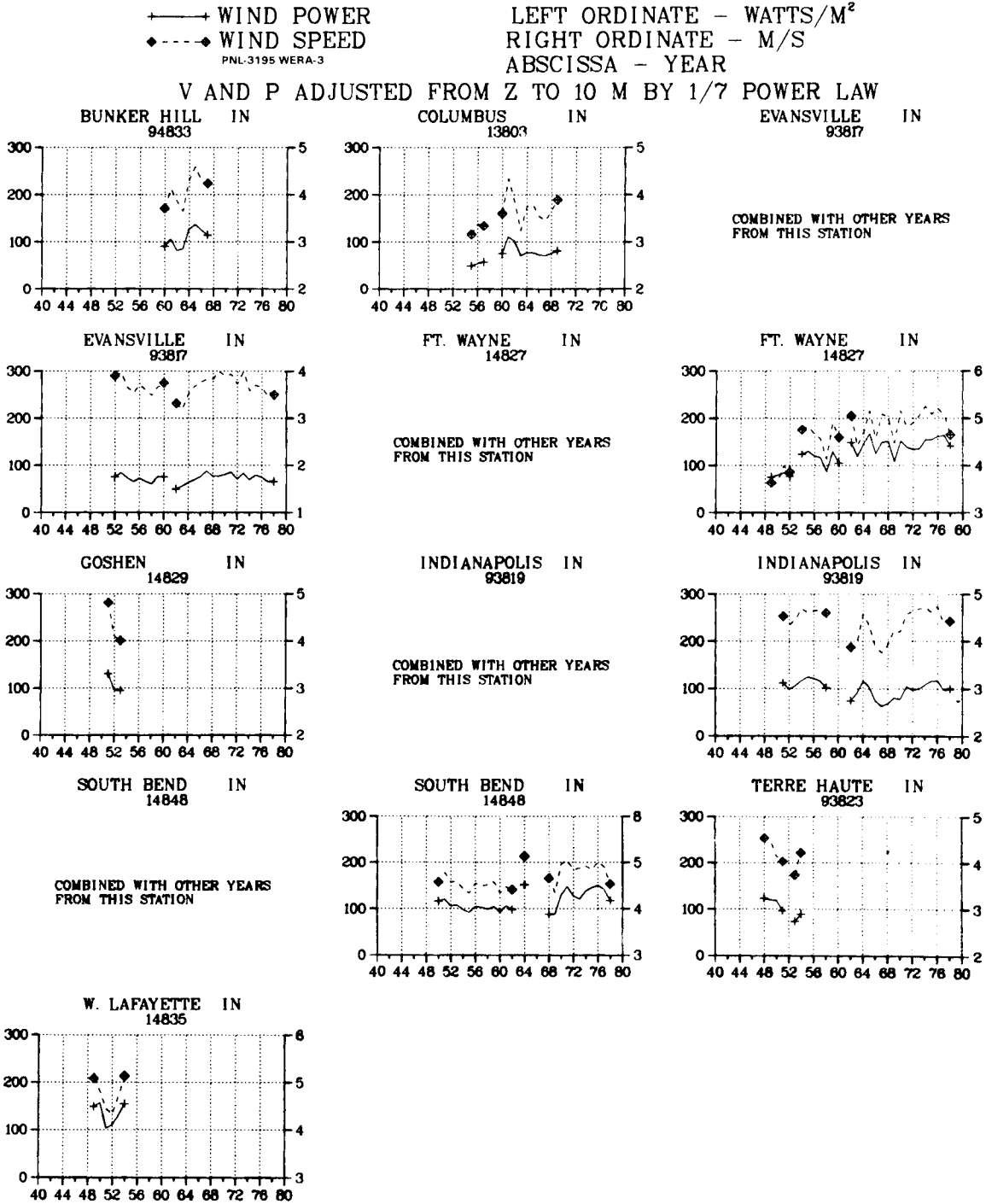


FIGURE 5.10. Interannual Wind Power and Speed for Indiana

—— WIND POWER  
 - - - - WIND SPEED  
 PNL-3195 WERA-3

LEFT ORDINATE -- WATTS/M<sup>2</sup>  
 RIGHT ORDINATE -- M/S  
 ABSCISSA -- MONTH

V AND P ADJUSTED FROM Z TO 10 M BY 1/7 POWER LAW

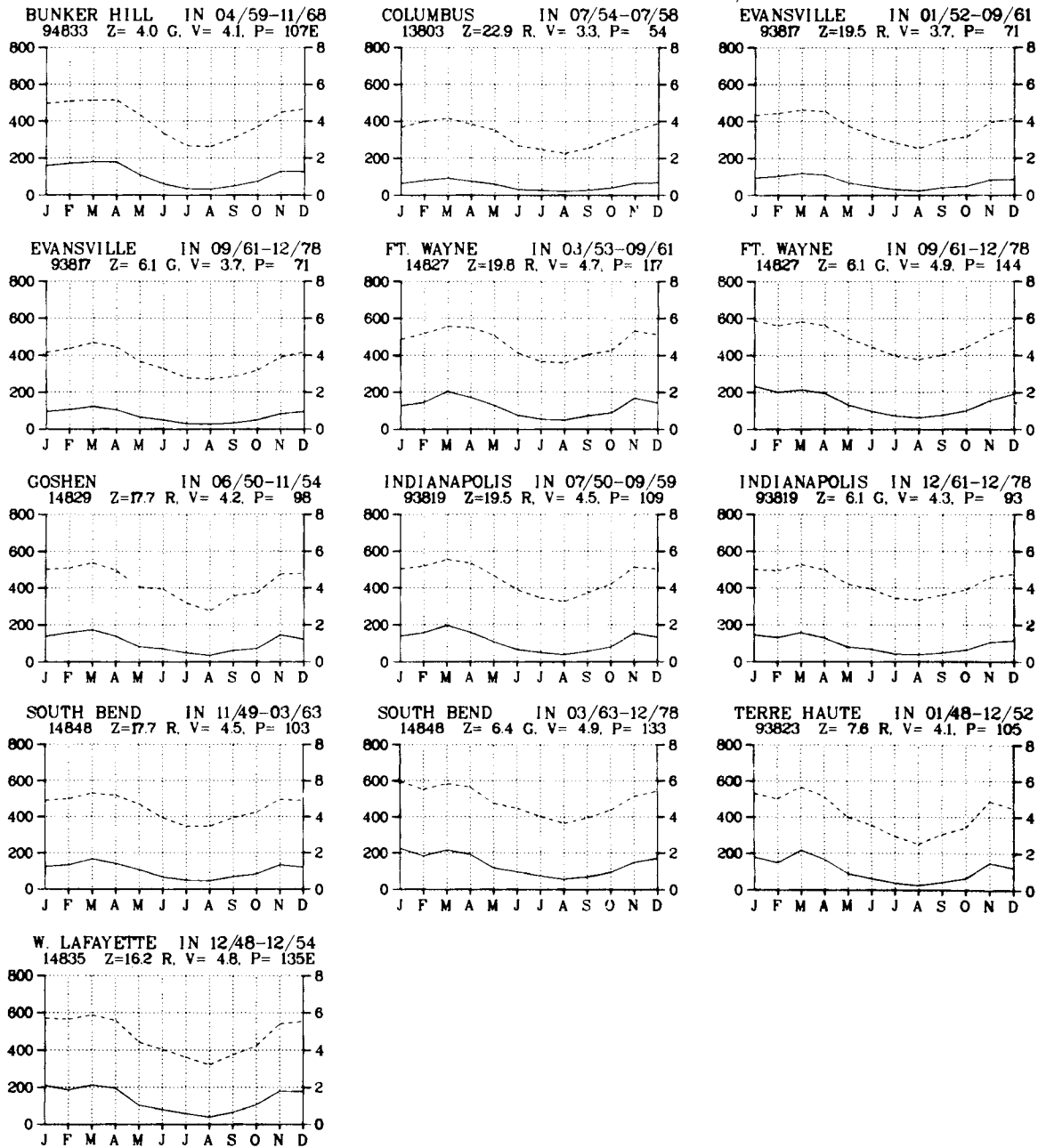


FIGURE 5.11. Monthly Average Wind Power and Speed for Indiana

——— WINTER      ◆---◆ SPRING  
 ⊕---⊕ SUMMER      ⊞---⊞ AUTUMN  
 PNL-3195 WERA-3

ORDINATE - M/S  
 ABSCISSA - HOUR

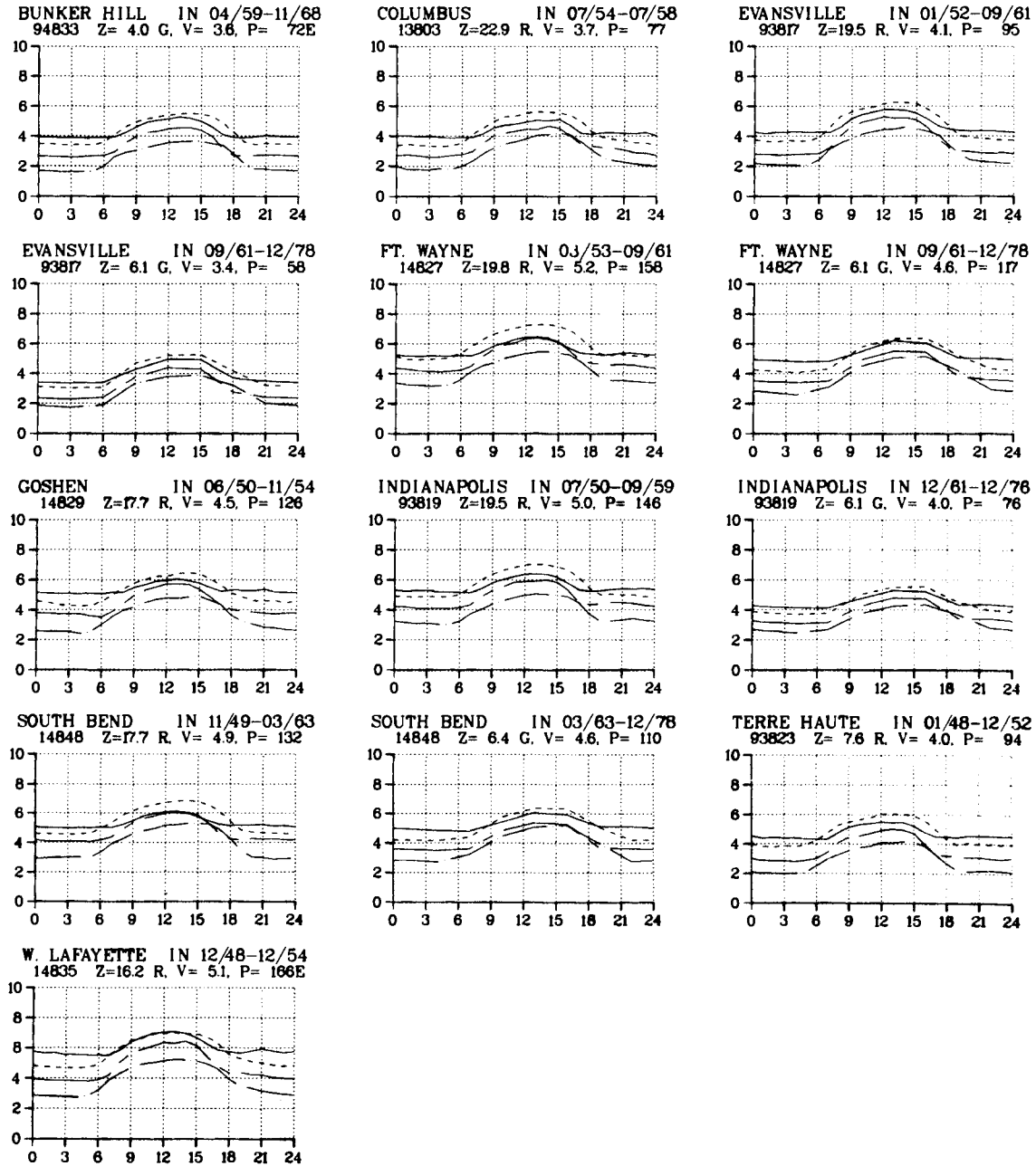


FIGURE 5.12. Diurnal Wind Speed by Season for Indiana

— PERCENT FREQUENCY LEFT ORDINATE - PERCENT  
 - - - WIND SPEED RIGHT ORDINATE - M/S  
PNL-3195 WERA-3  
 ABSCISSA - WIND DIRECTION

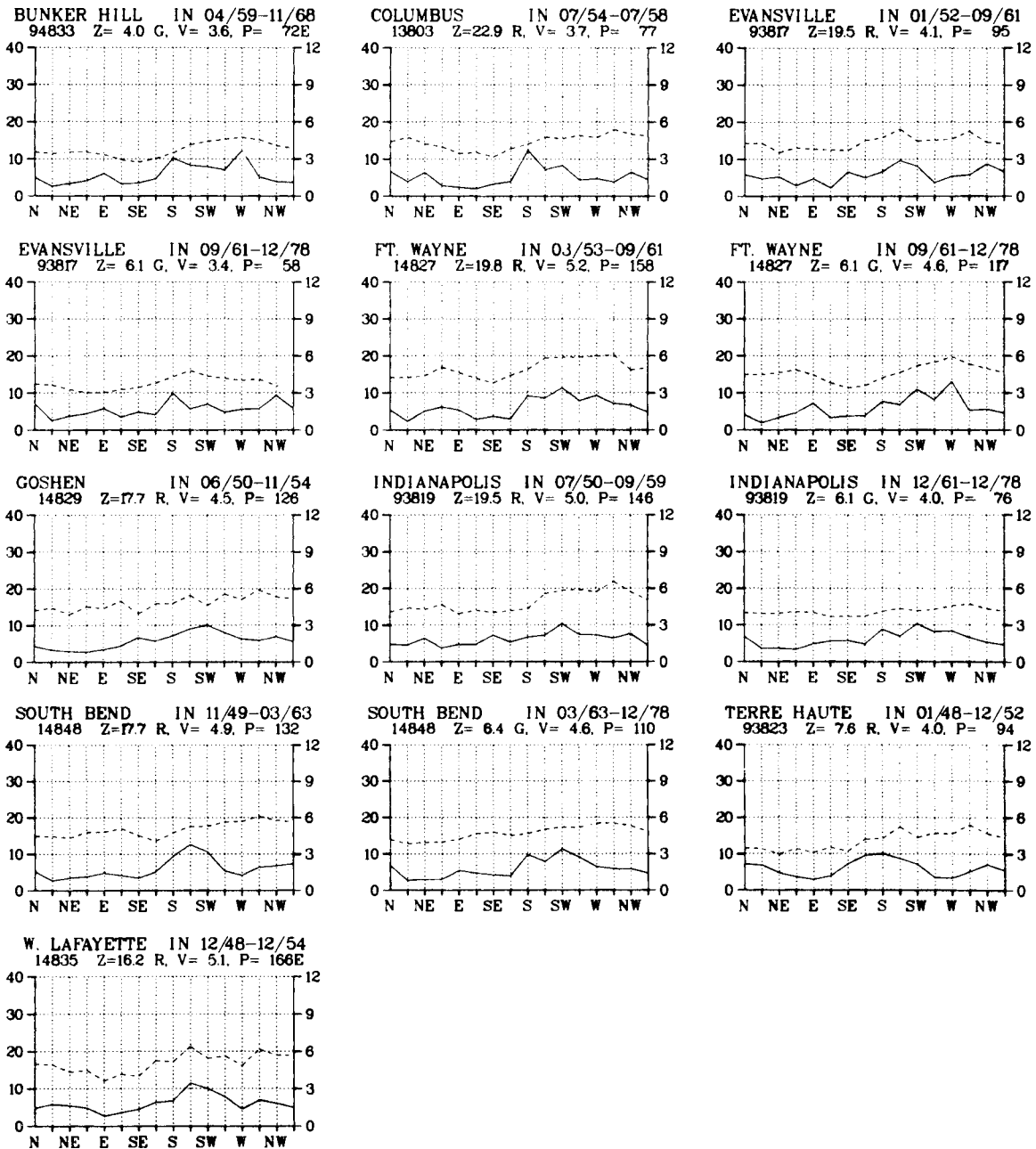


FIGURE 5.13. Directional Frequency and Average Wind Speed for Indiana

— ACTUAL DISTRIBUTION      ORDINATE - PERCENT  
 - - - RAYLEIGH DISTRIBUTION      ABSCISSA - M/S  
PNL-3195 WERA-3

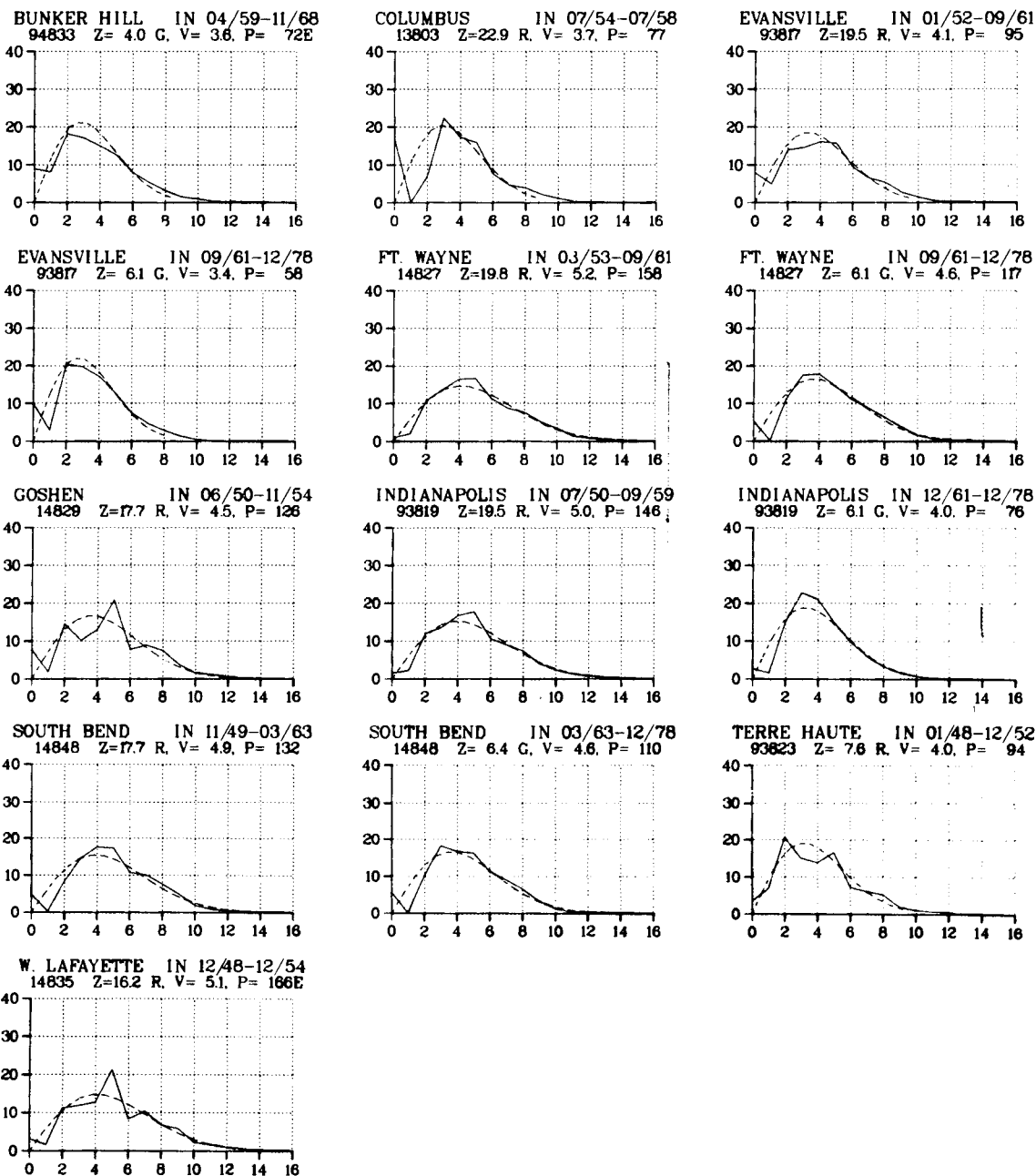


FIGURE 5.14. Annual Average Wind Speed Frequency for Indiana

ORDINATE - PERCENT  
 ABSCISSA - M/S  
 PNL-3195 WERA-3

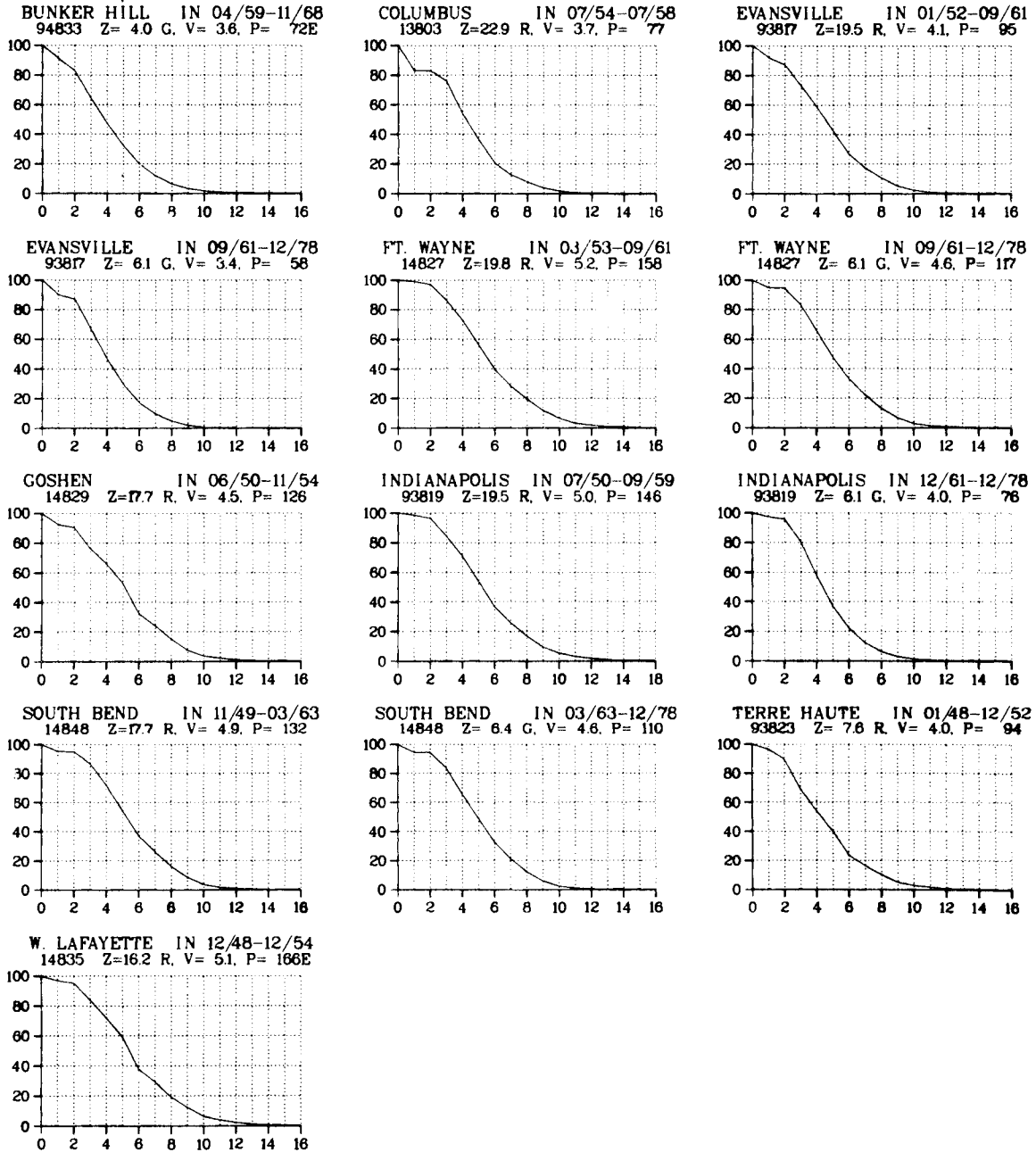
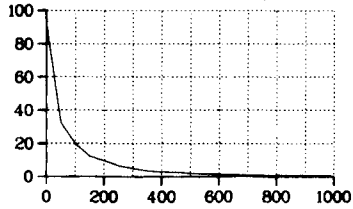


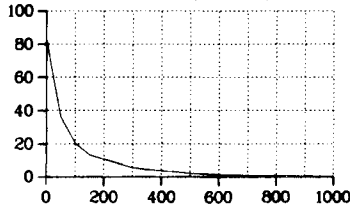
FIGURE 5.15. Annual Average Wind Speed Duration for Indiana

ORDINATE - PERCENT  
 ABSCISSA - WATTS/M<sup>2</sup>  
 PNL-3195 WERA-3

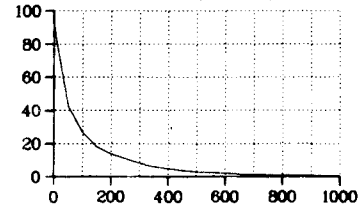
BUNKER HILL IN 04/59-11/68  
 94833 Z= 4.0 G. V= 3.6, P= 72E



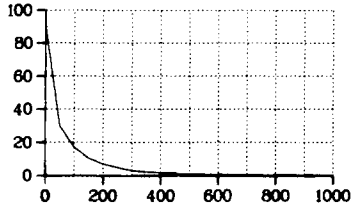
COLUMBUS IN 07/54-07/58  
 13803 Z=22.9 R. V= 3.7, P= 77



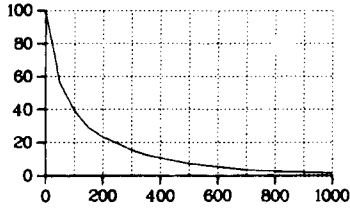
EVANSVILLE IN 01/52-09/61  
 93817 Z=19.5 R. V= 4.1, P= 95



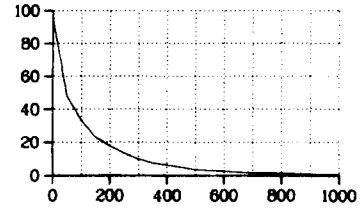
EVANSVILLE IN 09/61-12/78  
 93817 Z= 6.1 G. V= 3.4, P= 58



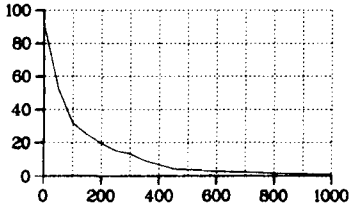
FT. WAYNE IN 03/53-09/61  
 14827 Z=19.8 R. V= 5.2, P= 158



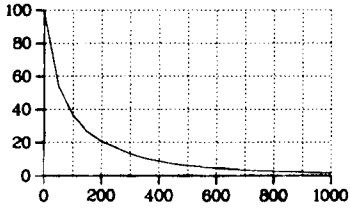
FT. WAYNE IN 09/61-12/78  
 14827 Z= 6.1 G. V= 4.8, P= 117



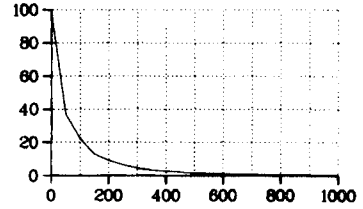
GOSHEN IN 06/50-11/54  
 14829 Z=17.7 R. V= 4.5, P= 128



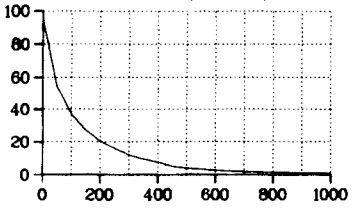
INDIANAPOLIS IN 07/50-09/59  
 93819 Z=19.5 R. V= 5.0, P= 148



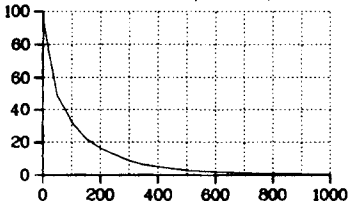
INDIANAPOLIS IN 12/61-12/78  
 93819 Z= 6.1 G. V= 4.0, P= 76



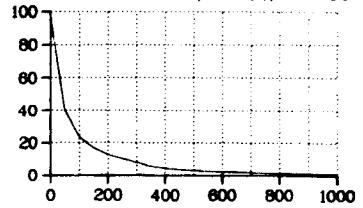
SOUTH BEND IN 11/49-03/63  
 14848 Z=17.7 R. V= 4.9, P= 132



SOUTH BEND IN 03/63-12/78  
 14848 Z= 6.4 G. V= 4.6, P= 110



TERRE HAUTE IN 01/48-12/52  
 93823 Z= 7.8 R. V= 4.0, P= 94



W. LAFAYETTE IN 12/48-12/54  
 14835 Z=16.2 R. V= 5.1, P= 166E

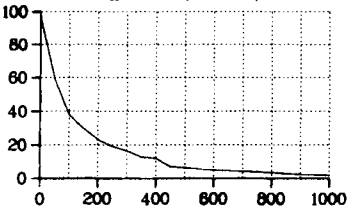


FIGURE 5.16. Annual Average Wind Power Duration for Indiana



**MICHIGAN**

Michigan, which had a population of 8,875,083 in 1970, covers an area of about 150,779 km<sup>2</sup> (58,216 mi<sup>2</sup>). Most of the inhabitants of Michigan live in the major cities of the Lower Peninsula (see Figure 6.1). Of the major cities, the Detroit area has the largest population (1,511,482). Much of the Upper Peninsula and northern sections of the Lower Peninsula are sparsely populated.

The topography of the eastern half of the Upper Peninsula varies from flat plains to rolling hills with heights ranging from 180 to 300 m (600 to 1,000 ft) (see Figure 6.2). To the west, elevations range from 420 to 480 m (1,400 to 1,600 ft), with the Porcupine Mountains rising to 617 m (2,023 ft). The Lower Peninsula has flat terrain to the southeast and gently rolling hills in the southwest with elevations from 240 to 300 m (800 to 1,000 ft). Sand dunes, rising to almost 120 m (400 ft), are present along Lake Michigan. The remaining part of the Lower Peninsula is flat (Figure 6.3).

The climate of Michigan is typically maritime in most sections, with little topographical protection from the prevailing winds and lake influences. Most of the Upper Peninsula is extensively forested. Wind data stations in Michigan, identified in Figures 6.4 and 6.5, are generally more dense in the Lower Peninsula than in the Upper Peninsula. The majority of the stations in the Upper Peninsula for which data are available from the National Climatic Center (NCC) are located near the coast of Lake Superior or Lake Michigan. Over the Lower Peninsula NCC stations are more uniformly distributed. The coastal stations are mostly Coast Guard towers. Their data are unsummarized, and often of unknown anemometer height and exposure. Therefore, whenever possible, summarized data collected at exposed coastal sites by utilities and private organizations were used to assess the wind power in these areas, instead of the Coast-Guard tower data. Data from the Nuclear Regulatory Commission (NRC) was obtained for seven nuclear facilities located in the Lower Peninsula near Lake Michigan or Lake Huron.

#### 6.1 ANNUAL AVERAGE WIND POWER

The annual average available wind power density in Michigan is shown in Figure 6.6. The analyses of mean wind power apply to terrain features that are favorably exposed to the wind, such as

hilltops, uplands, and open plains (see Section 1.6). However, nearby terrain features may interact with the wind field to cause the wind power at some exposed sites to vary as much as +50 to 100% from the assessment value. (See Wegley et al. 1980 for information on terrain features that may increase or reduce wind energy.) In forested or wooded areas, the estimates are representative of large clearings with good exposure to the prevailing strong winds, such as airports, where runways are generally aligned parallel to the prevailing wind direction(s). The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (Section 1.8).

The annual average wind power map for Michigan shows that the two regions of highest wind power potential for exposed sites are along the coasts of Lakes Michigan and Superior. The class 4 power estimates, along the western coast of the Lower Peninsula and along the northwestern coast of the Upper Peninsula, represent offshore areas and exposed coastal areas (that is, open shorelines that are not sheltered from the prevailing winds). Winds may be accelerated around and over capes and headlands, and exposed sites could have as much as class 5 or class 6 wind power (not indicated on the map). The abrupt increase of surface roughness inland from the coastline rapidly attenuates the wind resource landward of the coastline.

The candidate wind turbine site at Ludington illustrates well the local acceleration of winds resulting from the unique geometry of the site. This station is situated on a bluff directly on the coast. To the west the terrain drops sharply down to Lake Michigan. Westerly winds sweeping across the lake have a long, smooth fetch. When they reach the Ludington site, they are accelerated strongly over the bluff, resulting in a jet effect and winds that frequently exceed 6 m/s. This is a local effect, however, and is not typical of most exposed stations along the coast of Lake Michigan.

The class 4 wind power estimates along the Lake Michigan coast (including Beaver Island) and the western half of the Lake Superior coast up to Keweenaw Bay (including Isle Royale) are made based on the powerful northwesterly winds that reach the shoreline after sweeping over the smooth lake surfaces. Despite heavy

forest cover in the Upper Peninsula, areas of relatively high terrain (such as the Porcupine Mountains) make it possible for well exposed sites to experience powerful winds. East of the Huron Mountains, lower terrain and extensive forests make it difficult for sites to be well exposed. Class 3 wind power is assigned at the immediate shoreline but rapidly decreases to class 2 or 1 at inland locations. The Huron Mountains represent a transition region (lower wind power to the east, the higher wind power to the west). Here class 3 wind power is assigned not only to offshore sites but to the Huron Mountains and inland surrounding foothills. This reflects both the increased exposure due to terrain complexity (relative to the eastern coast) and the sheltering effect of the Keweenaw Peninsula to the north-northwest.

The band of class 3 denoted along the shores of Lake Huron and Lake Erie is largely a seasonal phenomenon. Winter and spring storm systems moving eastward give rise to northeasterly winds that blow landward off the water. In the narrow band of class 3 wind power bordering Lake Michigan, wind power is expected to decrease with increasing distance from the coast (because of increased surface roughness). The width of this band, however, should not be taken as exactly delineating the area experiencing this wind power; rather, it only delineates in a general manner the transition from the stronger coastal winds to the weaker inland winds.

Effects of local channeling are evident in the Straits of Mackinac. Class 3 or higher wind power may occur in the straits when prevailing westerlies are accelerated between the Upper and Lower Peninsula.

Although no data were available, the southern tip of the Garden Peninsula, situated on Lake Michigan, was assigned class 3 wind power. This was justified by the assumption that the Garden Peninsula has the same wind power potential as the Door Peninsula to the south. Furthermore, the Garden Peninsula is well exposed to winds having long fetches across Green Bay or Lake Michigan. Central sections of the Upper and Lower Peninsula are too far inland to be exposed to winds off the lakes - as indicated by assigning wind power classes 1 and 2 to these areas.

### 6.1.1 Certainty Rating of the Wind Resource

Low certainty ratings are assigned to almost all the coastal areas in Michigan. None of the areas of Michigan have both large wind resources and high certainty, because the offshore marine data and coastal data used in estimating the coastal wind resource were not considered highly representative of nearby exposed areas. Also, the very high spatial variability of the wind power resource along the coastlines results in low overall certainty ratings. The areas of certainty rating 2 in the Upper Peninsula largely reflect the sparseness of data in the inland regions. The southern sections of the Upper Peninsula are assigned higher certainty ratings because of more data stations and lower spatial variability of the wind power resource.

In the Lower Peninsula, the certainty rating of the wind power increases inland from the coast because wind spatial variability decreases with distance from the coast. Moreover, because the terrain is not complex and more well-exposed data stations exist with long periods of record, the wind resource can be assigned much higher certainty estimates.

### 6.1.2 Areal Distribution

The broad extent of class 1 and class 2 wind power in the Upper Peninsula and interior sections of the Lower Peninsula is evident in the areal distribution of wind power classes (Table 6.1). The modest areal contribution from class 3 wind power is due mostly to areas bordering Lake Michigan, Lake Huron, and Lake Superior. The only areas of class 4 or greater wind power are along the Lake Michigan and Lake Superior coastlines. Because of the very small fractional areas that are assigned wind power classes 4 and 5, the corresponding maps in Figure 6.8 are almost featureless.

## 6.2 SEASONAL WIND POWER

Wind power maps for each season are shown in Figure 6.9. Throughout the entire state, the season of least wind power potential is summer. During the winter, the wind power resource is at its maximum everywhere but in the western half of the Lake Superior shoreline (where maximum wind power is attained in the spring).

### 6.2.1 Winter

In the winter, the Lake Michigan shoreline (including Beaver Island) is estimated to have class 5 wind power. Prevailing winds flow from the northwest across a long, smooth fetch. The high wind speeds recorded at exposed coastal and offshore sites along Lake Michigan reflect the low surface roughness of the fetches. As indicated by the band, class 4 wind power is attenuated rapidly over land with increasing surface roughness. Inland wind power is estimated at class 2 or 3, indicating the landward reduction in wind power.

Along the east coast of Michigan, the wind resources increase again as the shores of Lake Huron and Erie are approached. Class 4 wind power reflects the prevalence of eastward-moving storm systems in winter. Such storms are associated with northeasterly flow as they pass over the east coast of the Lower Peninsula.

The rapid attenuation of the wind resource over land is most readily observed on the northeastern coast of Lake Huron. Figure 6.9 shows a reduction from class 4 to class 2; most likely a very narrow band of class 3 may also be present, but could not be resolved in this analysis.

The western half of the Lake Superior coast on the Upper Peninsula has been assigned a wind power of class 4, whereas Isle Royale is assigned class 5. As in the Lower Peninsula, these wind power densities reflect the prevailing northwesterlies. The Lake Superior shoreline west of the Keweenaw Peninsula is oriented so that winds from all sectors (except the sector from east through south-southwest) have a wide open-water fetch. Consequently, westerly and northeasterly winds are not significantly inhibited by frictional drag and reach the shoreline with high velocities. The elevated relief in the areas (e.g., the Porcupine and Huron mountains) contributes to the wind power potential of this region.

Over the extreme eastern portion of the Upper Peninsula, easterly winds are frequently experienced during late fall and winter. These winds, observed at Sault St. Marie, arise in response to the eastward-moving cyclonic disturbances south of the peninsula and the anti-cyclonic movement across southern Canada. The easterly winds experience over-water fetch along this section of the Upper Peninsula, and the resulting

surface wind speeds are not as high as those measured over the western half of the peninsula. The class 3 wind resource assigned to the Huron Mountains serves to indicate the combined effects of the topographical relief and the Keweenaw Peninsula. The abrupt decrease in wind power from class 4 to class 1 in western sections results from flatter terrain and increased surface roughness.

### 6.2.2 Spring

During spring, the wind power resource over Michigan is not unlike that of winter; the major differences occur along the western shore of Lake Superior and the Lake Michigan shoreline. Class 5 wind power has been estimated for the area extending eastward from the Wisconsin border out to the Keweenaw Peninsula; stations east of the peninsula do not indicate a springtime increase in wind power. On the Lake Michigan shoreline, wind power decreases from March to May, which is represented by assigning class 4 wind power. This observed decrease in wind power is largely due to the decrease in the frequency and intensity of the coastward moving storms. The lake-breeze effect increases from March to May, but this is not significant enough to maintain the powerful winter winds.

### 6.2.3 Summer

Summer is the season of minimum wind power everywhere in the state. Surface pressure and temperature gradients are typically at their lowest. Prevailing winds are from the southwest due to the position of the Bermuda High and are weak. Summer lake breezes are light and extend inland only a few (13 to 16) km (8 to 10 mi).

### 6.2.4 Autumn

The autumn wind power map reflects the strengthening of surface pressure gradients and the land-water temperature gradients. Class 4 wind power is once again estimated for exposed coastal and offshore sites on the western coast of Lake Michigan and for the western half of the Lake Superior shore. Here, the power-producing winds are generally from the west-southwest and west-northwest. The channeling effects in the Straits of Mackinac reappear as winds shift towards the west.

## 6.3 FEATURES OF SELECTED STATIONS

Table 6.2 gives the locations, the annual wind speeds, and annual wind power

densities of 18 stations in Michigan. Graphs of other features of the wind resource are shown in Figures 6.10 to 6.16. Of these, 3 stations are located on the Upper Peninsula and 9 stations are situated in coastal areas.

Alpena/Phelps Collins Field, located in the northeastern part of the Lower Peninsula is 10 km (6 mi) inland from Thunder Bay and 16 to 19 km (10 to 12 mi) from Lake Huron. The terrain is generally flat, but the site exposure is uncertain because of the sheltering effect of the small peninsula to the east.

Cadillac Municipal Airport, in the north central part of the Lower Peninsula, is surrounded by relatively flat terrain. Exposure appears excellent.

Detroit/City Airport, in the southeastern corner of the Lower Peninsula, is 10 to 13 km (6 to 8 mi) west of the Lake St. Clair shoreline. The terrain is flat and the exposure to prevailing winds appears good.

Detroit/Metro-Wayne Airport is located in the southeastern corner of Michigan on the edge of metropolitan Detroit. Like Detroit/City Airport, the terrain is flat and the exposure appears good.

Flint/Bishop Airport is situated in southeastern Michigan where the terrain is generally flat. The site seems to be very well exposed to prevailing winds.

Gladwin Municipal Airport is in central Michigan on relatively flat terrain. Low wind speeds suggest uncertain anemometer exposure.

Grand Marais is located on the shore of Lake Superior in the Upper Peninsula of Michigan. The site is east of the Pictured Rocks National Lakeshore. Observed wind speeds are quite low and the anemometer exposure is questionable.

Grand Rapids/Kent County Airport is in west central Michigan near the Grand River. The region is hilly with irregular plains. The data indicate good exposure to prevailing winds.

Gwinn/Sawyer Air Force Base (AFB) is in the middle of the Upper Peninsula, roughly 16 km (10 mi) north of Lake Michigan. Much of the surrounding area is extensively forested but the site appears to have good exposure and is considered representative of exposed sites in the area.

Houghton County Airport is located in the middle part of the Keweenaw Peninsula approximately 10 km (6 mi) from Lake Superior. The airport seems to be on a ridge in the peninsula and the exposure is apparently quite good.

Jackson/Reynolds Airport is located on the south central part of the Lower Peninsula. The surrounding area is characterized by irregular plains. The site seems to be representative of exposed sections in this region.

Lansing/Capitol City Airport sits on relatively flat terrain in south central Michigan. The anemometer is apparently unobstructed so that the site is considered representative of the area.

Mount Clemens/Selfridge AFB is in southeastern Michigan on the shores of Lake St. Clair. Anemometer exposure is not well known.

Muskegon County Airport is situated in west central Michigan about 3 to 5 km (2 to 3 mi) inland from the shores of Lake Michigan. So situated, it seems representative of the area but not of stations on the immediate coast or offshore.

Oscoda/Wurtsmith AFB is located on the western shore of Lake Huron just above the Saginaw Bay. The terrain is flat, but low observed wind speeds suggest questionable exposures.

Saginaw Tri-City Airport is in central Michigan, approximately 24 km (15 mi) inland from Saginaw Bay. Lack of topographical relief makes the site well exposed to prevailing winds.

Sault St. Marie Municipal Airport is located on the eastern tip of northern Michigan near Lake Superior on St. Mary's River. The site may be sheltered somewhat, although exposure is not certain.

Traverse City is located at the end of Grande Traverse Bay in northwestern Michigan. The area is characterized by plains with hills. Escarpments to the west make the anemometer exposure questionable.

### 6.3.1 Interannual Wind Power and Speed

Ten of the 18 selected stations have periods of record of 10 years or more during which the anemometer was not moved (Figure 6.10). The interannual variability ranges from low at Traverse City to high at Gwinn. In general,

however, the variability is not large. Where the variability is large, it occurs between periods of record during which the anemometer was moved.

### 6.3.2 Monthly Average Wind Power and Speed

With some exceptions, winter is the season of maximum wind power (see Figure 6.11). Selected stations with spring maxima include Jackson, Houghton, and Gladwin; other stations show spring wind power about equal to the winter wind power. In all cases, the minimum wind power is in August. Alpena and Traverse City show the least seasonal variation; Jackson shows the largest seasonal variation.

### 6.3.3 Diurnal Wind Speed by Season

Maximum wind speed in all cases is reached between 1200 and 1500 LST (Figure 6.12). The largest seasonal variation is found at Jackson. The diurnal variation is largest in summer and smallest during the winter. In Detroit/City for example, the winter afternoon increase in wind speed is barely discernable.

### 6.3.4 Directional Frequency and Average Speed

In general, the prevailing wind direction at each station is largely

dependent on its location and its proximity to the lakes (Figure 6.13). At Grand Marais and Gwinn, prevailing winds flow from the north. Sault St. Marie and Houghton, both coastal stations, experience prevailing winds from the east-southeast and the west-northwest. Other stations have prevailing winds from the southwest, but the strong winds are generally from the northwest.

### 6.3.5 Annual Average Wind Speed Frequency

Observer bias is readily apparent at Cadillac, Detroit/City, Gladwin, Grand Marais, Gwinn, Houghton, Jackson, Mt. Clemens, Oscoda, Saginaw, and Traverse City, as evidenced by the peaks at 2, 5, and 8 m/s (5, 10, and 15 knots) seen in Figure 6.14. Stations with more recent records show less evidence of observer bias.

### 6.3.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in Figures 6.15 and 6.16. Abrupt changes in the slope of the duration correspond to peaks in the speed frequency distribution caused by observer bias and by instrument threshold velocity.



FIGURE 6.1. Geographic Map of Michigan

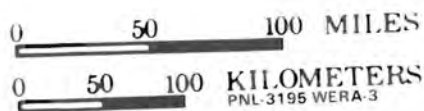
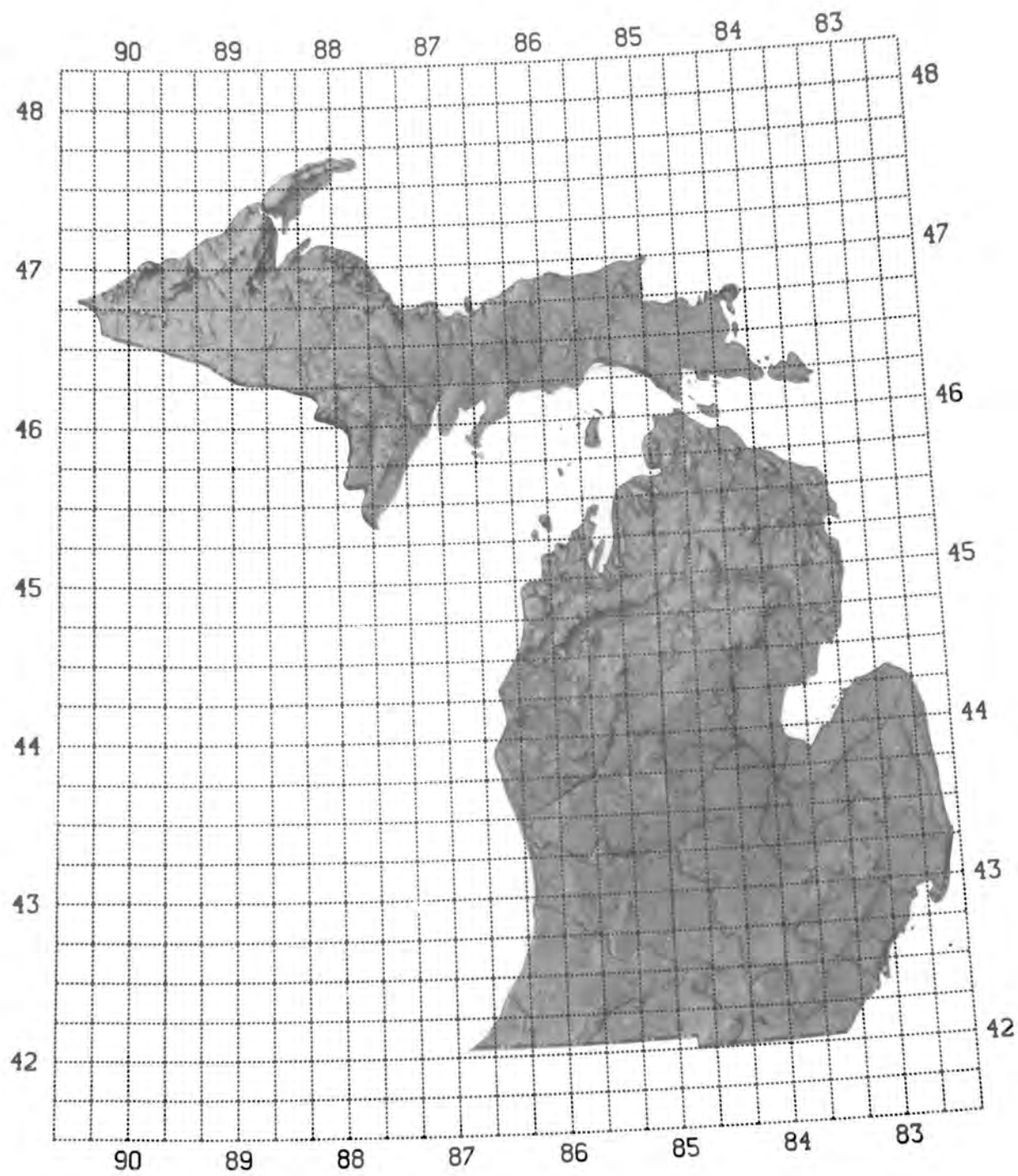


FIGURE 6.2. Topographic Map of Michigan

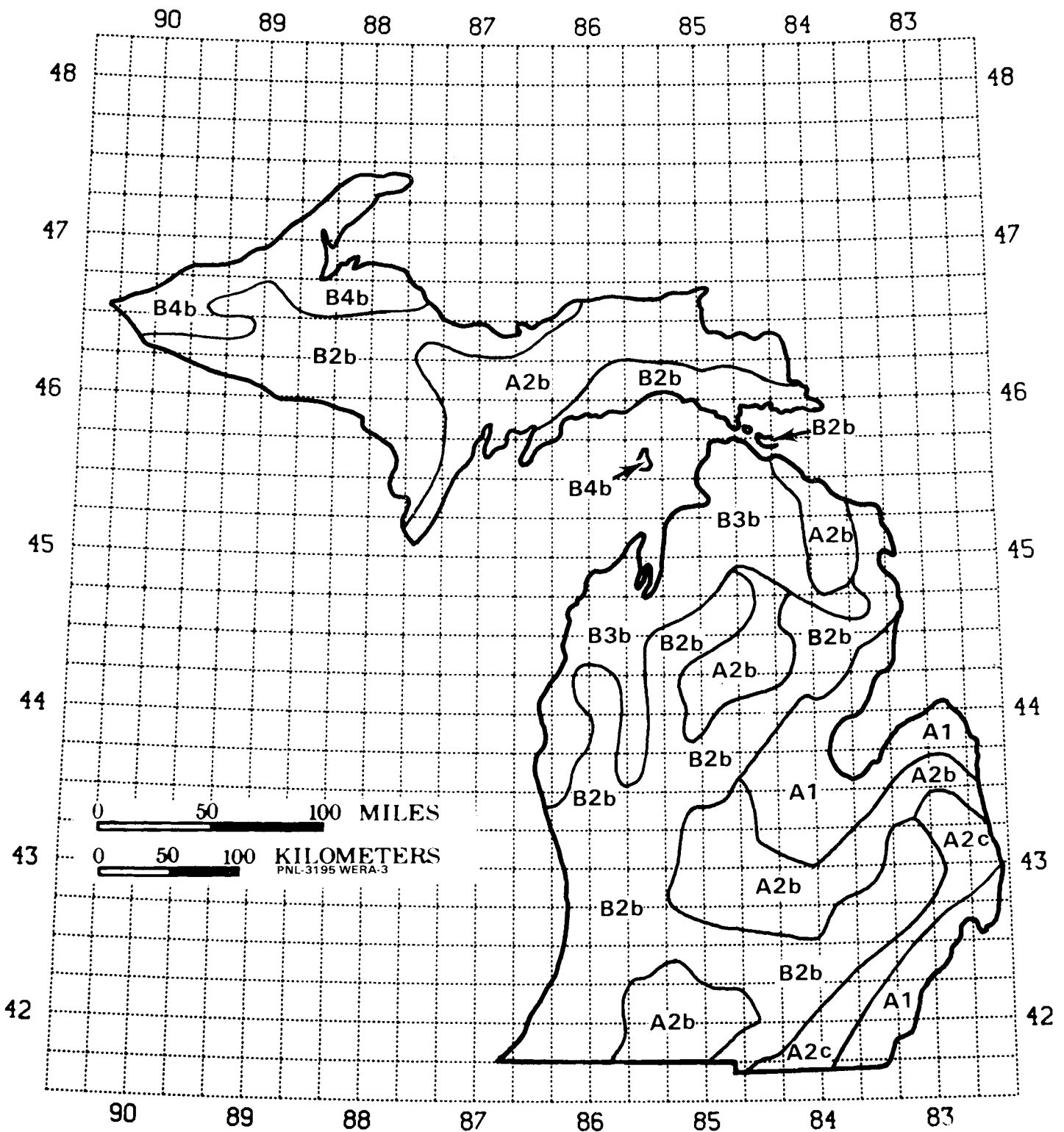


FIGURE 6.3. Classes of Land-Surface Form in Michigan

## LAND-SURFACE FORM LEGEND

### PLAINS

|    |                                 |
|----|---------------------------------|
| A1 | FLAT PLAINS                     |
| A2 | SMOOTH PLAINS                   |
| B1 | IRREGULAR PLAINS, SLIGHT RELIEF |
| B2 | IRREGULAR PLAINS                |

### PLAINS WITH HILLS OR MOUNTAINS

|         |                            |
|---------|----------------------------|
| A,B3a,b | PLAINS WITH HILLS          |
| B4,a,b  | PLAINS WITH HIGH HILLS     |
| B5a,b   | PLAINS WITH LOW MOUNTAINS  |
| B6a,b   | PLAINS WITH HIGH MOUNTAINS |

### OPEN HILLS AND MOUNTAINS

|    |                     |
|----|---------------------|
| C2 | OPEN LOW HILLS      |
| C3 | OPEN HILLS          |
| C4 | OPEN HIGH HILLS     |
| C5 | OPEN LOW MOUNTAINS  |
| C6 | OPEN HIGH MOUNTAINS |

### HILLS AND MOUNTAINS

|    |                |
|----|----------------|
| D3 | HILLS          |
| D4 | HIGH HILLS     |
| D5 | LOW MOUNTAINS  |
| D6 | HIGH MOUNTAINS |

### TABLELANDS

|       |                                 |
|-------|---------------------------------|
| B3c,d | TABLELANDS, MODERATE RELIEF     |
| B4c,d | TABLELANDS, CONSIDERABLE RELIEF |
| B5c,d | TABLELANDS, HIGH RELIEF         |
| B6c,d | TABLELANDS, VERY HIGH RELIEF    |

### SCHEME OF CLASSIFICATION

#### SLOPE (1st LETTER)

|   |                               |
|---|-------------------------------|
| A | >80% OF AREA GENTLY SLOPING   |
| B | 50-80% OF AREA GENTLY SLOPING |
| C | 20-50% OF AREA GENTLY SLOPING |
| D | <20% OF AREA GENTLY SLOPING   |

#### LOCAL RELIEF (2nd LETTER)

|   |                                |
|---|--------------------------------|
| 1 | 0 TO 30m (1 TO 100 ft)         |
| 2 | 30 TO 90m (100 TO 300 ft)      |
| 3 | 90 TO 150m (300 TO 500 ft)     |
| 4 | 150 TO 300m (500 TO 1000 ft)   |
| 5 | 300 TO 900m (1000 TO 3000 ft)  |
| 6 | 900 TO 1500m (3000 TO 5000 ft) |

#### PROFILE TYPE (3rd LETTER)

|   |                                      |
|---|--------------------------------------|
| a | >75% OF GENTLE SLOPE IS IN LOWLAND   |
| b | 50-75% OF GENTLE SLOPE IS IN LOWLAND |
| c | 50-75% OF GENTLE SLOPE IS ON UPLAND  |
| d | >75% OF GENTLE SLOPE IS ON UPLAND    |



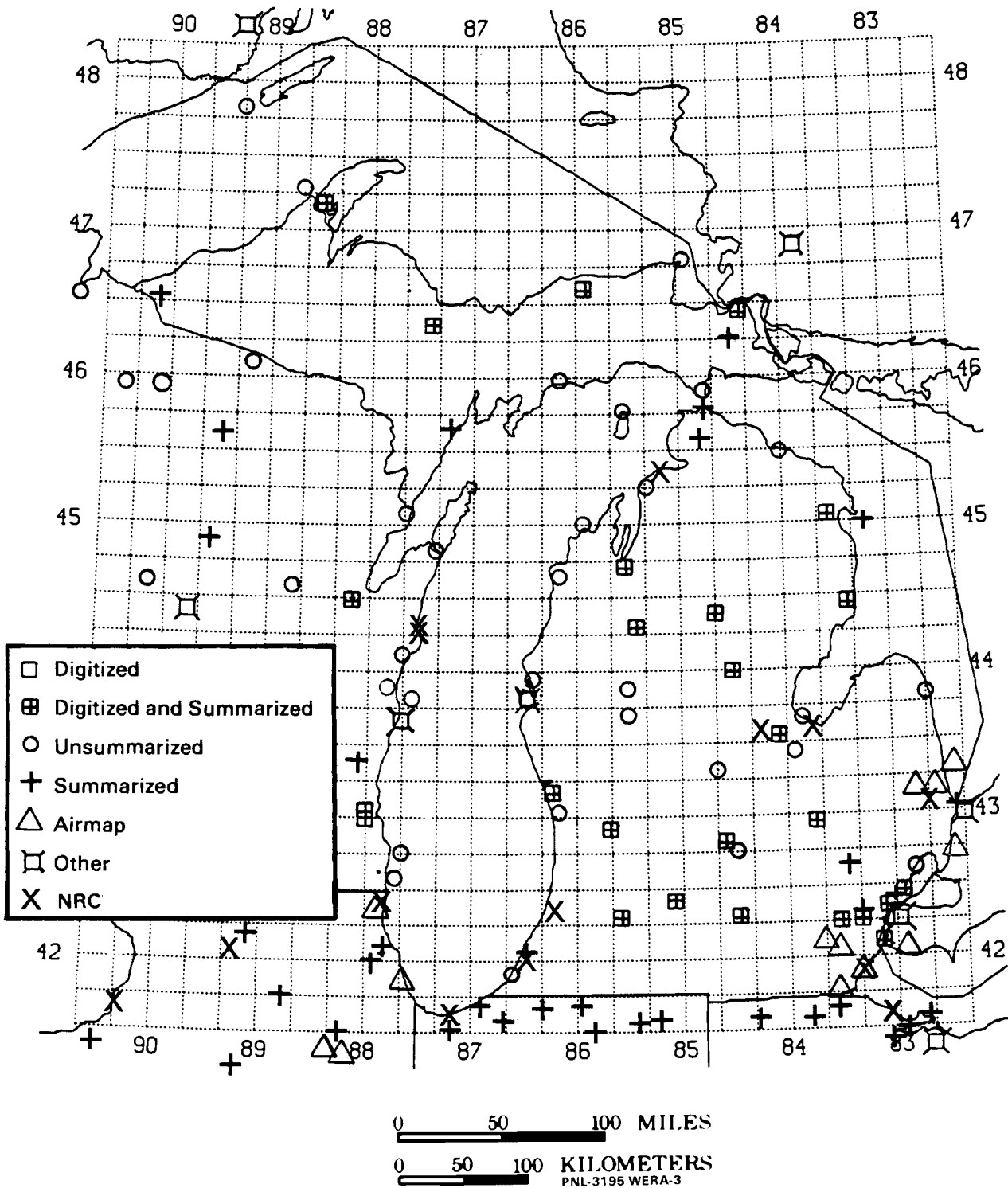


FIGURE 6.5. Location of Stations Used in Michigan Resource Assessment

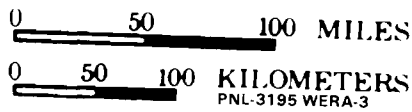
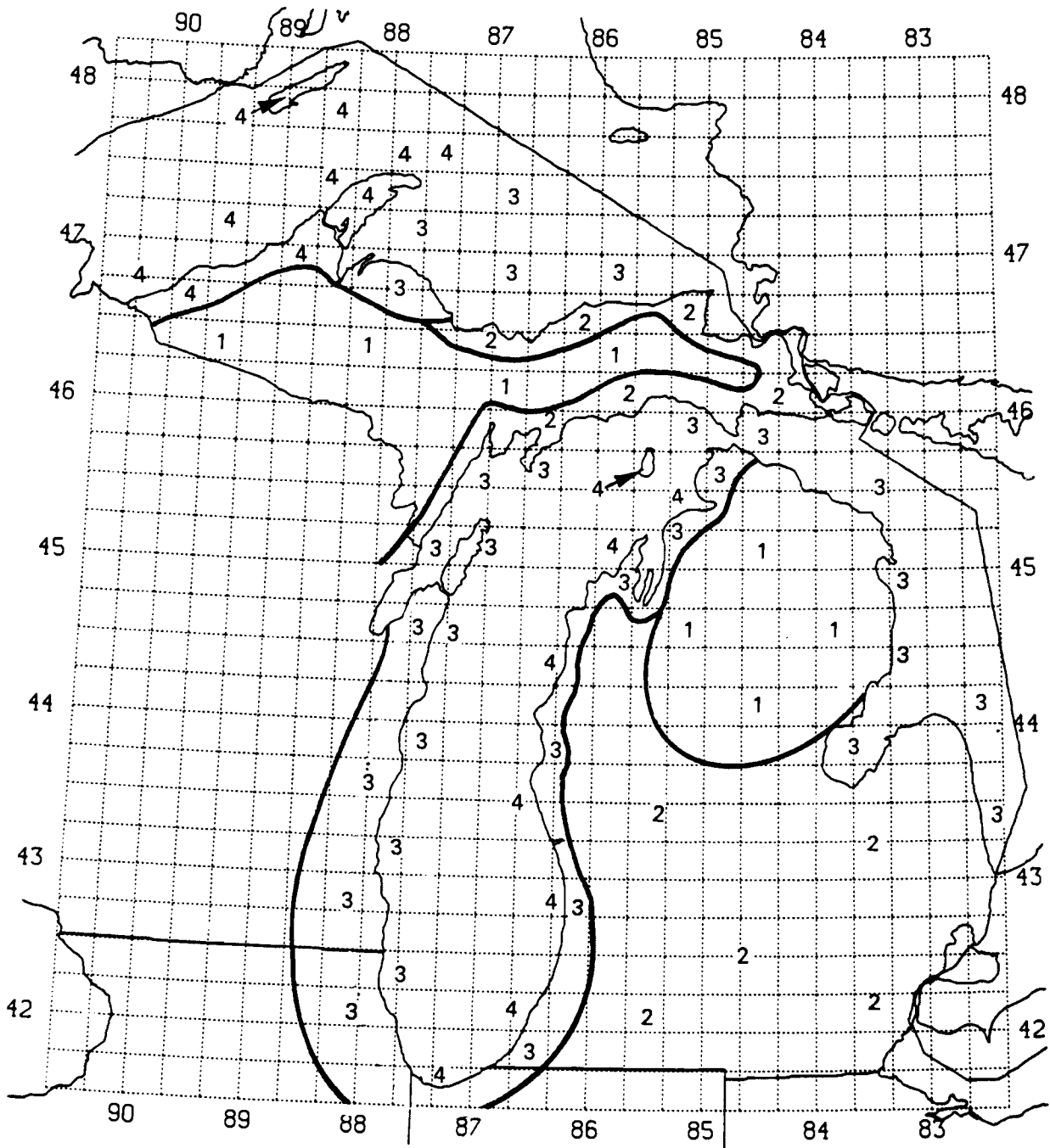


FIGURE 6.6. Michigan Annual Average Wind Power

Classes of Wind Power Density at 10 m and 50 m<sup>(a)</sup>

| Wind Power Class | 10 m (33 ft)                             |                                 | 50 m (164 ft)                            |                                 |
|------------------|--|---------------------------------|--|---------------------------------|
|                  | Wind Power Density, watts/m <sup>2</sup> | Speed, <sup>(b)</sup> m/s (mph) | Wind Power Density, watts/m <sup>2</sup> | Speed, <sup>(b)</sup> m/s (mph) |
| 0                | 0  | 0                               | 0  | 0                               |
| 1                | 100                                      | 4.4 (9.8)                       | 200                                      | 5.6 (12.5)                      |
| 2                | 150                                      | 5.1 (11.5)                      | 300                                      | 6.4 (14.3)                      |
| 3                | 200                                      | 5.6 (12.5)                      | 400                                      | 7.0 (15.7)                      |
| 4                | 250                                      | 6.0 (13.4)                      | 500                                      | 7.5 (16.8)                      |
| 5                | 300                                      | 6.4 (14.3)                      | 600                                      | 8.0 (17.9)                      |
| 6                | 400                                      | 7.0 (15.7)                      | 800                                      | 8.8 (19.7)                      |
| 7                | 1000                                     | 9.4 (21.1)                      | 2000                                     | 11.9 (26.6)                     |

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 6.1. Areal Distribution (km<sup>2</sup>) of Wind Power Classes in Michigan

| Power Class | Land Area | Percent Land Area | Cumulative Land Area | Percent Cumulative Land Area |
|-------------|-----------|-------------------|----------------------|------------------------------|
| 1           | 47,000    | 35.0              | 135,000              | 100.0                        |
| 2           | 64,000    | 47.0              | 88,000               | 65.0                         |
| 3           | 20,000    | 15.0              | 24,000               | 18.0                         |
| 4           | 4,200     | 3.1               | 4,500                | 3.3                          |
| 5           | 168       | 0.12              | 281                  | 0.21                         |
| 6           | 113       | 0.08              | 113                  | 0.08                         |
| 7           | 0         | 0                 | 0                    | 0                            |

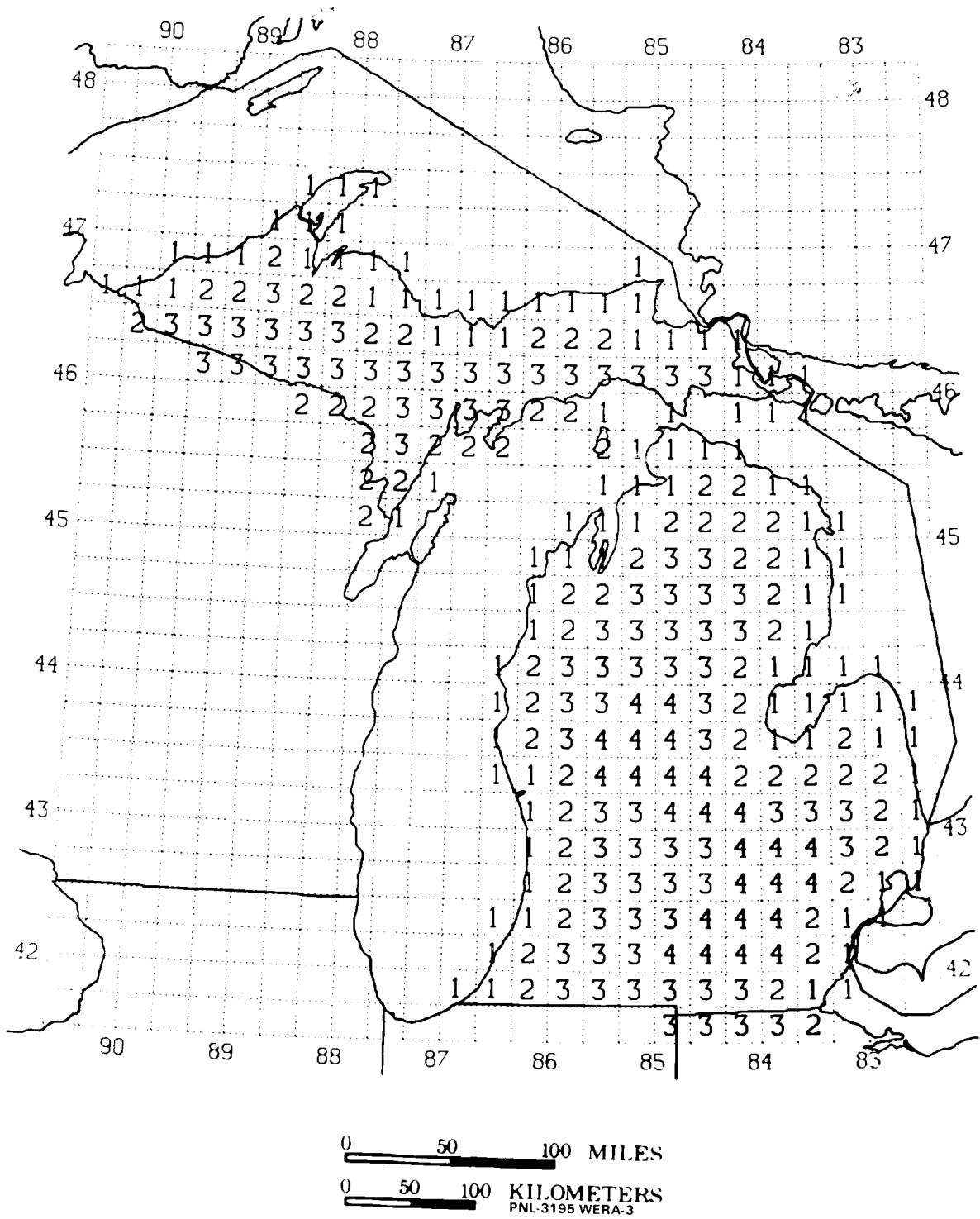


FIGURE 6.7. Certainty Rating of Michigan Wind Resource

### CERTAINTY RATING LEGEND

| Rating | Definition   |
|--------|--|
| 1      | <p>The lowest degree of certainty. A combination of the following conditions exists:</p> <ol style="list-style-type: none"><li>1) No data exist in the vicinity of the cell.</li><li>2) The terrain is highly complex.</li><li>3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.</li></ol>   |
| 2      | <p>A low-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"><li>1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data.</li><li>2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.</li></ol> |
| 3      | <p>A high-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"><li>1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data.</li><li>2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.</li></ol>       |
| 4      | <p>The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.</p>   |

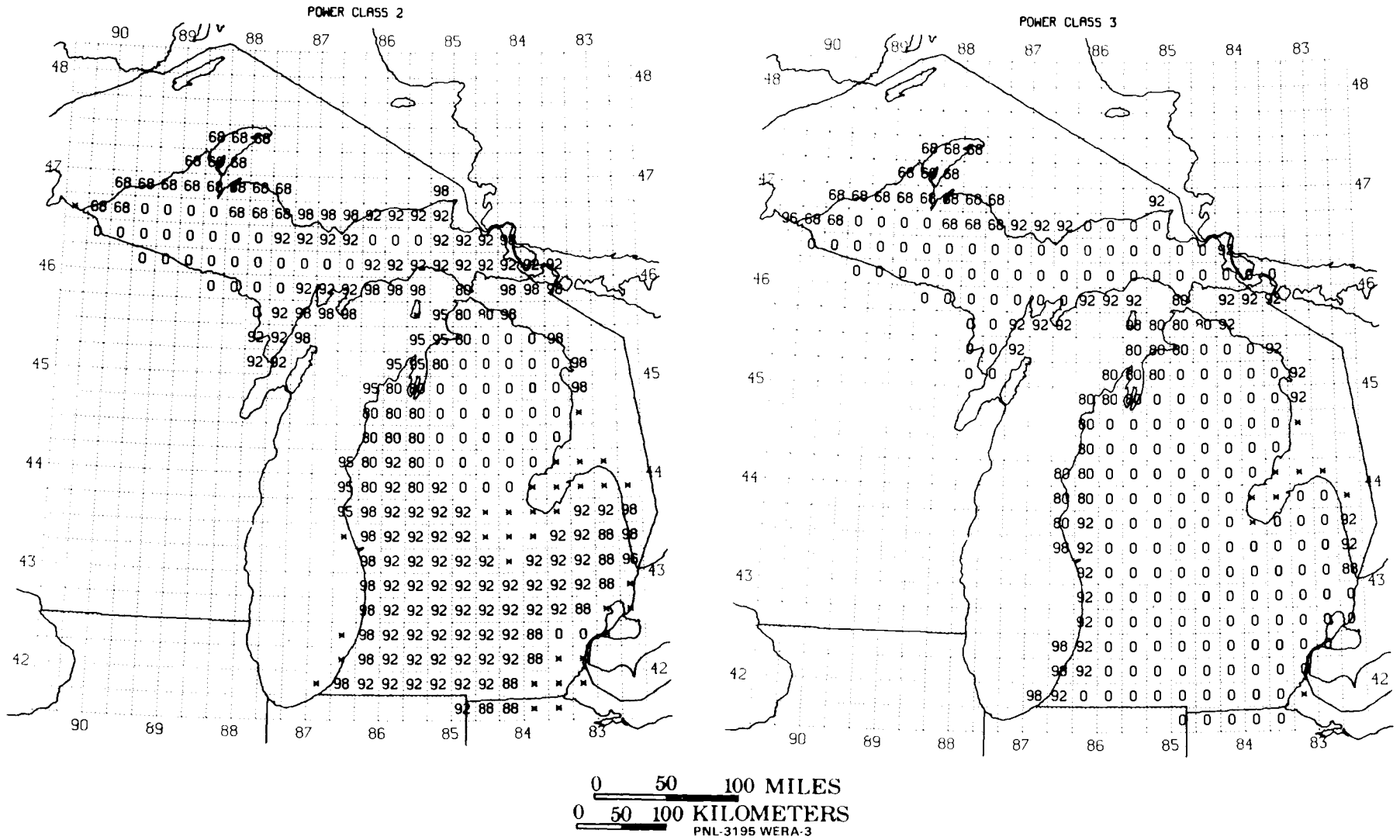


FIGURE 6.8. Areal Distribution of Wind Resource in Michigan (Power Classes 2 and 3); Percent of Land Area With or Exceeding Power Class Shown. An asterisk denotes 100%.

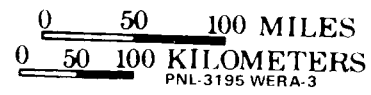
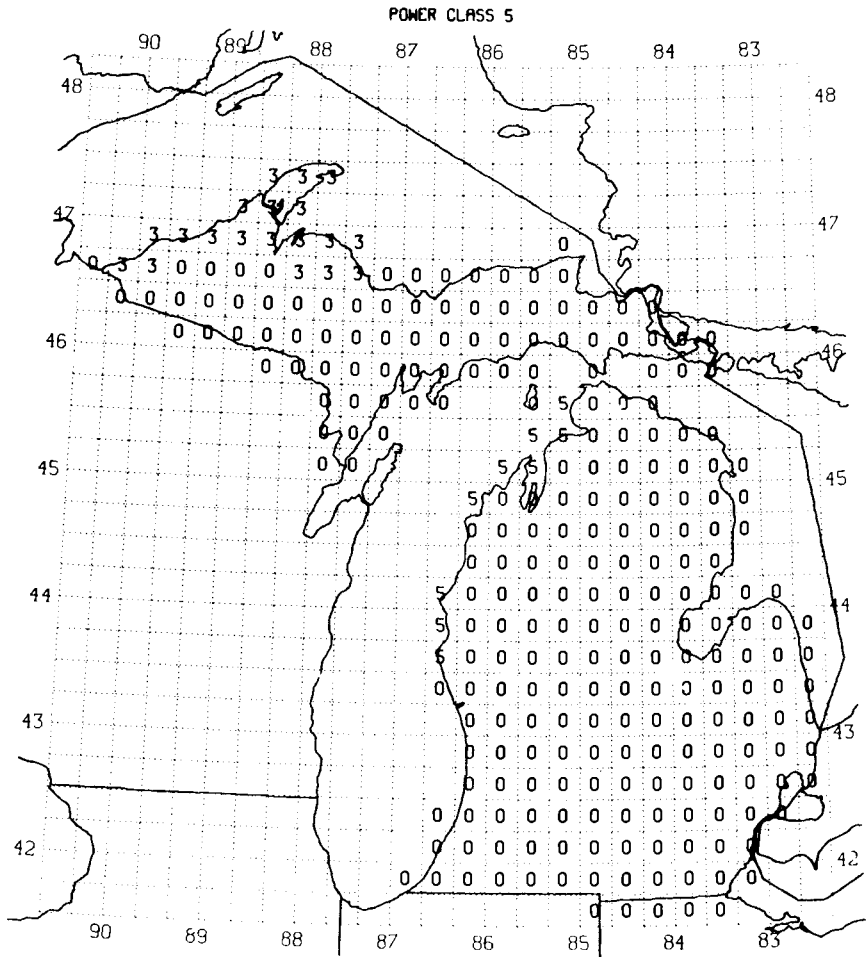
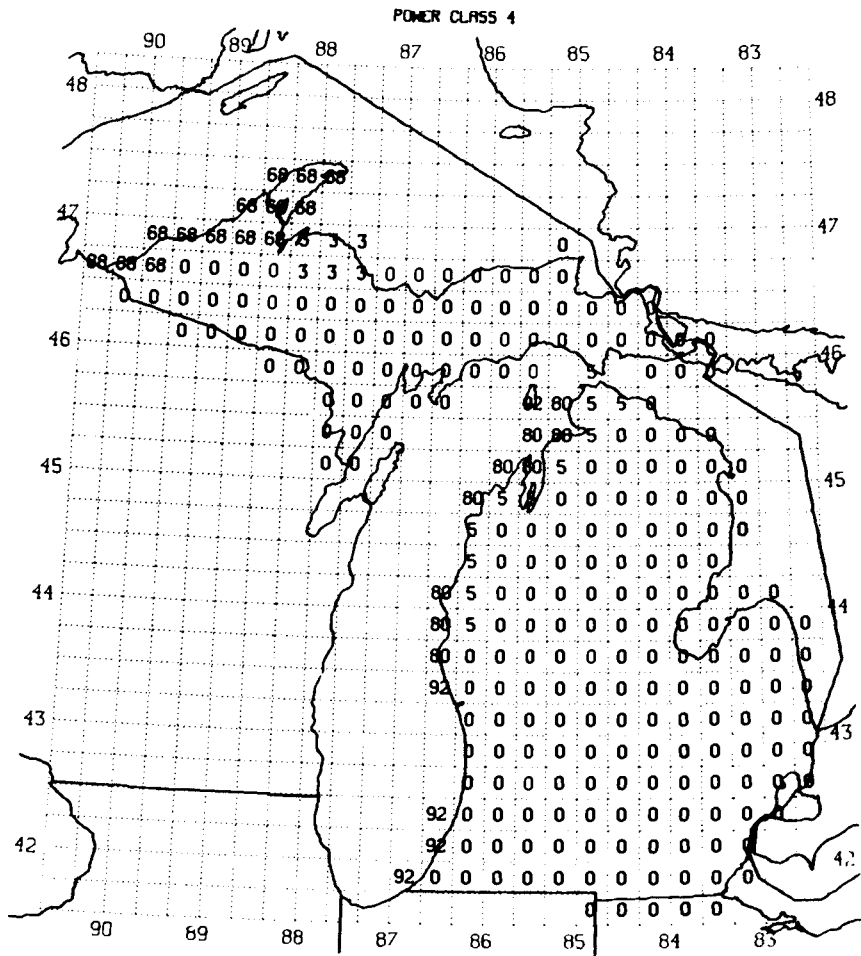


FIGURE 6.8 (Continued). Areal Distribution of Wind Resource in Michigan (Power Classes 4 and 5); Percent of Land Area With or Exceeding Power Class Shown.

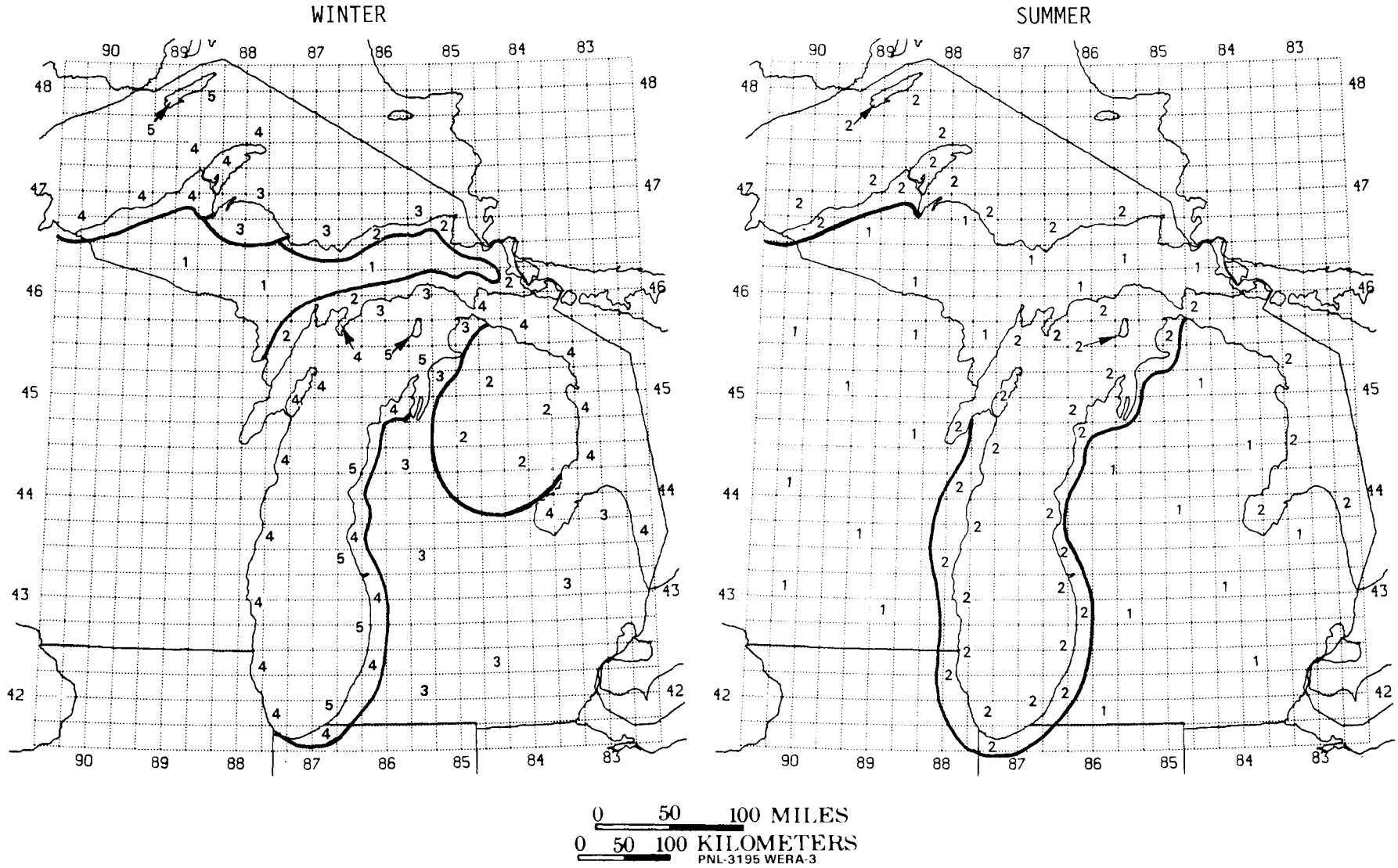


FIGURE 6.9. Seasonal Average Wind Power in Michigan

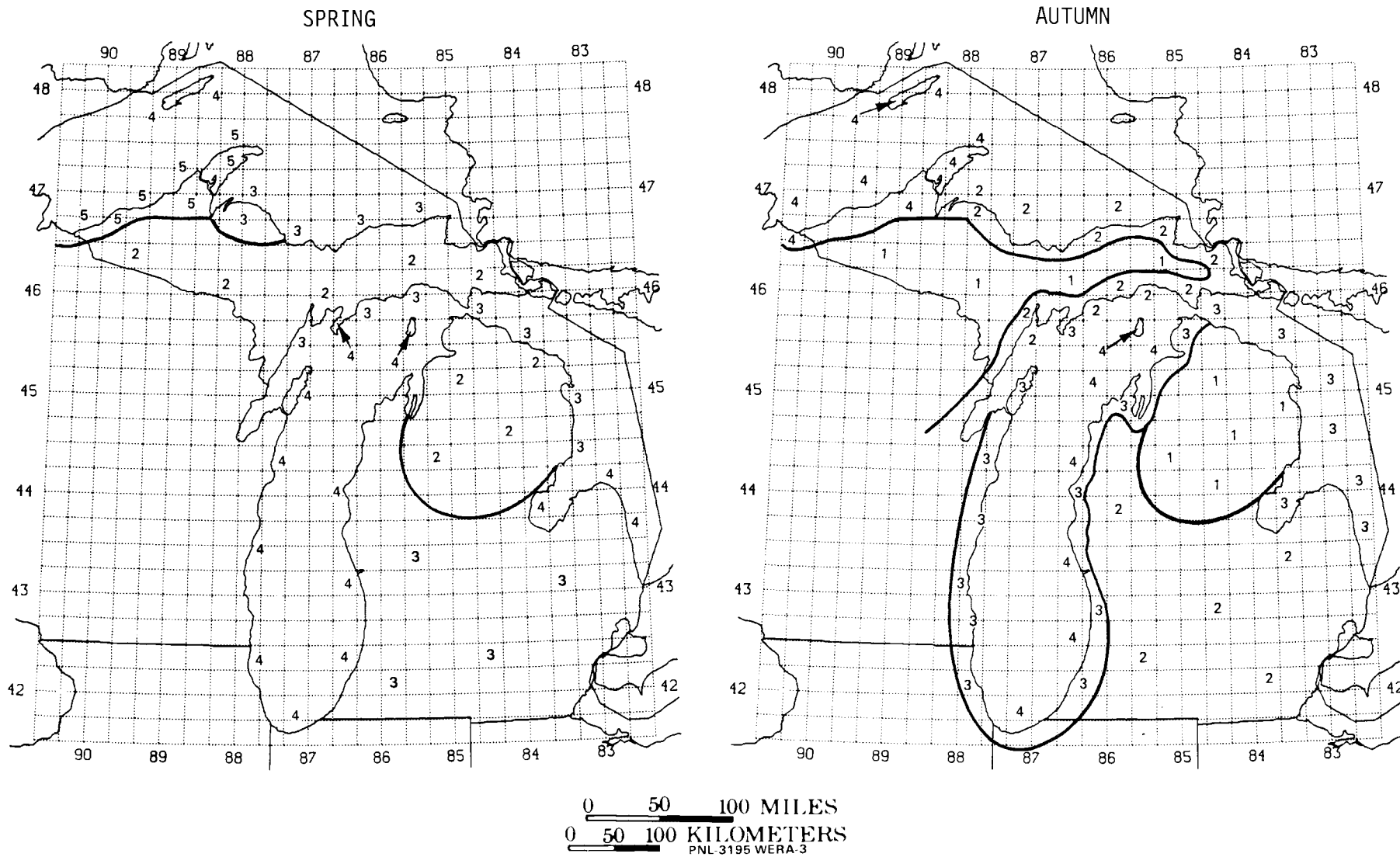


FIGURE 6.9 (Continued). Seasonal Average Wind Power in Michigan

TABLE 6.2. Michigan Stations with Graphs of the Wind Characteristics

| Station            | Station Name <sup>(a)</sup>  | Latitude,<br>Degrees North | Longitude,<br>Degrees West | Elevation of<br>Station, m | Period of<br>Record,<br>mm/yy | Anemometer<br>Height, m | Annual Average<br>Wind Speed, m/s |            |            | Annual Average<br>Wind Power<br>Watts/m <sup>2</sup> |            |            |
|--------------------|------------------------------|----------------------------|----------------------------|----------------------------|-------------------------------|-------------------------|-----------------------------------|------------|------------|--|------------|------------|
|                    |                              |                            |                            |                            |                               |                         | Anemometer<br>Height              | At<br>10 m | At<br>50 m | Anemometer<br>Height                                 | At<br>10 m | At<br>50 m |
| Alpena             | Phelps Collins<br>Field WBAS | 45.06                      | 83.56                      | 211                        | 07/74-12/78                   | 6.7                     | 3.9                               | 4.1        | 5.2        | 71   | 84         | 168        |
| Cadillac           | Municipal Airport CAA        | 44.28                      | 85.41                      | 399                        | 12/48-12/54                   | 9.1                     | 4.7                               | 4.7        | 5.9        | 159  | 165        | 329        |
| Detroit City       | Detroit City Airport<br>WBAS | 42.39                      | 83.00                      | 189                        | 05/70-12/78                   | 12.8                    | 4.8                               | 4.7        | 5.9        | 114  | 103        | 204        |
| Detroit/Wayne      | Detroit Metro-Wayne          | 42.23                      | 83.33                      | 197                        | 09/61-12/78                   | 6.1                     | 4.6                               | 4.9        | 6.2        | 111  | 137        | 274        |
| Flint              | Bishop Airport WBAS          | 42.96                      | 83.73                      | 234                        | 09/63-12/78                   | 6.4                     | 4.5                               | 4.8        | 6.1        | 104  | 126        | 251        |
| Gladwin            | Municipal Airport            | 43.98                      | 84.48                      | 241                        | 12/48-12/54                   | 9.8                     | 3.2                               | 3.2        | 4.0        | 58   | 59         | 117        |
| Grand Marais       | Coast Guard                  | 46.61                      | 85.91                      | 255                        | 12/48-12/54                   | 15.2                    | 4.7                               | 4.4        | 5.6        | 123  | 103        | 205        |
| Grand Rapids       | Kent Co. Airport             | 42.39                      | 85.66                      | 213                        | 12/63-12/78                   | 6.1                     | 4.5                               | 4.8        | 6.0        | 104  | 129        | 256        |
| Gwinn              | KI/Sawyer AFB                | 46.34                      | 87.39                      | 378                        | 01/58-12/70                   | 4.0                     | 3.8                               | 4.3        | 5.4        | 83   | 123        | 246        |
| Houghton           | Houghton Airport CAA         | 47.16                      | 88.50                      | 330                        | 12/54-12/64                   | 7.9                     | 4.7                               | 4.8        | 6.1        | 126  | 139        | 277        |
| Jackson            | Reynolds Airport             | 42.26                      | 84.46                      | 310                        | 01/49-12/54                   | 10.1                    | 4.4                               | 4.4        | 5.5        | 122  | 122        | 243        |
| Lansing            | Capital City Airport         | 42.78                      | 84.78                      | 269                        | 08/63-12/78                   | 6.1                     | 4.3                               | 4.6        | 5.8        | 102  | 126        | 251        |
| Mt. Clemens        | Selfridge AFB                | 42.59                      | 82.83                      | 178                        | 05/65-12/70                   | 4.0                     | 3.8                               | 4.3        | 5.4        | 77   | 114        | 228        |
| Muskegon           | Muskegon Co. Airport         | 43.16                      | 86.23                      | 192                        | 07/61-12/78                   | 6.1                     | 4.9                               | 5.2        | 6.6        | 134  | 166        | 336        |
| Oscoda             | Wurtsmith AFB                | 44.46                      | 83.36                      | 188                        | 04/61-03/68                   | 4.0                     | 3.5                               | 4.0        | 5.0        | 64   | 95         | 190        |
| Saginaw            | Tri-City Airport CAA         | 43.53                      | 84.08                      | 204                        | 12/48-12/54                   | 8.5                     | 4.7                               | 4.8        | 6.1        | 138  | 148        | 294        |
| Sault<br>St. Marie | Municipal Airport<br>WBAS    | 46.28                      | 84.22                      | 221                        | 10/66-12/78                   | 6.1                     | 3.9                               | 4.2        | 5.3        | 76   | 94         | 187        |
| Traverse City      | Cherry Cap CAA               | 44.73                      | 85.58                      | 193                        | 08/62-12/78                   | 6.1                     | 4.0                               | 4.2        | 5.3        | 74   | 91         | 182        |

<sup>a</sup>AFB - Air Force Base; WBAS - Weather Bureau Airport Station; CAA - Civil Aeronautics Administration; NAS - Naval Air Station.

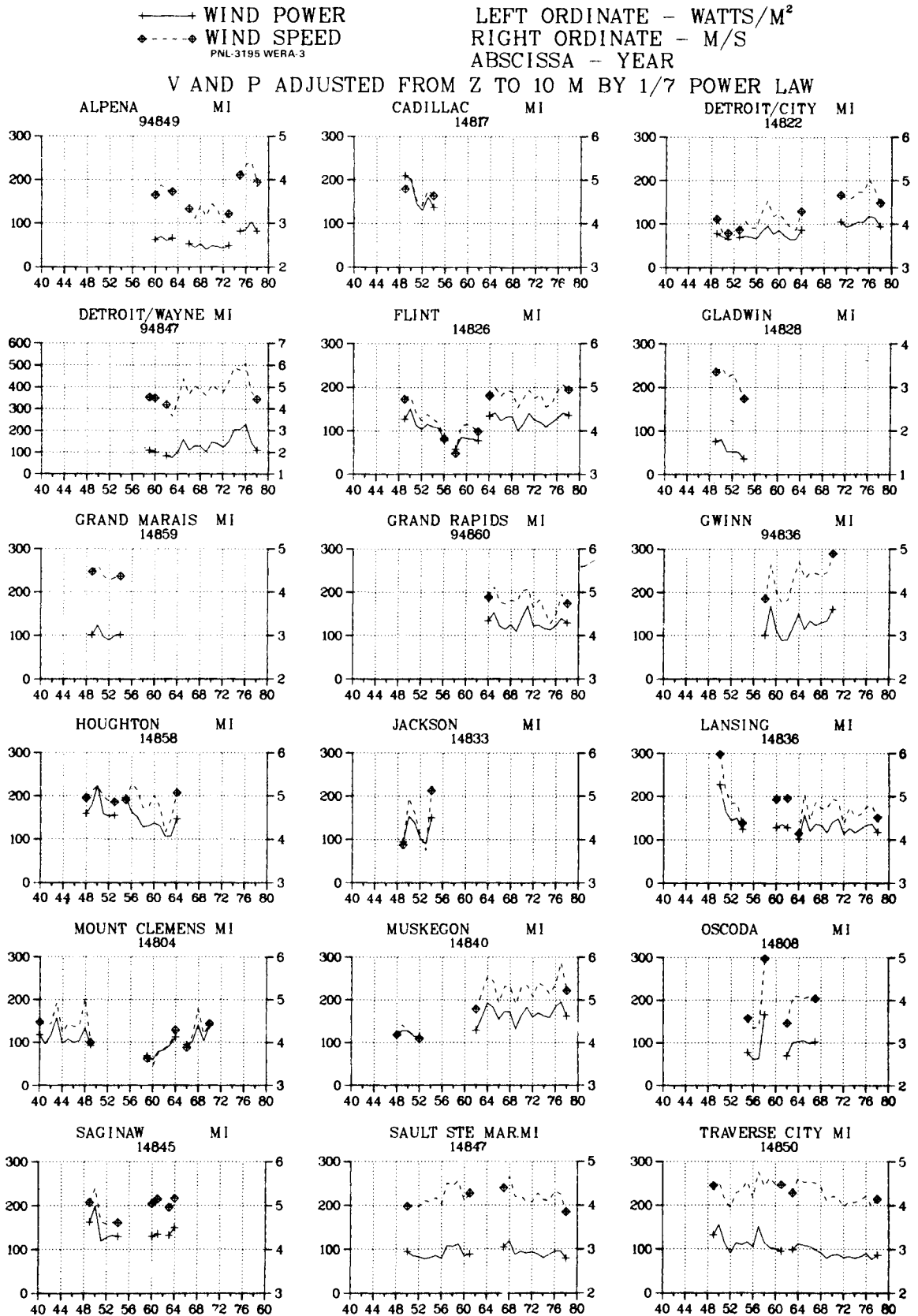


FIGURE 6.10. Interannual Wind Power and Speed for Michigan

— WIND POWER  
 - - - WIND SPEED  
 PNL-3195 WERA-3

LEFT ORDINATE - WATTS/M<sup>2</sup>  
 RIGHT ORDINATE - M/S  
 ABSCISSA - MONTH

V AND P ADJUSTED FROM Z TO 10 M BY 1/7 POWER LAW

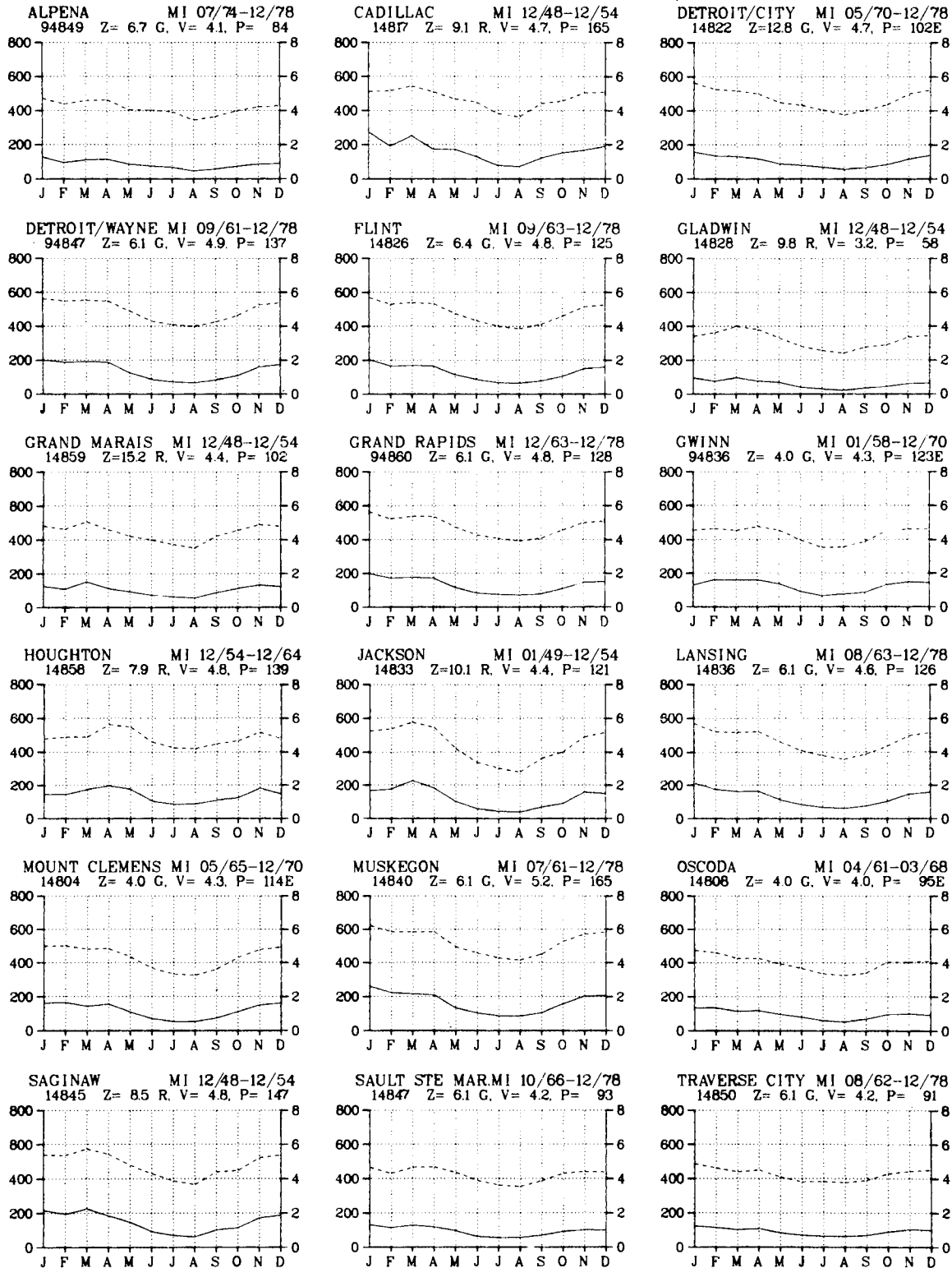
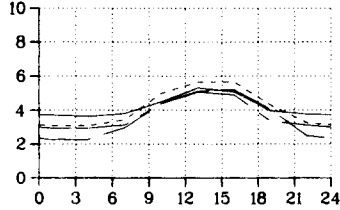


FIGURE 6.11. Monthly Average Wind Power and Speed for Michigan

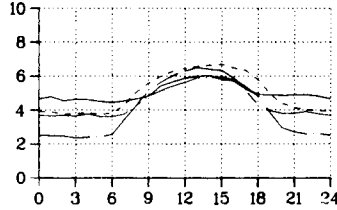
+---+ WINTER      ◆---◆ SPRING  
 ⊕---⊕ SUMMER      ⊞---⊞ AUTUMN  
PNL-3195 WERA-3

ORDINATE - M/S  
 ABSCISSA - HOUR

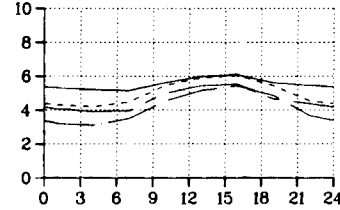
ALPENA MI 07/74-12/78  
94849 Z= 6.7 G, V= 3.9, P= 71



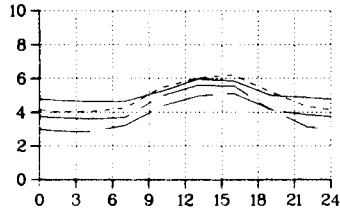
CADILLAC MI 12/48-12/54  
14877 Z= 9.1 R, V= 4.7, P= 159



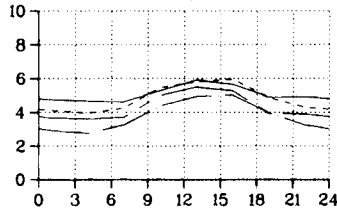
DETROIT/CITY MI 05/70-12/78  
14822 Z=12.8 G, V= 4.8, P= 114E



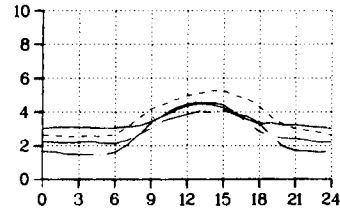
DETROIT/WAYNE MI 09/61-12/78  
94847 Z= 6.1 G, V= 4.6 P= 111



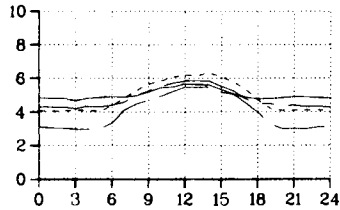
FLINT MI 09/63-12/78  
14826 Z= 6.4 G, V= 4.5, P= 104



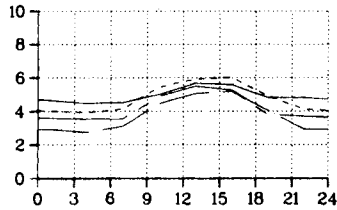
GLADWIN MI 12/48-12/54  
14828 Z= 9.8 R, V= 3.2, P= 58



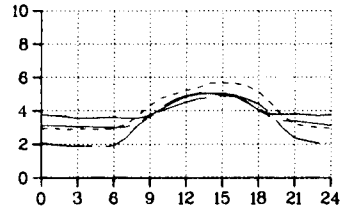
GRAND MARAIS MI 12/48-12/54  
14859 Z=15.2 R, V= 4.7, P= 123



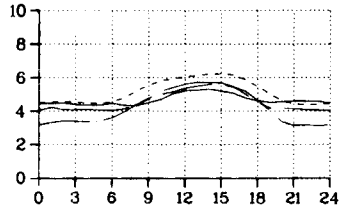
GRAND RAPIDS MI 12/63-12/78  
94860 Z= 6.1 G, V= 4.5, P= 104



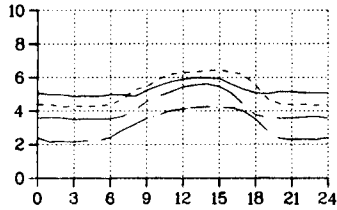
GWINN MI 01/58-12/70  
94836 Z= 4.0 G, V= 3.8, P= 83E



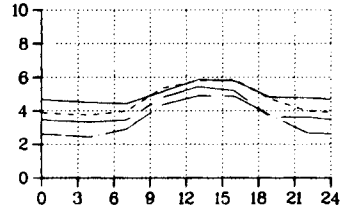
HOUGHTON MI 12/54-12/64  
14858 Z= 7.9 R, V= 4.7, P= 126



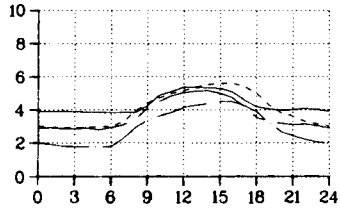
JACKSON MI 01/49-12/54  
14833 Z=10.1 R, V= 4.4, P= 122



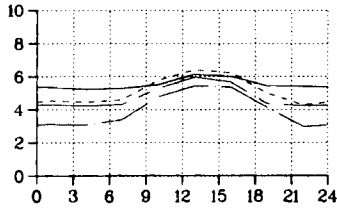
LANSING MI 08/63-12/78  
14838 Z= 6.1 G, V= 4.3, P= 102



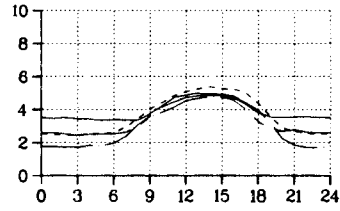
MOUNT CLEMENS MI 05/65-12/70  
14804 Z= 4.0 G, V= 3.8, P= 77E



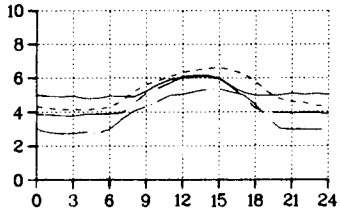
MUSKEGON MI 07/61-12/78  
14840 Z= 6.1 G, V= 4.9, P= 134



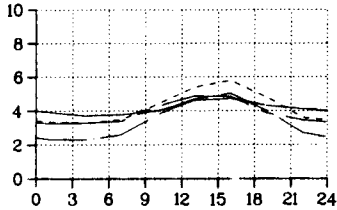
OSCODA MI 04/61-03/68  
14808 Z= 4.0 G, V= 3.5, P= 64E



SAGINAW MI 12/48-12/54  
14845 Z= 8.5 R, V= 4.7, P= 138



SAULT STE MAR MI 10/66-12/78  
14847 Z= 6.1 G, V= 3.9, P= 76



TRAVERSE CITY MI 08/62-12/78  
14850 Z= 6.1 G, V= 4.0, P= 74

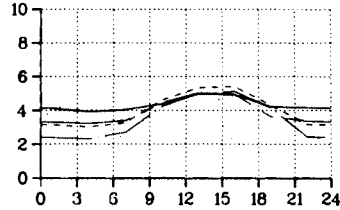


FIGURE 6.12. Diurnal Wind Speed by Season for Michigan

— PERCENT FREQUENCY LEFT ORDINATE - PERCENT  
 - - - WIND SPEED RIGHT ORDINATE - M/S  
 PNL-3195 WERA-3  
 ABSCISSA - WIND DIRECTION

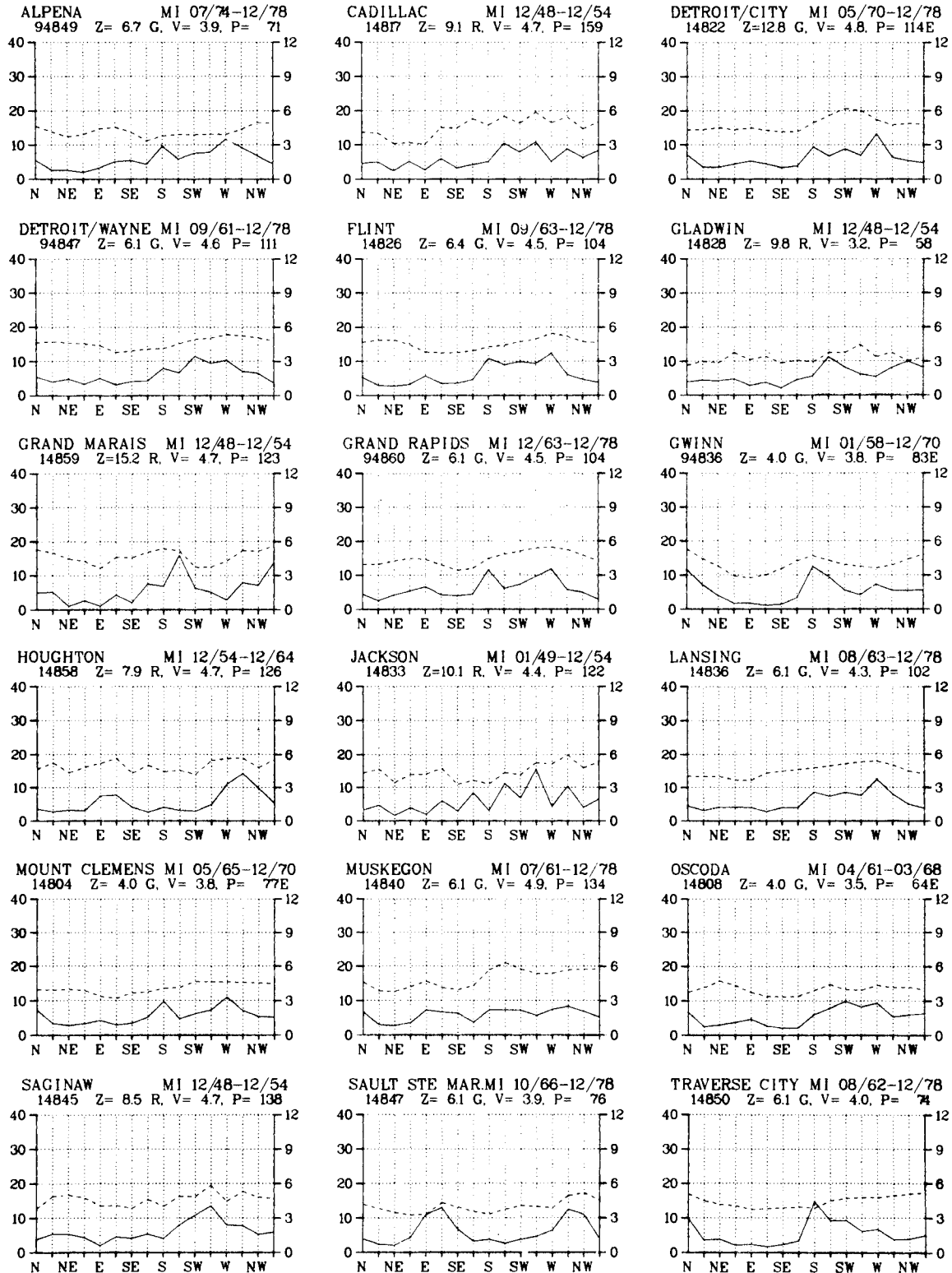


FIGURE 6.13. Directional Frequency and Average Wind Speed for Michigan

— ACTUAL DISTRIBUTION      ORDINATE - PERCENT  
 - - - RAYLEIGH DISTRIBUTION      ABSCISSA - M/S  
 PNL-3195 WERA-3

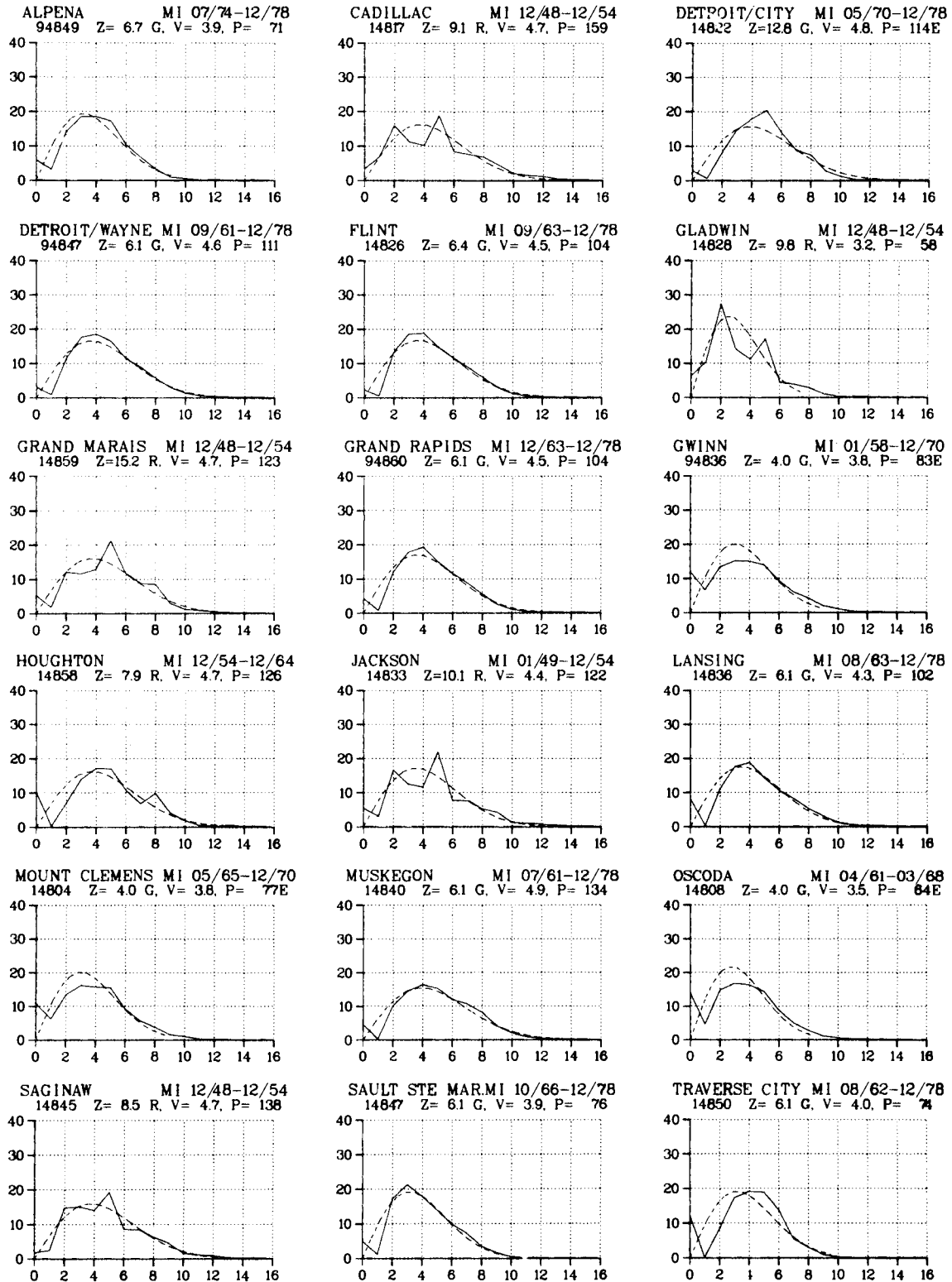


FIGURE 6.14. Annual Average Wind Speed Frequency for Michigan

ORDINATE - PERCENT  
 ABSCISSA - M/S  
 PNL 3195 WERA-3

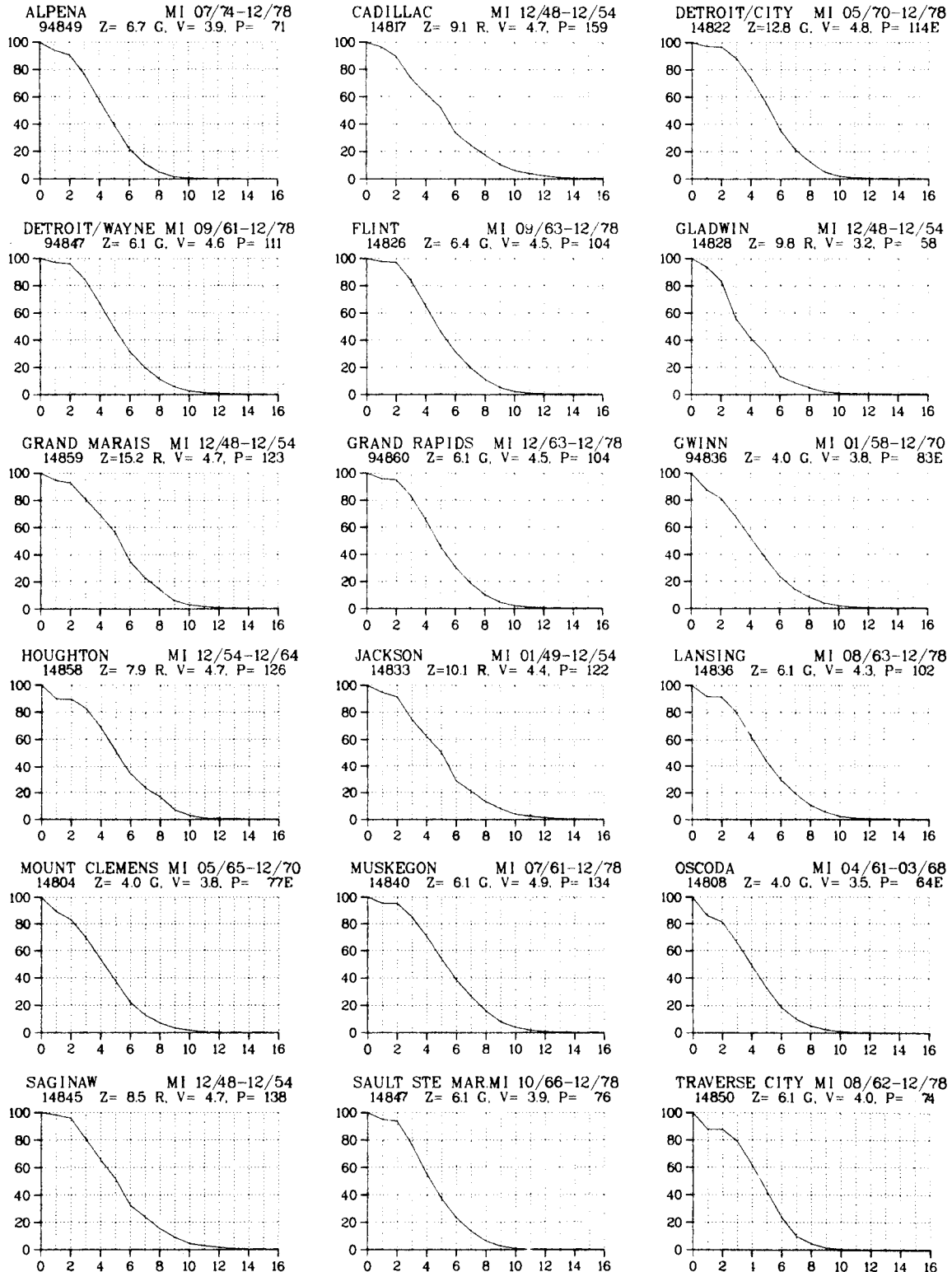


FIGURE 6.15. Annual Average Wind Speed Duration for Michigan

ORDINATE - PERCENT  
 ABSCISSA - WATTS/M<sup>2</sup>  
 PNL-3195 WERA-3

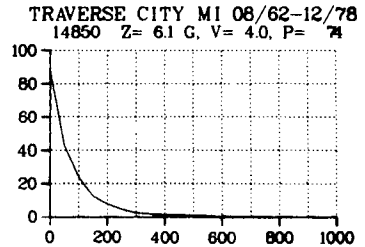
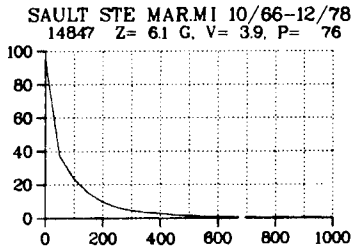
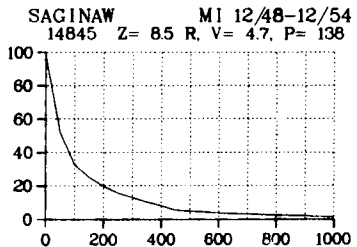
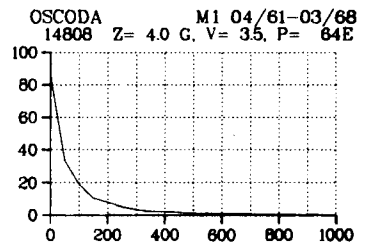
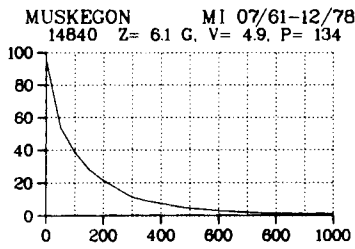
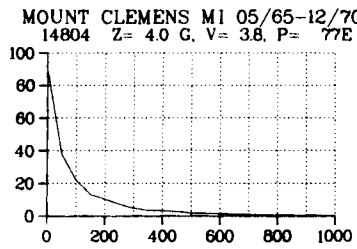
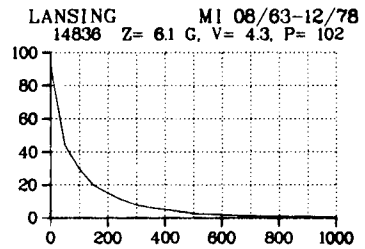
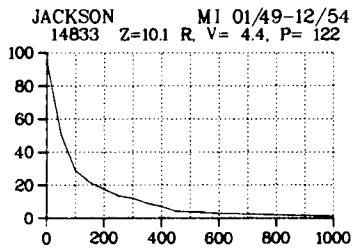
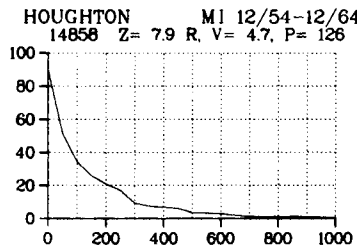
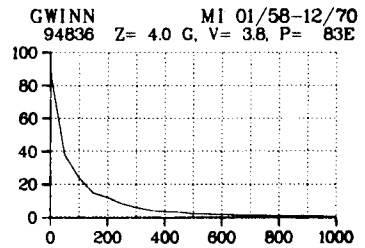
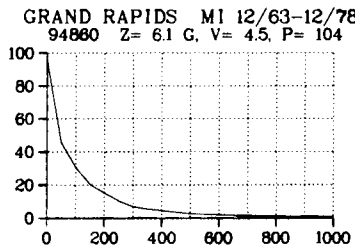
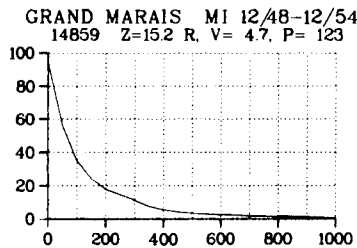
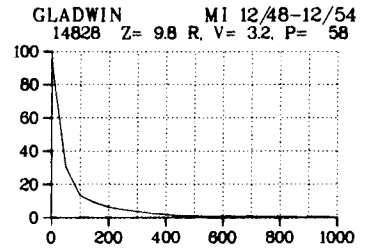
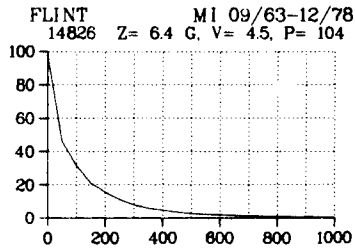
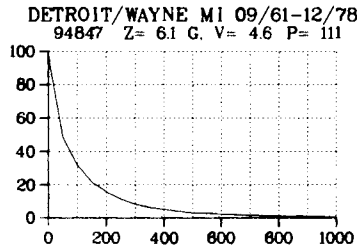
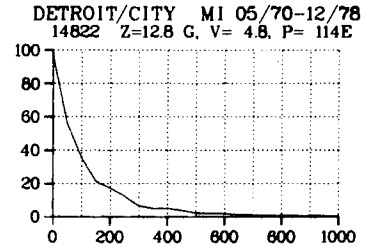
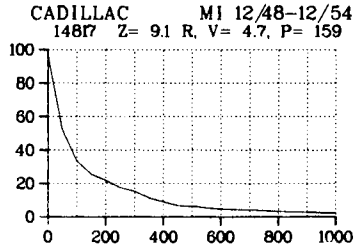
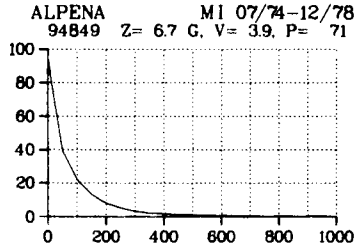


FIGURE 6.16. Annual Average Wind Power Duration for Michigan



**OHIO**

Ohio covers an area of 106,765 km<sup>2</sup> (41,222 mi<sup>2</sup>). Almost half of Ohio's population (10,652,017 in 1970) lives in one of several major cities (including Cincinnati, Columbus, Dayton, Toledo, and Cleveland). Other major towns and cities are fairly well distributed throughout the state (Figure 7.1).

The state, exposed to Lake Erie only in the extreme northern sections, experiences a typically continental climate of cold winters and warm summers (see Figure 7.2). Areas along the immediate coast are favored by a modified continental climate tempered by Lake Erie.

More than half of the western part of the state is plains with little relief. Eastern and southeastern Ohio are characterized by unglaciated rough terrain, which forms the foothills of the Appalachian Mountain Range (Figure 7.3). Terrain heights in Ohio range from 130 m (430 ft) in southwestern parts to 450 m (1,500 ft) in the unglaciated sections.

Wind data in Ohio are fairly abundant and uniformly distributed (Figures 7.4 and 7.5). The data sites in southeastern Ohio are generally well exposed and well representative. They also have summarized data. Coastal stations were mostly Coast Guard sites, often with unknown exposure. Data from these stations were generally unsummarized and of questionable quality. However, two coastal stations (Nuclear Regulatory Commission data), are believed to represent conditions along Lake Erie. Data from the National Climatic Center (NCC) are plentiful throughout the state and are available in summarized and unsummarized form.

## 7.1 ANNUAL AVERAGE WIND POWER

The annual average available wind power density in Ohio is shown in Figure 7.6. The analyses of mean wind power apply to terrain features that are favorably exposed to the wind, such as hilltops, uplands, and open plains (see Section 1.6). However, nearby terrain features may interact with the wind field to cause the wind power at some exposed sites to vary as much as  $\pm 50$  to 100% from the assessment value. (See Wegley et al. 1980 for information on terrain features that may increase or reduce wind energy.) In forested or wood areas, the estimates are representative of large clearings with good exposure to the prevailing strong winds, such as

airports, where runways are generally aligned parallel to the prevailing wind direction(s). The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (Section 1.8).

The annual average wind power map for Ohio shows class 3 or higher wind power only along the area bordering Lake Erie. Class 2 wind power is found in the flat plains of northwestern Ohio. Southwestern Ohio, like southern Indiana and Illinois, is estimated as having class 1 wind power. The region of class 1 wind power in southeastern Ohio reflects the influence of the Bermuda High and the effects of increased surface roughness.

Class 4 power estimates along the Ohio coast represent offshore and exposed coastal areas, e.g., open shorelines that are not sheltered from prevailing winds. Winds may be accelerated around and over capes and headlands, where exposed areas can have classes 5 or 6 wind power (not indicated in the figure). The abrupt increase of surface roughness because of vegetation and topography inland from the coastline rapidly attenuates the wind resource landward of the coastline. Winds from the northwest to northeast quadrants have long open-water fetches across Lake Erie and reach the Ohio shoreline with high speeds.

Although southeastern Ohio has very rugged terrain and more relief than any other area in the Great Lakes Region, it was assigned class 1 wind power, because the data were mostly recorded from stations which, although generally well exposed, were situated in valleys rather than on hilltops. One or two stations that indicated a class 2 wind power were not believed to be typical of the region; these higher wind speeds were thought to reflect only local enhancement effects, not the entire unglaciated area. For conservatism, the area was estimated to have wind power class 1, the same as the region in southwestern Ohio.

### 7.1.1 Certainty Rating of the Wind Resource

High certainty ratings are assigned over much of the plains area in the western half of Ohio (Figure 7.7), but this area is estimated to have low annual average wind resources (classes 1 or 2). No areas in Ohio combine a large wind resource (class 3 or greater) with a

high degree of certainty. The areas of large wind resource lie along the coast of Lake Erie, but the offshore marine data and coastal data used in estimating the coastal wind resource were largely from stations of unknown exposure or data quality. When combined with the high spatial variability of the wind resource along the coast, the resulting certainty rating was low (1 or 2).

The certainty rating of 2 shown in southeastern Ohio is indicative of the rough terrain that characterizes this part of the state. Most of the stations in this region were located in valleys, sheltered from prevailing winds. Thus, although spatial variability of the wind resource was believed to be low, the complex terrain and absence of well-exposed and representative stations reduced the certainty rating to 2.

#### 7.1.2 Areal Distribution

The areal distribution of wind power in Ohio is illustrated in Figure 7.8. The summary information given in Table 7.1 indicates that the wind energy resource for the state of Ohio is not large. Less than 7% of the land area experiences a wind power of class 3 or higher; only about 1% has class 4 or higher. Much of the land area has been assigned wind power class 1. Only the coastal areas experience annual wind power densities of class 3 or higher. The hilly region in southeastern Ohio has a large percentage of area with class 1. Because of the low wind power resource in Ohio the map of areal distribution for class 4 and higher wind power is almost featureless.

### 7.2 SEASONAL WIND POWER

Wind power maps for each season are shown on facing pages in Figure 7.9. Three main factors influence the wind power in Ohio: topography, Lake Erie, and proximity to storm tracks. Throughout the state, winter is the season of maximum wind power and summer the season of minimum wind power.

#### 7.2.1 Winter

In winter, exposed coastal and offshore sites along Lake Erie are estimated to have class 4 and 5 wind power. Prevailing winter winds from the southwest to northwest quadrants have long fetches across the lake (reflected in the high wind speeds recorded in northeastern Ohio). The more sheltered areas in Sandusky Bay are not as well exposed to these power-producing winds

and have been assigned a wind power of class 4.

Class 3 wind power is estimated for the plains in northwestern Ohio where sites are exposed to winter westerlies. In southern Ohio the wind power resource decreases from class 3 to class 1 (west to east) following the west-to-east increase in terrain complexity. The high surface roughness of the foothills of the Appalachian mountains acts to weaken prevailing winds; the contour separating the regions of classes 3 and 1 approximately follows the land-surface form isopleth.

#### 7.2.2 Spring

As spring progresses from March to May, the mean surface winds decrease in intensity. During the early part of the spring, wind speeds are at a maximum. The rapid weakening of wind power in April and May, however, causes the average speeds to be lower in spring than in winter. This is denoted in Figure 7.9 by the assignment of class 4 wind power for exposed offshore and coastal sites, and class 3 wind power immediately landward of the shore. The wide expanse of class 2 wind power denotes the decrease in average wind speed from March to May as the pressure gradient forces weaken and the winds aloft decrease. The class 1 area in southeastern Ohio in the western fringe of the Appalachian Mountains persists throughout the spring.

#### 7.2.3 Summer

In summer, class 1 wind power is estimated throughout the state, with the exception of the immediate shoreline and offshore area (where class 2 or higher is indicated). This is due to very light prevailing winds from the south, and the weakened land-water temperature gradient. Exposed sites in southeastern Ohio may experience some topographical enhancement of winds, but it could not be seen in the data.

#### 7.2.4 Autumn

Upper-air winds tend to gradually increase from September to November. Surface pressure gradients, however, tend to remain weak in the early fall and increase from November to December with the increasing frequency and strength of mid-latitude cyclones. The reappearance of class 3 for exposed offshore and coastal sites reflects, in part, the destabilizing influence of the warm water upon air advected over Lake Erie, as well as the shifting of the winds to the northwest.

### 7.3 FEATURES OF SELECTED STATIONS

Graphs of the detailed wind characteristics are presented for 13 stations in Ohio (Table 7.2). Three of these stations are located along the Lake Erie shore; the rest are concentrated in central sections.

Akron/Canton Airport is located in northeastern Ohio on rolling plains. Judging from the data, the exposure appears to be good.

Cleveland Airport is in the northwestern corner of the state. The airport within 8 km (5 mi) of the shoreline of Lake Erie. The terrain rises slightly to the south of the site but it is estimated to be very well exposed to winds of the lake.

Port Columbus Airport, situated in the central part of the state, has surrounding terrain of rolling plains. Exposure to prevailing winds is rated as good.

Columbus/Lockburne Airport on the Scioto River in central Ohio, is just south of Port Columbus Airport. The terrain characteristics are the same as at Port Columbus, but the data here suggest questionable exposure.

Dayton/Cox Airport is located in the southwestern quadrant near the Miami River. The site is on an irregular rolling plain, and the exposure is apparently good.

Dayton/Wright-Patterson Airport, immediately southeast of Dayton/Cox is situated on rolling terrain. Power-producing winds are apparently from the west and the observed wind speeds suggest uncertain anemometer exposure.

Findlay Civil Aeronautics Administration (CAA), near the Blanchard River, is located in the northwestern part of the state. Flat terrain and moderately high wind speeds both indicate good exposure to prevailing winds.

Mansfield Airport is located in the north central part of the state where terrain is generally flat. Judging from the wind data alone, the exposure appears excellent.

Perry CAA is situated on Lake Erie in the extreme northwest corner of the state. It is ideally located for exposure to winds off the lake. Unfortunately, the anemometer height is unknown and only one year of summarized data was available.

Toledo Airport, near the Maumee River in northern Ohio, is roughly 32 km (20 mi) from the western end of Lake Erie. The terrain is flat and the site apparently has good exposure to the power-producing winds.

Wilmington-Clinton County Air Force Base (AFB), in the southwestern corner of Ohio, has surrounding terrain which is best described as plains. The data indicate the possibility of questionable exposure.

Youngstown Airport, in the northeastern part of the state, is situated near the Manening River. The terrain surrounding the site is somewhat irregular but the exposure was considered to be good.

Zanesville Airport is situated in an unglaciated (hilly) section of southwestern Ohio. The site is in the Muskingum River Valley with terrain sloping up rd to the west and east. Exposure to prevailing winds appear to be good.

#### 7.3.1 Interannual Wind Power and Speed

With the exception of Mansfield, there is very little variation in wind power at the 13 selected stations (Figure 7.10). At Mansfield, apparently the interannual variations differ with the period of record. In the earlier period of record, the maximum wind power is more than twice as large as the minimum. This same change of interannual variation with period can be seen at Cleveland and Columbus.

Nearby stations do not necessarily display the same interannual variation. This can be seen at Dayton/Cox Airport, Lockburne Airport, and Columbus Airport.

#### 7.3.2 Monthly Average Wind Power and Speed

The 13 selected stations for Ohio all show a summer minimum in wind power; the maximum occurs either in spring or winter. Winter maxima are evident at Akron/Canton Apt., Cleveland (1959-1978), Findlay, Mansfield Airport, Perry, Toledo, and Youngstown; all other stations show a spring maximum with the peak in March. The erratic behavior of the wind speed and power curves at Perry reflects the short period of record. Except for this station, the site with longest variation is Mansfield Airport, where the ratio of maximum to minimum wind power is about 1.5 (Figure 7.11).

In some areas, such as Zanesville, there appear to be two secondary maxima;

one in spring and the other in the fall, usually November. Cleveland (1948-1955) and Dayton/Cox (1974-1978) exhibit a similar behavior.

### 7.3.3 Diurnal Wind Speed by Season

In all seasons for all 13 stations, peak wind power occurs in the mid-morning and afternoon (900-1800 LST), the maximum between 1200-1500 LST. For most of the stations, the largest diurnal variations appear in the summer, the smallest in the winter. Some stations, such as Akron/Canton and Mansfield (1961-1978), show very little diurnal variation in any season (Figure 7.12).

### 7.3.4 Directional Frequency and Average Speed

With few exceptions (e.g., Findlay), the stations have prevailing winds from the southwest quadrant (Figure 7.13). Strongest winds generally tend to blow from the west or northwest.

At Zanesville, the winds are largely influenced by topography, with the

strongest winds from the west-southwest through west-northwest.

### 7.3.5 Annual Average Wind Speed Frequency

Because observer bias and low instrument threshold speeds distort the observed frequency distribution (Figure 7.14), the representativeness of the Rayleigh speed distribution is hard to evaluate. Observer bias is readily observable at all stations excepting Akron/Canton, Cleveland (1959-1978), Columbus (1959-1978), Dayton/Cox, and Youngstown. Spikes are most evident at 5 m/sec. Note that nearby stations such as Dayton/Cox and Dayton/Wright do not have similar frequency distribution curves.

### 7.3.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in Figures 7.15 and 7.16. Abrupt changes in the slope of the duration curves correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity.





FIGURE 7.1. Geographic Map of Ohio

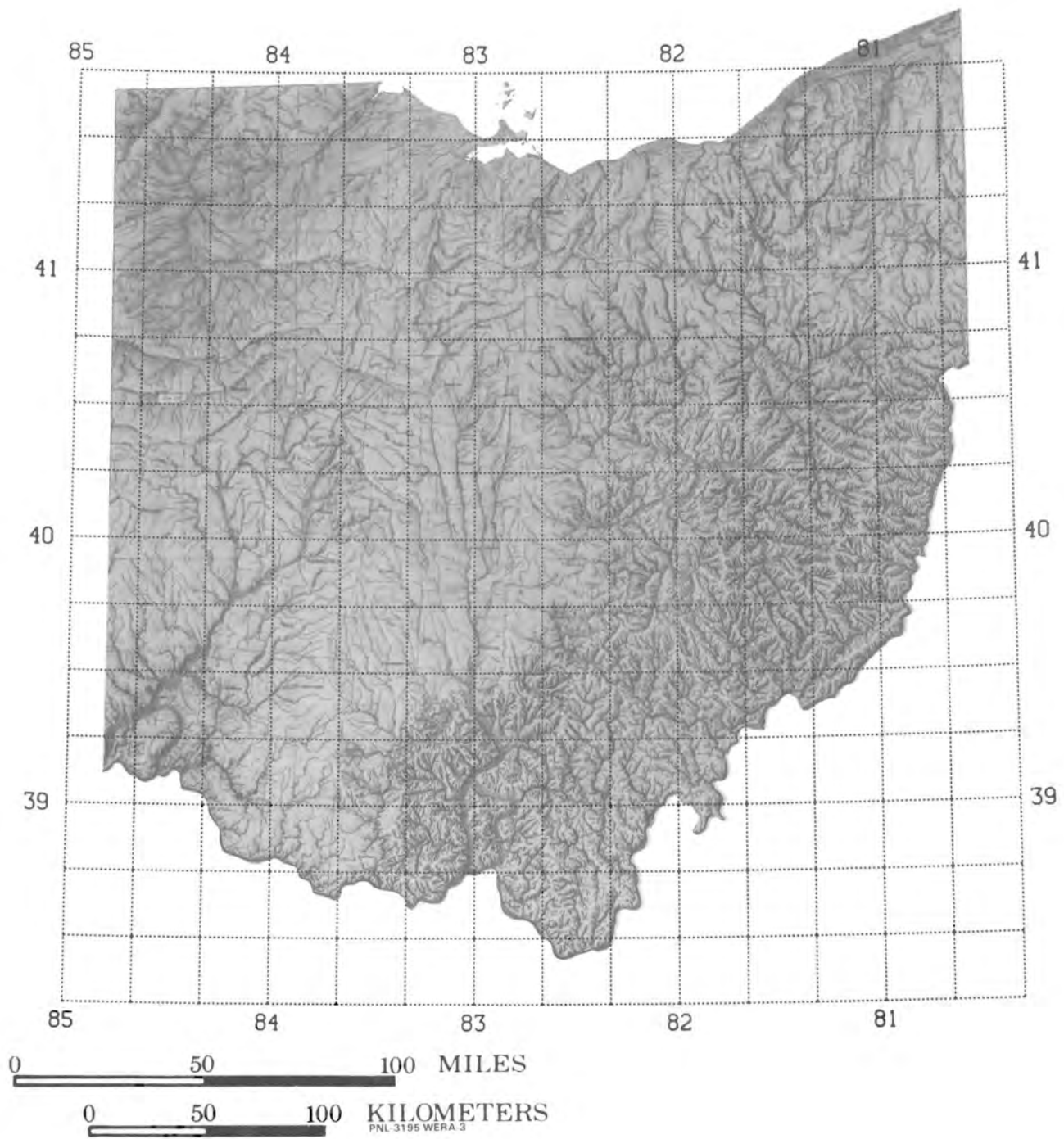


FIGURE 7.2. Topographic Map of Ohio

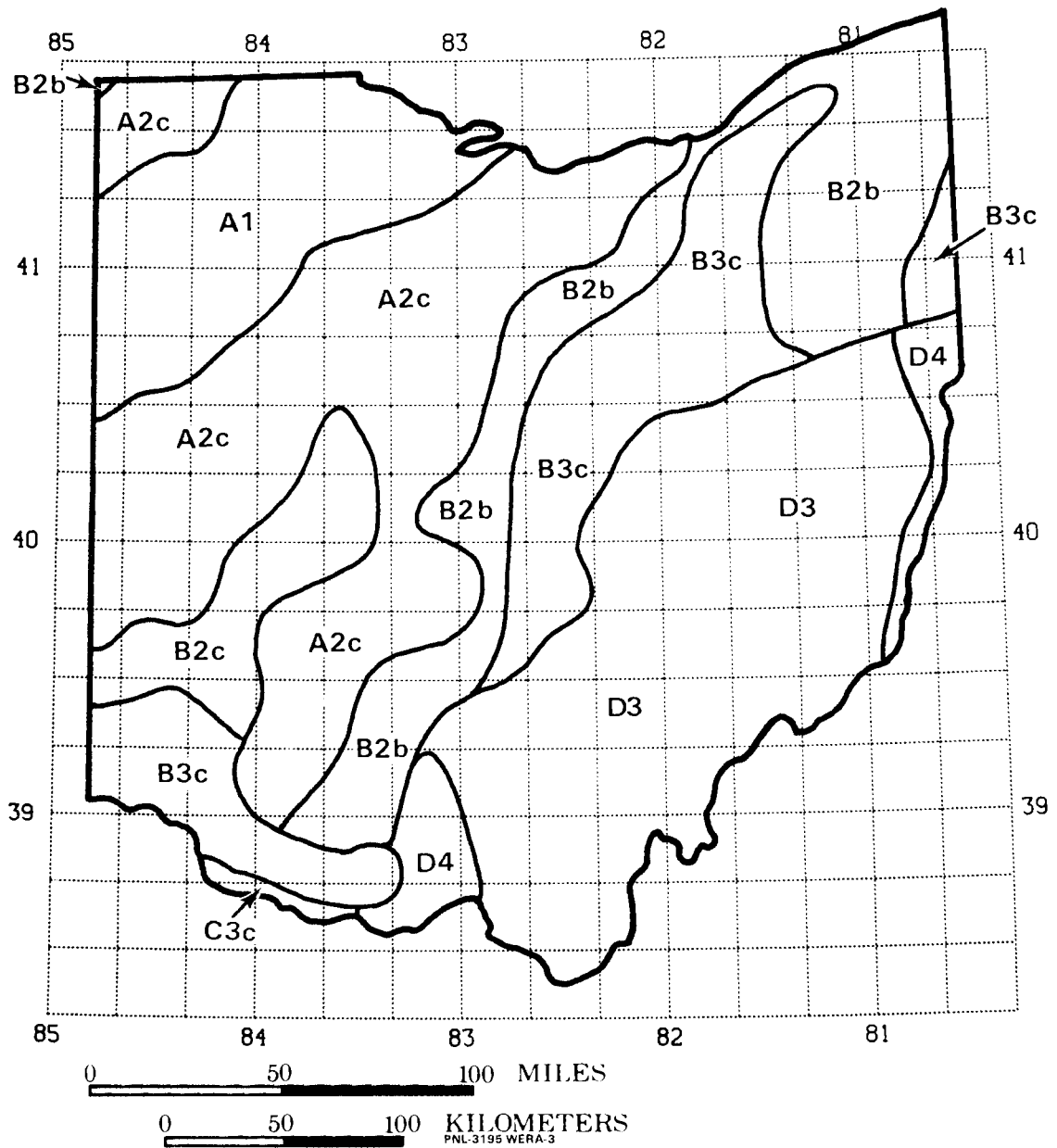


FIGURE 7.3. Land-Surface Form Map for Ohio

## LAND-SURFACE FORM LEGEND

### PLAINS

|    |                                 |
|----|---------------------------------|
| A1 | FLAT PLAINS                     |
| A2 | SMOOTH PLAINS                   |
| B1 | IRREGULAR PLAINS, SLIGHT RELIEF |
| B2 | IRREGULAR PLAINS                |

### TABLELANDS

|       |                                 |
|-------|---------------------------------|
| B3c,d | TABLELANDS, MODERATE RELIEF     |
| B4c,d | TABLELANDS, CONSIDERABLE RELIEF |
| B5c,d | TABLELANDS, HIGH RELIEF         |
| B6c,d | TABLELANDS, VERY HIGH RELIEF    |

### PLAINS WITH HILLS OR MOUNTAINS

|         |                            |
|---------|----------------------------|
| A,B3a,b | PLAINS WITH HILLS          |
| B4,a,b  | PLAINS WITH HIGH HILLS     |
| B5a,b   | PLAINS WITH LOW MOUNTAINS  |
| B6a,b   | PLAINS WITH HIGH MOUNTAINS |

### SCHEME OF CLASSIFICATION

#### SLOPE (1st LETTER)

|   |                               |
|---|-------------------------------|
| A | >80% OF AREA GENTLY SLOPING   |
| B | 50-80% OF AREA GENTLY SLOPING |
| C | 20-50% OF AREA GENTLY SLOPING |
| D | <20% OF AREA GENTLY SLOPING   |

### OPEN HILLS AND MOUNTAINS

|    |                     |
|----|---------------------|
| C2 | OPEN LOW HILLS      |
| C3 | OPEN HILLS          |
| C4 | OPEN HIGH HILLS     |
| C5 | OPEN LOW MOUNTAINS  |
| C6 | OPEN HIGH MOUNTAINS |

#### LOCAL RELIEF (2nd LETTER)

|   |                                |
|---|--------------------------------|
| 1 | 0 TO 30m (1 TO 100 ft)         |
| 2 | 30 TO 90m (100 TO 300 ft)      |
| 3 | 90 TO 150m (300 TO 500 ft)     |
| 4 | 150 TO 300m (500 TO 1000 ft)   |
| 5 | 300 TO 900m (1000 TO 3000 ft)  |
| 6 | 900 TO 1500m (3000 TO 5000 ft) |

### HILLS AND MOUNTAINS

|    |                |
|----|----------------|
| D3 | HILLS          |
| D4 | HIGH HILLS     |
| D5 | LOW MOUNTAINS  |
| D6 | HIGH MOUNTAINS |

#### PROFILE TYPE (3rd LETTER)

|   |                                      |
|---|--------------------------------------|
| a | >75% OF GENTLE SLOPE IS IN LOWLAND   |
| b | 50-75% OF GENTLE SLOPE IS IN LOWLAND |
| c | 50-75% OF GENTLE SLOPE IS ON UPLAND  |
| d | >75% OF GENTLE SLOPE IS ON UPLAND    |

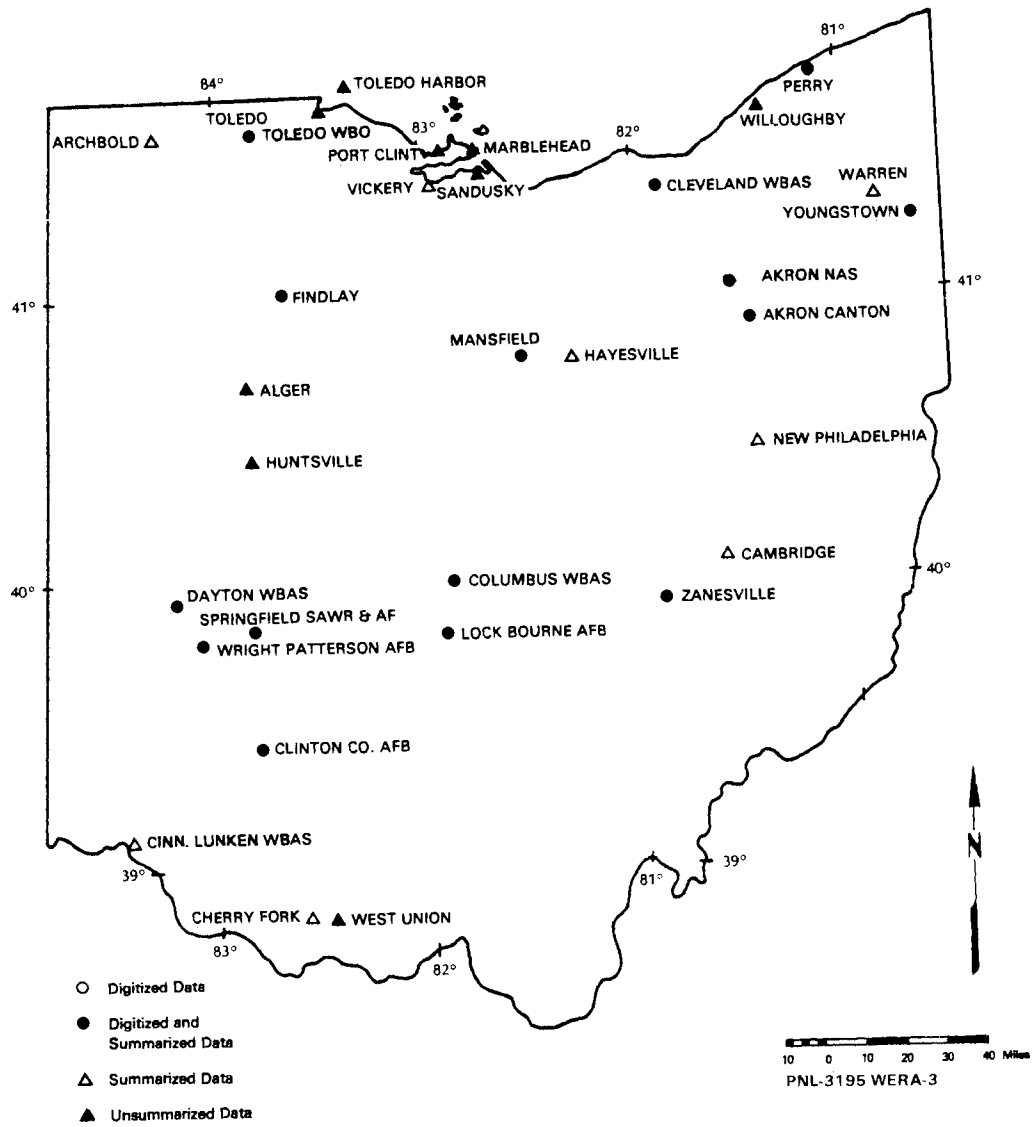


FIGURE 7.4. NCC Station Locations in Ohio

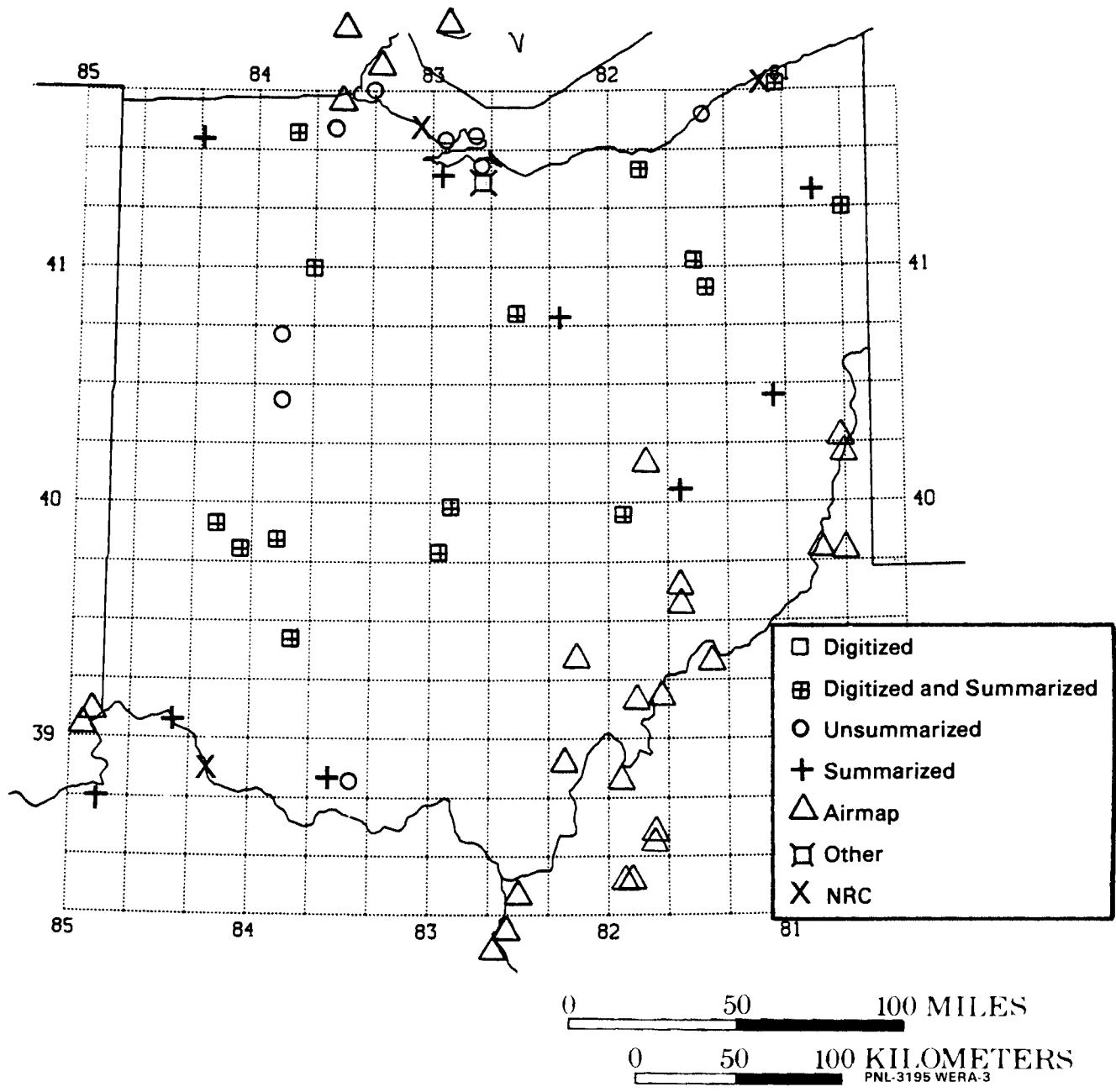


FIGURE 7.5. Location of Stations Used in Ohio Resource Assessment

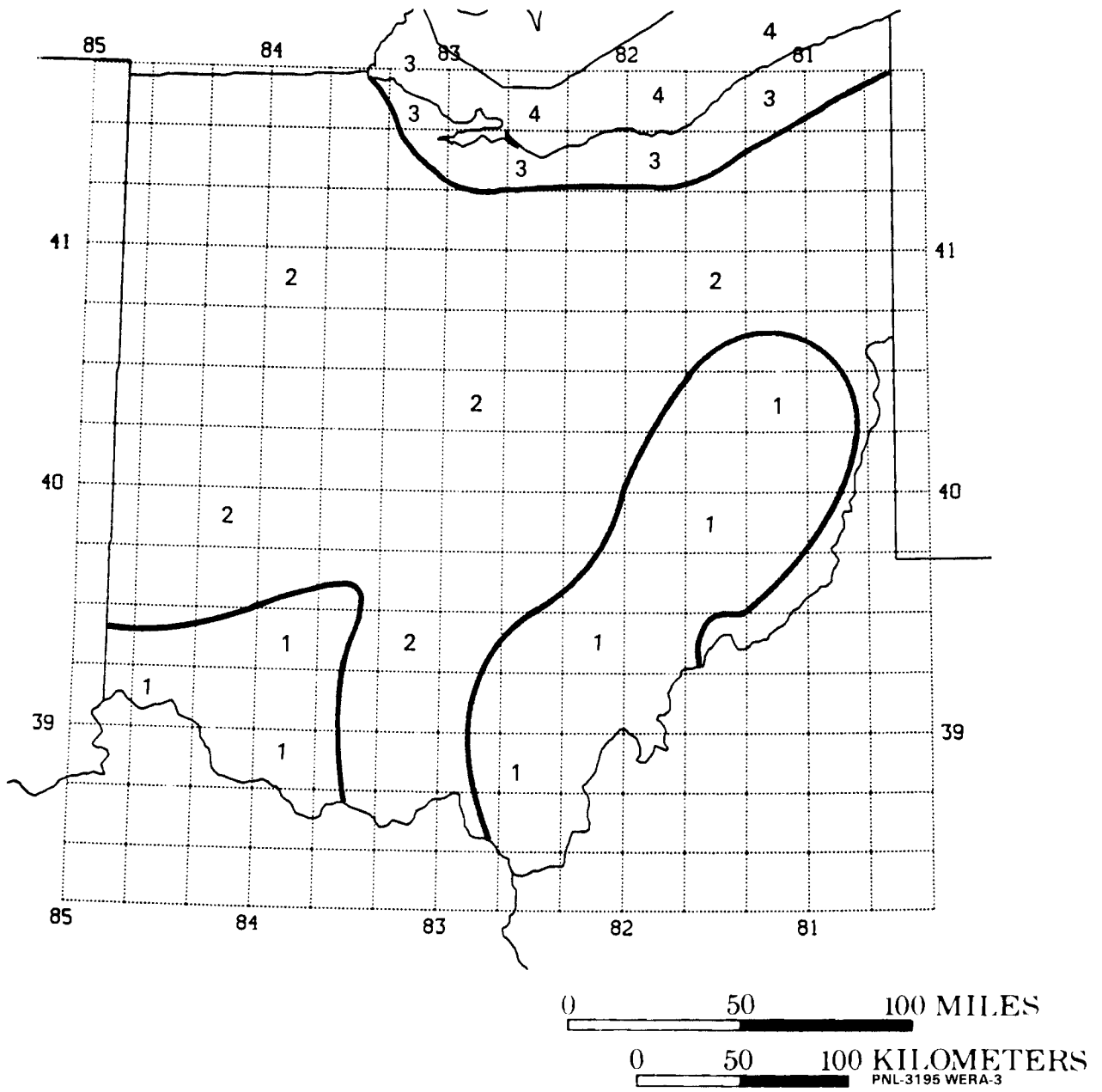


FIGURE 7.6. Ohio Annual Average Wind Power

Classes of Wind Power Density at 10 m and 50 m<sup>(a)</sup>

| Wind Power Class | 10 m (33 ft)                             |                                 | 50 m (164 ft)                            |                                 |
|------------------|--|---------------------------------|--|---------------------------------|
|                  | Wind Power Density, watts/m <sup>2</sup> | Speed, <sup>(b)</sup> m/s (mph) | Wind Power Density, watts/m <sup>2</sup> | Speed, <sup>(b)</sup> m/s (mph) |
| 0                | 0  | 0                               | 0  | 0                               |
| 1                | 100                                      | 4.4 (9.8)                       | 200                                      | 5.6 (12.5)                      |
| 2                | 150                                      | 5.1 (11.5)                      | 300                                      | 6.4 (14.3)                      |
| 3                | 200                                      | 5.6 (12.5)                      | 400                                      | 7.0 (15.7)                      |
| 4                | 250                                      | 6.0 (13.4)                      | 500                                      | 7.5 (16.8)                      |
| 5                | 300                                      | 6.4 (14.3)                      | 600                                      | 8.0 (17.9)                      |
| 6                | 400                                      | 7.0 (15.7)                      | 800                                      | 8.8 (19.7)                      |
| 7                | 1000                                     | 9.4 (21.1)                      | 2000                                     | 11.9 (26.6)                     |

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 7.1. Areal Distribution (km<sup>2</sup>) of Wind Power Classes in Ohio

| Power Class | Land Area | Percent Land Area | Cumulative Land Area | Percent Cumulative Land Area |
|-------------|-----------|-------------------|----------------------|------------------------------|
| 1           | 50,000    | 50.0              | 100,000              | 100.0                        |
| 2           | 42,000    | 42.0              | 50,000               | 50.0                         |
| 3           | 6,900     | 6.89              | 7,900                | 7.89                         |
| 4           | 1,000     | 1.01              | 1,000                | 1.01                         |
| 5-7         | 0         | 0.00              | 0                    | 0.00                         |

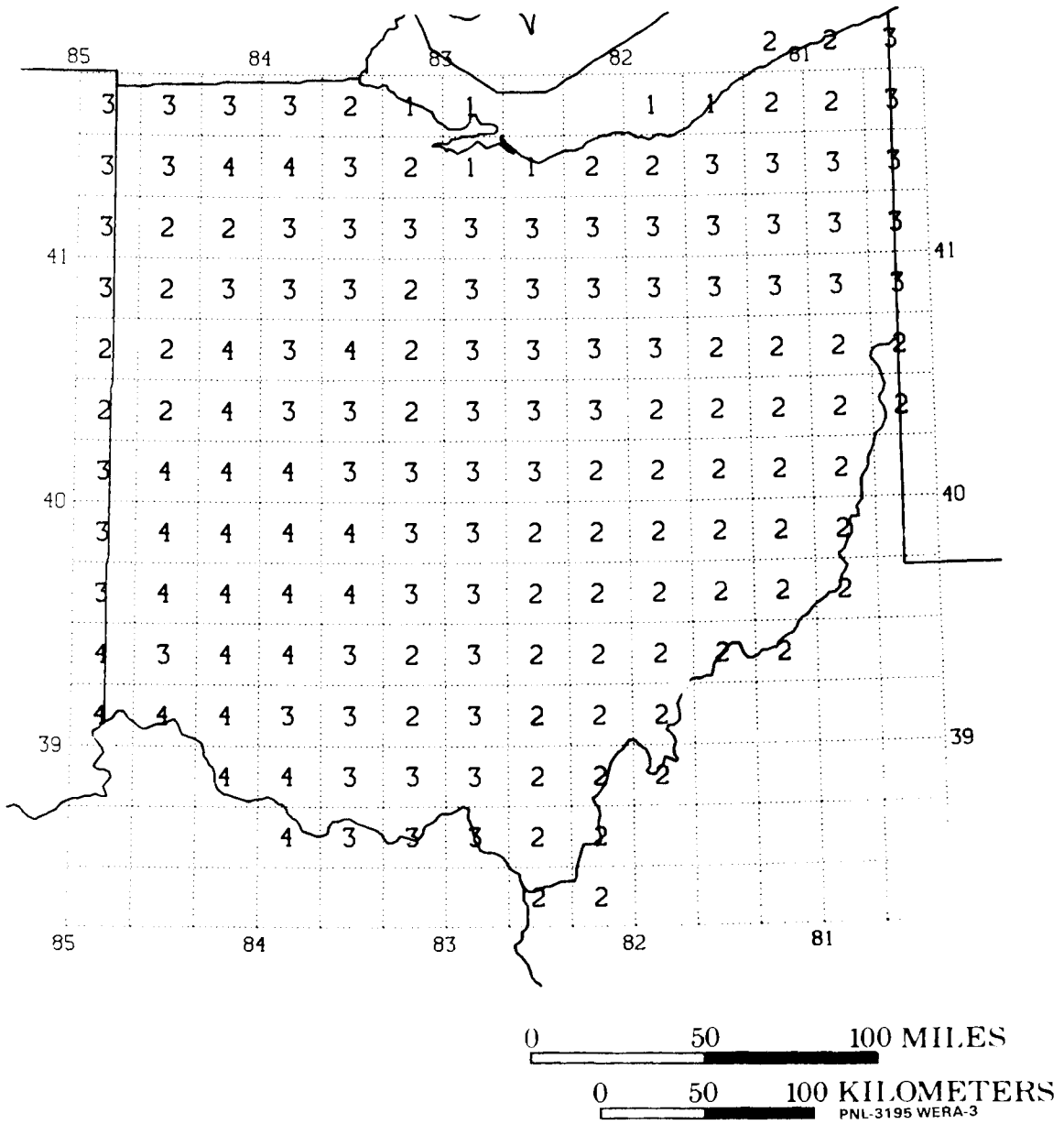


FIGURE 7.7. Certainty Rating of Ohio Wind Resource

### CERTAINTY RATING LEGEND

| Rating | Definition   |
|--------|--|
| 1      | <p>The lowest degree of certainty. A combination of the following conditions exists:</p> <ol style="list-style-type: none"><li>1) No data exist in the vicinity of the cell.</li><li>2) The terrain is highly complex.</li><li>3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.</li></ol>   |
| 2      | <p>A low-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"><li>1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data.</li><li>2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.</li></ol> |
| 3      | <p>A high-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"><li>1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data.</li><li>2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.</li></ol>       |
| 4      | <p>The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.</p>   |

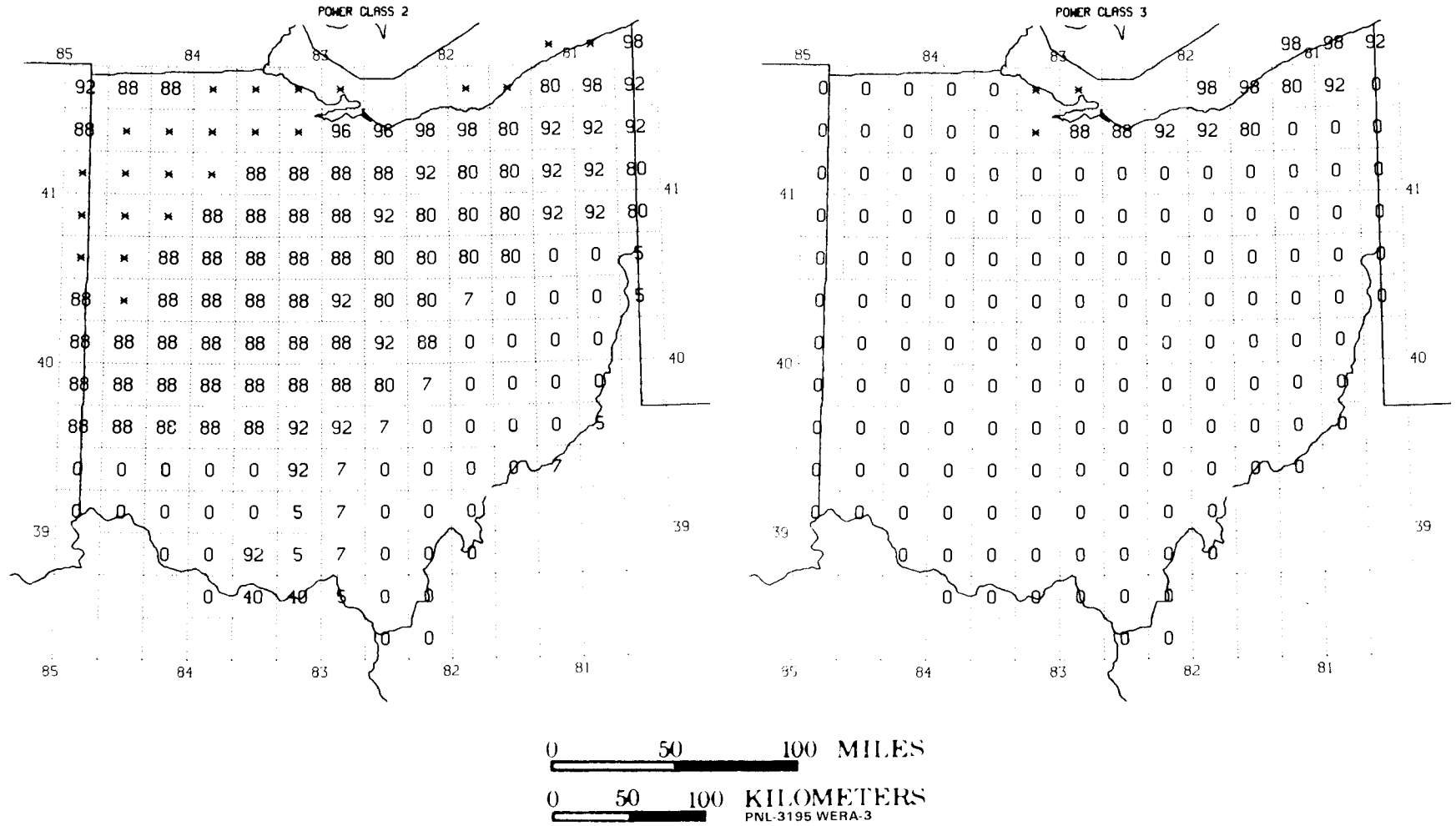


FIGURE 7.8. Areal Distribution of Wind Resource in Ohio (Power Classes 2 and 3); Percent of Land Area With or Exceeding Power Class Shown. An asterisk denotes 100%.

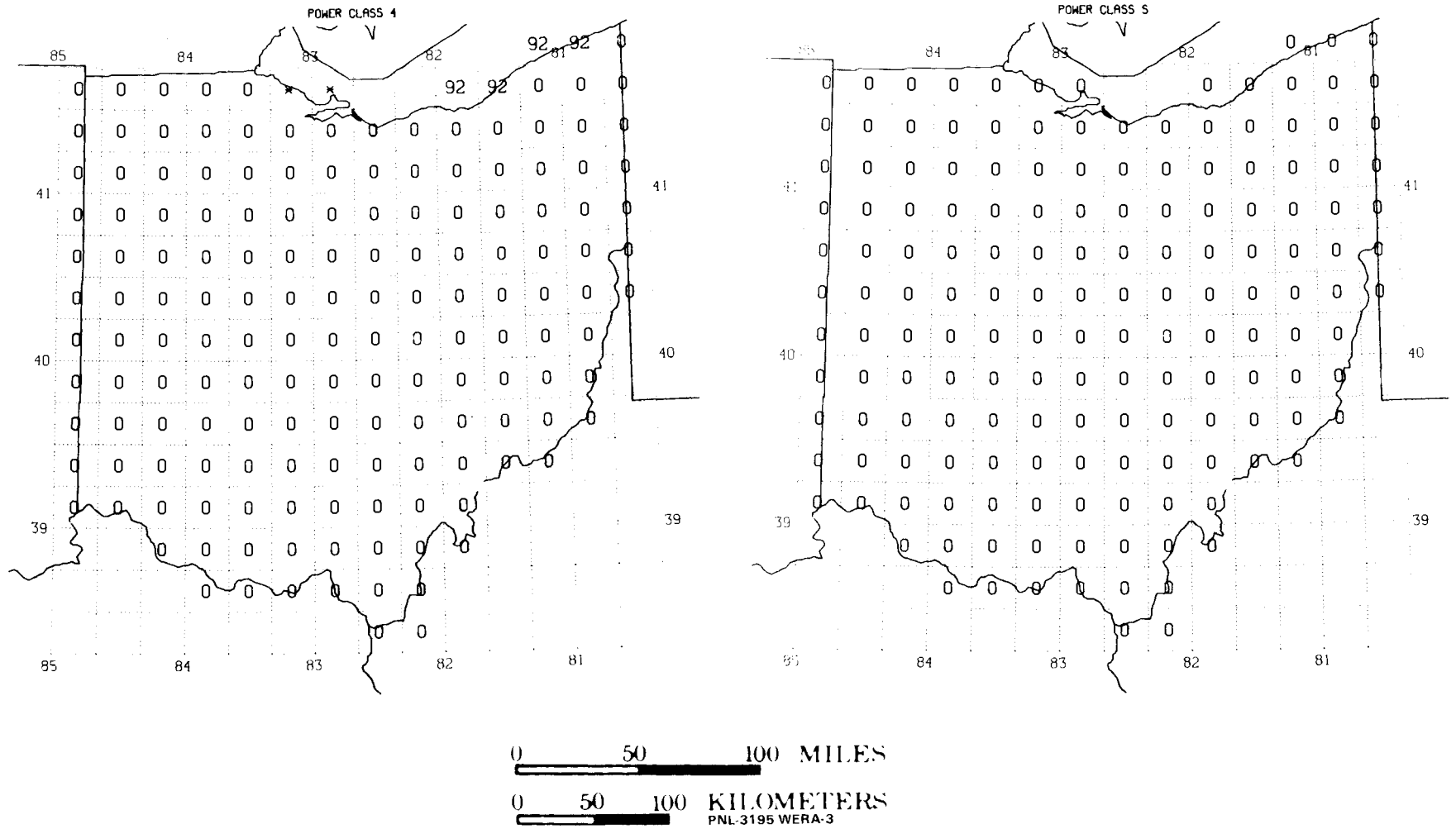


FIGURE 7.8 (Continued). Areal Distribution of Wind Resource in Ohio (Power Classes 4 and 5); Percent of Land Area With or Exceeding Power Class Shown.

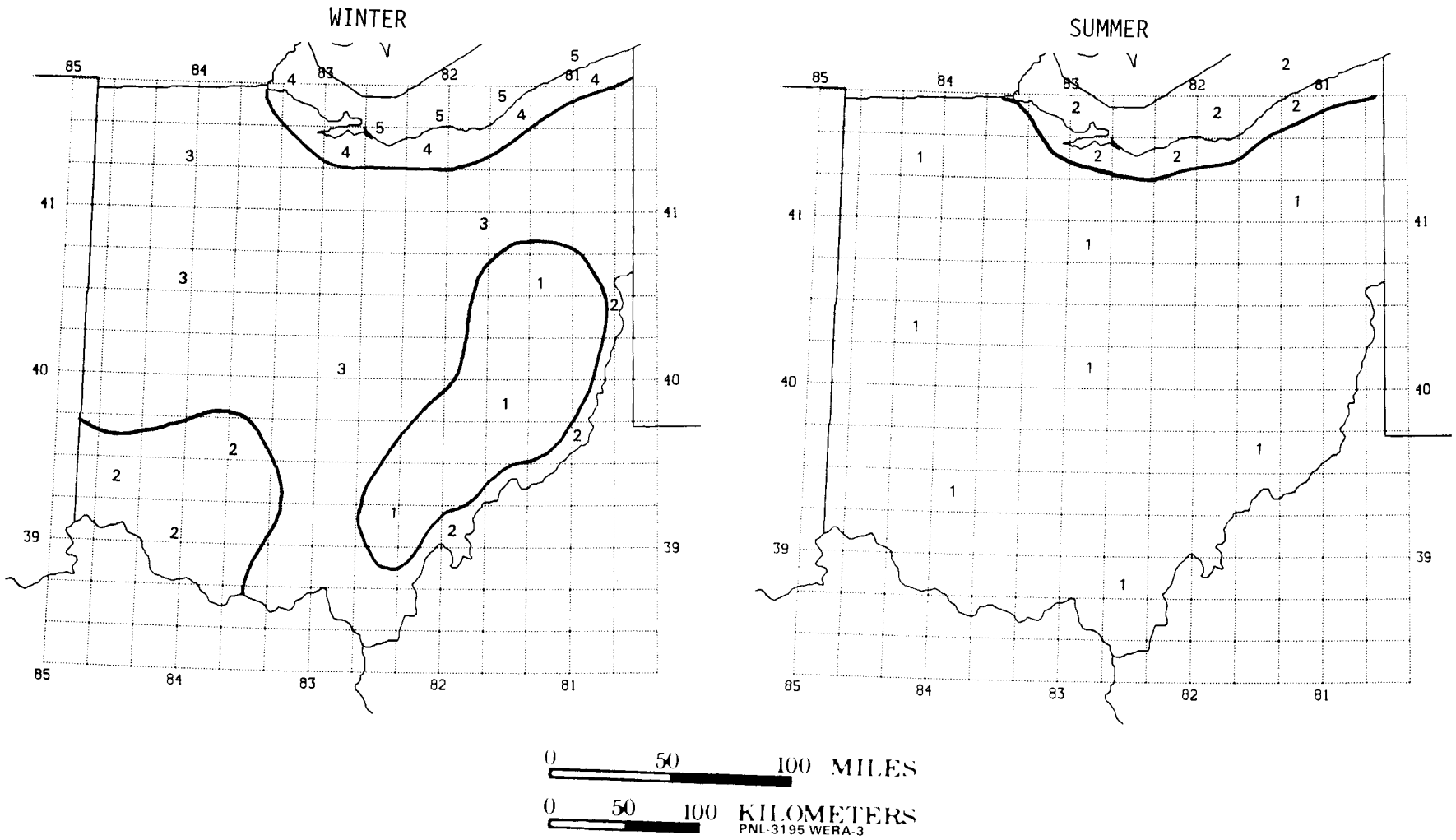


FIGURE 7.9. Seasonal Average Wind Power in Ohio

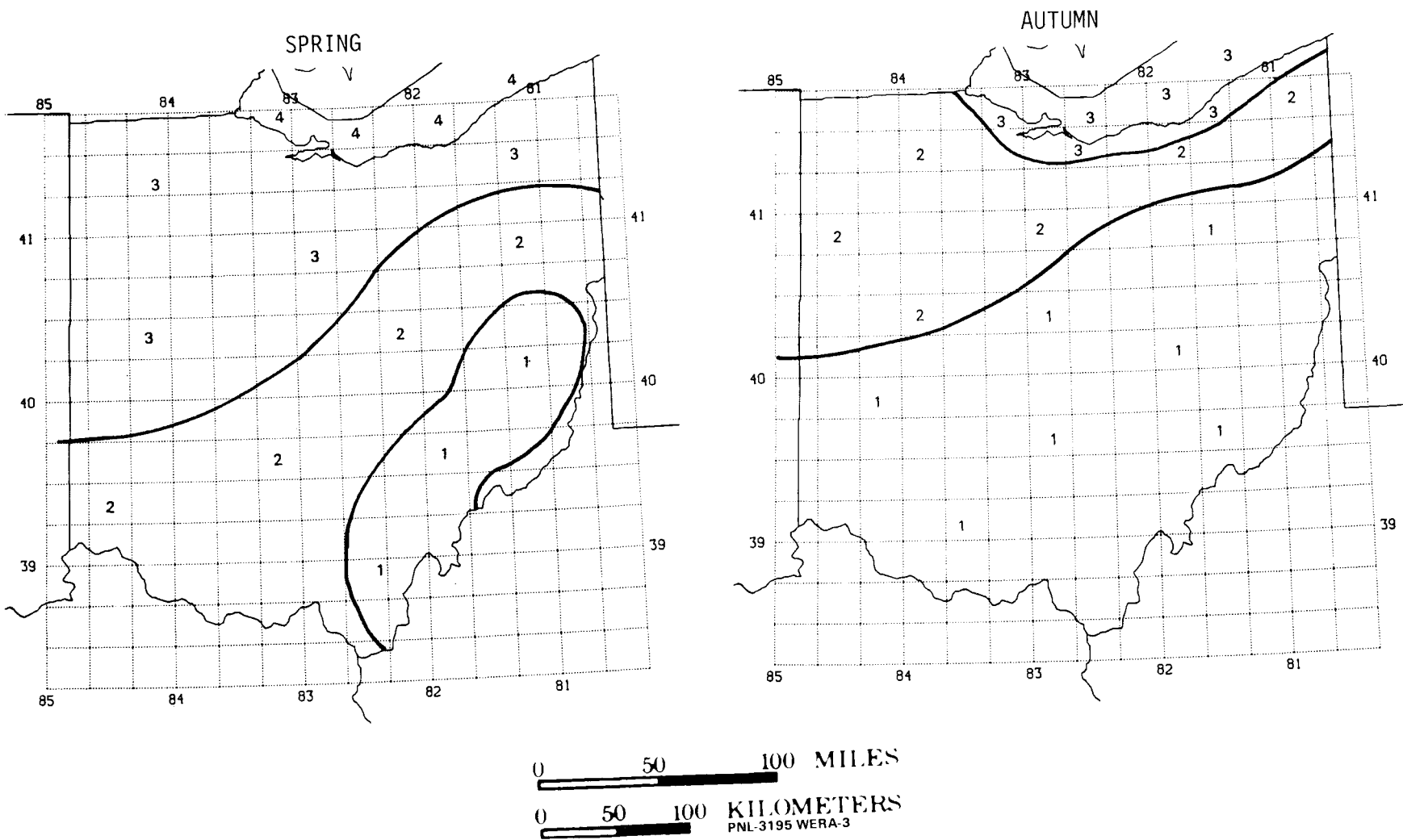


FIGURE 7.9 (Continued). Seasonal Average Wind Power in Ohio

TABLE 7.2. Ohio Stations with Graphs of the Wind Characteristics

| Station                 | Station Name(a)                  | Latitude,<br>Degrees North | Longitude,<br>Degrees West | Elevation of<br>Station, m | Period of<br>Record,<br>mm/yy | Anemometer<br>Height, m | Annual Average<br>Wind Speed, m/s |            |            | Annual Average<br>Wind Power<br>Watts/m <sup>2</sup> |            |            |
|-------------------------|----------------------------------|----------------------------|----------------------------|----------------------------|-------------------------------|-------------------------|-----------------------------------|------------|------------|--|------------|------------|
|                         |                                  |                            |                            |                            |                               |                         | At<br>Anemometer<br>Height        | At<br>10 m | At<br>50 m | At<br>Anemometer<br>Height                           | At<br>10 m | At<br>50 m |
| Akron/Canton            | Akron/Canton Airport             | 40.91                      | 81.43                      | 379                        | 02/62-12/78                   | 6.1                     | 4.3                               | 4.6        | 5.8        | 83   | 103        | 205        |
| Cleveland               | Hopkins International<br>Airport | 41.39                      | 81.84                      | 245                        | 01/48-12/55                   | 17.1                    | 4.9                               | 4.5        | 5.7        | 138  | 110        | 219        |
| Cleveland               | Hopkins International<br>Airport | 41.39                      | 81.84                      | 245                        | 06/59-12/78                   | 6.1                     | 4.6                               | 4.9        | 6.2        | 107  | 132        | 264        |
| Columbus/<br>Lockbourne | Lockbourne AFB                   | 39.81                      | 82.93                      | 293                        | 05/56-12/70                   | 4.3                     | 3.1                               | 3.5        | 4.4        | 52   | 75         | 149        |
| Columbus                | Pt. Columbus Airport             | 39.98                      | 82.86                      | 286                        | 10/59-12/78                   | 6.1                     | 4.0                               | 4.3        | 5.4        | 80   | 99         | 197        |
| Dayton/Cox              | JM Cox/Dayton                    | 39.89                      | 84.21                      | 313                        | 12/61-02/74                   | 6.1                     | 4.4                               | 4.7        | 6.0        | 96   | 119        | 237        |
| Dayton/Cox              | JM Cox/Dayton                    | 39.89                      | 84.21                      | 313                        | 02/74-12/78                   | 6.7                     | 4.4                               | 4.6        | 5.8        | 90   | 107        | 213        |
| Dayton/Wright           | Wright-Patterson AFB             | 39.81                      | 84.03                      | 250                        | 03/57-12/70                   | 4.0                     | 2.9                               | 3.4        | 4.2        | 52   | 77         | 154        |
| Findlay                 | CAA                              | 41.01                      | 83.66                      | 244                        | 12/48-12/54                   | 21.3                    | 5.0                               | 4.5        | 5.6        | 147  | 106        | 212        |
| Mansfield               | LAHM Municipal Airport           | 40.81                      | 82.51                      | 376                        | 12/48-12/54                   | 8.2                     | 5.0                               | 5.1        | 6.4        | 143  | 155        | 310        |
| Mansfield               | LAHM Municipal Airport           | 40.81                      | 82.51                      | 396                        | 08/61-12/78                   | 6.1                     | 5.0                               | 5.3        | 6.7        | 122  | 151        | 301        |
| Perry                   | CAA                              | 41.78                      | 81.06                      | 211                        | 12/48-01/50                   | UNK <sup>(b)</sup>      | 5.3                               | 5.3        | 6.6        | 188  | 188        | 375        |
| Toledo                  | Express Airport WBAS             | 41.59                      | 83.79                      | 212                        | 11/68-12/78                   | 9.1                     | 4.2                               | 4.3        | 5.4        | 84   | 87         | 174        |
| Toledo                  | WBAS                             | 41.34                      | 83.28                      | 194                        | 01/46-01/55                   | 14.3                    | 4.9                               | 4.6        | 4.8        | 154  | 132        | 263        |
| Wilmington              | Clinton Co. AFB                  | 39.43                      | 83.79                      | 322                        | 06/65-06/68                   | 4.0                     | 3.2                               | 3.6        | 4.5        | 50   | 74         | 148        |
| Youngstown              | Municipal Airport WBAS           | 41.26                      | 80.66                      | 365                        | 11/58-12/78                   | 6.1                     | 4.5                               | 4.8        | 6.0        | 94   | 116        | 232        |
| Zanesville              | Municipal Airport CAA            | 39.94                      | 81.86                      | 270                        | 12/48-12/54                   | 8.2                     | 4.0                               | 4.1        | 5.1        | 106  | 115        | 230        |

a AFB - Air Force Base; WBAS - Weather Bureau Airport Station; CAA - Civil Aeronautics Administration; NAS - Naval Air Station.  
b UNK - Anemometer height is unknown. Height of 10 m was assumed for estimating wind speed and power at 10 and 50 m.

+-----+ WIND POWER  
 ◆-----◆ WIND SPEED  
PNL-3195 WERA-3

LEFT ORDINATE - WATTS/M<sup>2</sup>  
 RIGHT ORDINATE - M/S  
 ABSCISSA - YEAR

V AND P ADJUSTED FROM Z TO 10 M BY 1/7 POWER LAW

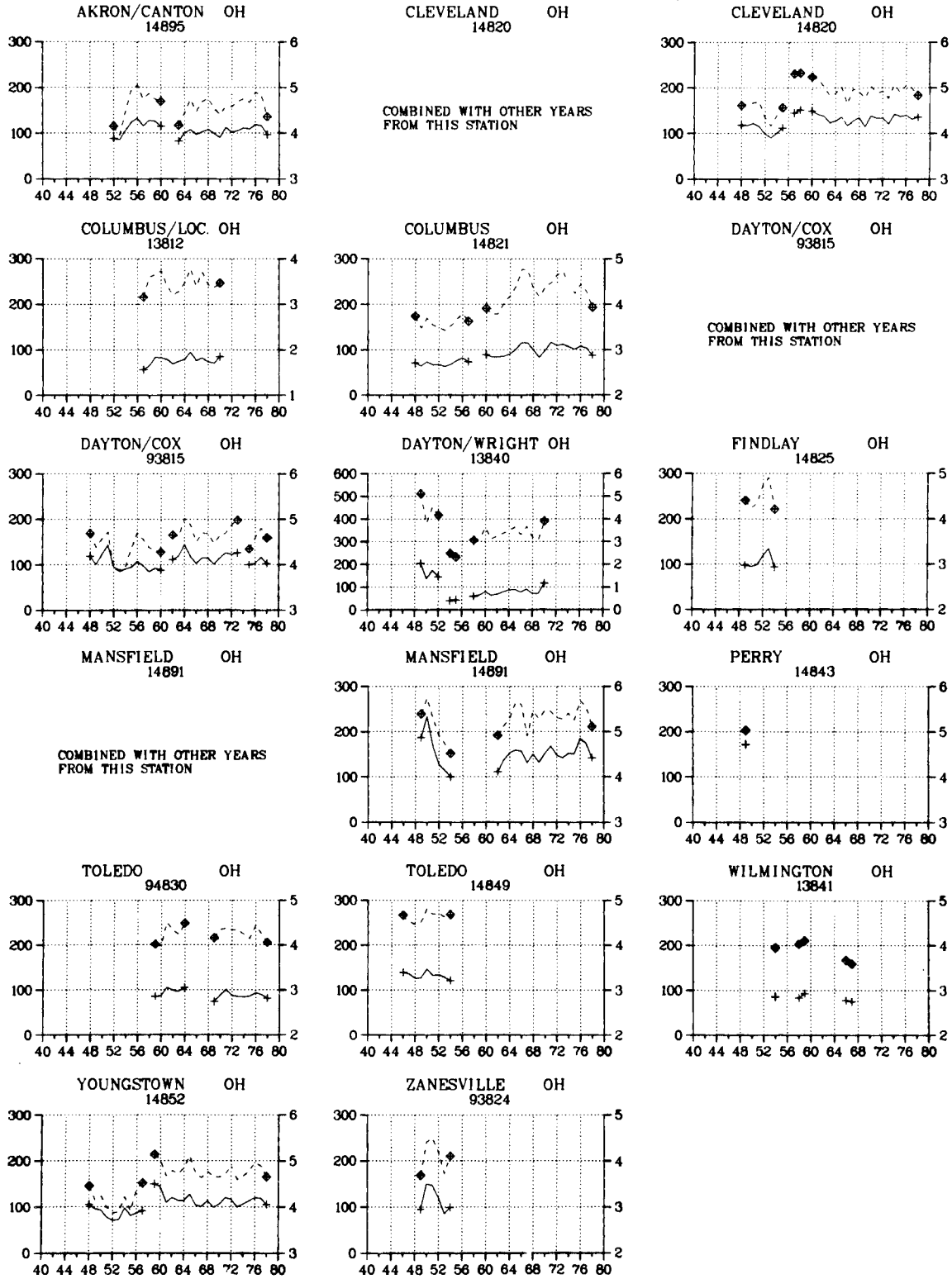


FIGURE 7.10. Interannual Wind Power and Speed for Ohio

— WIND POWER  
 - - - WIND SPEED  
 PNL-3195 WERA-3

LEFT ORDINATE - WATTS/M<sup>2</sup>  
 RIGHT ORDINATE - M/S  
 ABSCISSA - MONTH

V AND P ADJUSTED FROM Z TO 10 M BY 1/7 POWER LAW

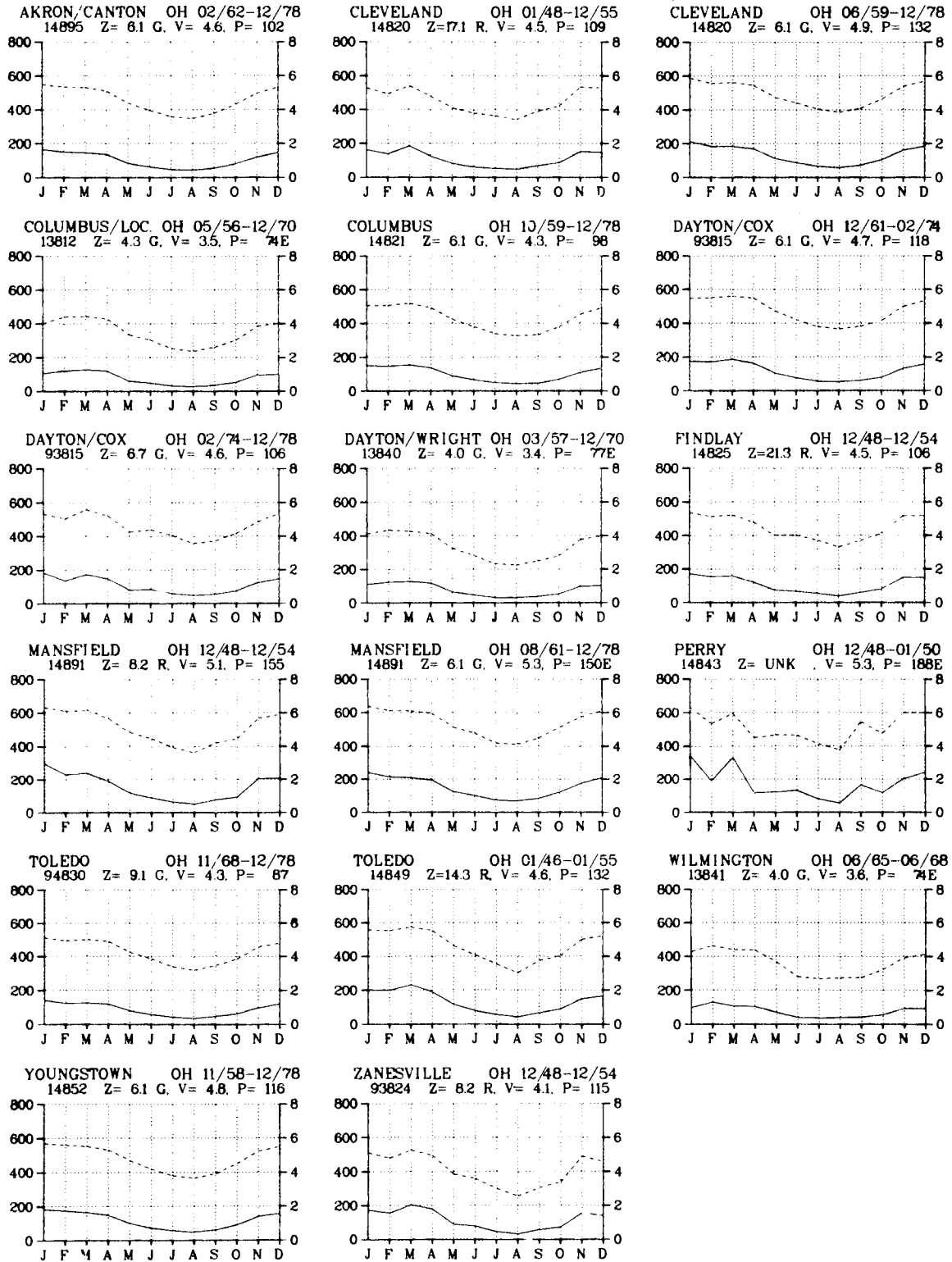
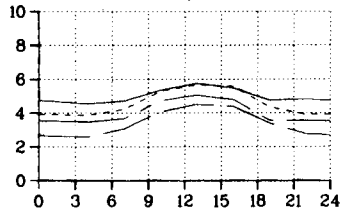


FIGURE 7.11. Monthly Average Wind Power and Speed for Ohio

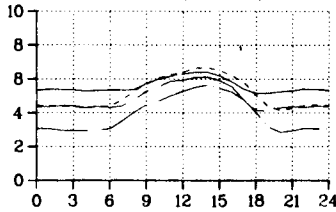
——— WINTER      ◆ - - - ◆ SPRING  
 ⊕ - - ⊕ SUMMER      ⊞ - - ⊞ AUTUMN  
PNL-3195 WERA-3

ORDINATE - M/S  
 ABSCISSA - HOUR

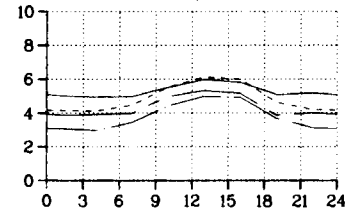
AKRON/CANTON OH 02/62-12/78  
14895 Z= 6.1 G, V= 4.3, P= 83



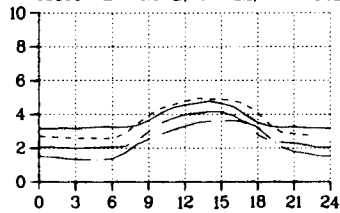
CLEVELAND OH 01/48-12/55  
14820 Z=17.1 R, V= 4.9, P= 138



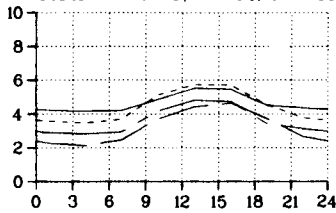
CLEVELAND OH 06/59-12/78  
14820 Z= 6.1 G, V= 4.6, P= 107



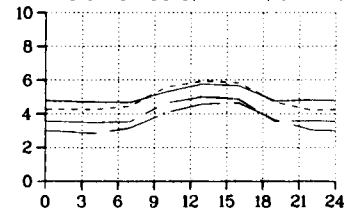
COLUMBUS/LOC. OH 05/56-12/70  
13812 Z= 4.3 G, V= 3.1, P= 52E



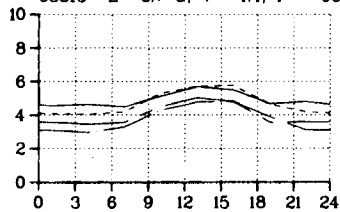
COLUMBUS OH 10/59-12/78  
14821 Z= 6.1 G, V= 4.0, P= 80



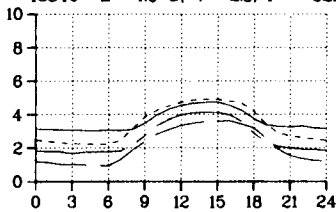
DAYTON/COX OH 12/61-02/74  
93815 Z= 6.1 G, V= 4.4, P= 96



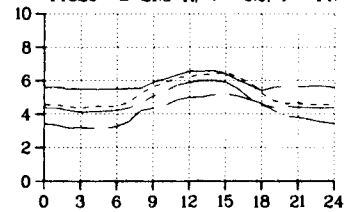
DAYTON/COX OH 02/74-12/78  
93815 Z= 6.7 G, V= 4.4, P= 90



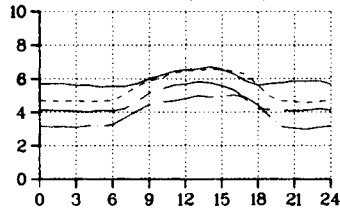
DAYTON/WRIGHT OH 03/57-12/70  
13840 Z= 4.0 G, V= 2.9, P= 52E



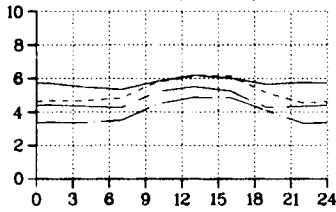
FINDLAY OH 12/48-12/54  
14825 Z=21.3 R, V= 5.0, P= 147



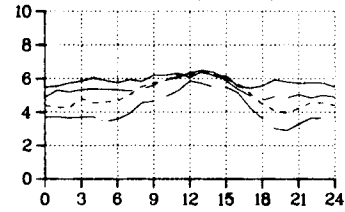
MANSFIELD OH 12/48-12/54  
14891 Z= 8.2 R, V= 5.0, P= 143



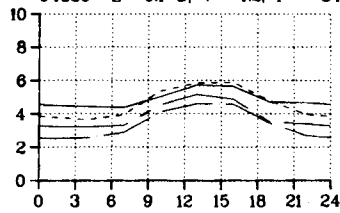
MANSFIELD OH 08/61-12/78  
14891 Z= 6.1 G, V= 5.0, P= 122E



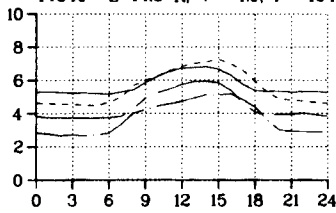
PERRY OH 12/48-01/50  
14843 Z= UNK, V= 5.3, P= 188E



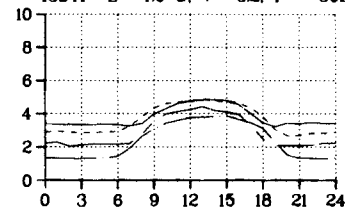
TOLEDO OH 11/68-12/78  
94830 Z= 9.1 G, V= 4.2, P= 84



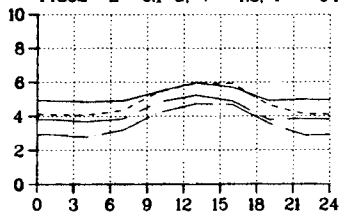
TOLEDO OH 01/46-01/55  
14849 Z=14.3 R, V= 4.9, P= 154



WILMINGTON OH 06/65-06/68  
13841 Z= 4.0 G, V= 3.2, P= 50E



YOUNGSTOWN OH 11/58-12/78  
14852 Z= 6.1 G, V= 4.5, P= 94



ZANESVILLE OH 12/48-12/54  
93824 Z= 8.2 R, V= 4.0, P= 106

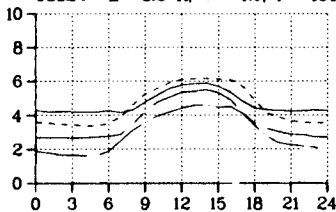


FIGURE 7.12. Diurnal Wind Speed by Season for Ohio

— PERCENT FREQUENCY LEFT ORDINATE - PERCENT  
 - - - WIND SPEED RIGHT ORDINATE - M/S  
 PNL-3195 WERA-3  
 ABSCISSA - WIND DIRECTION

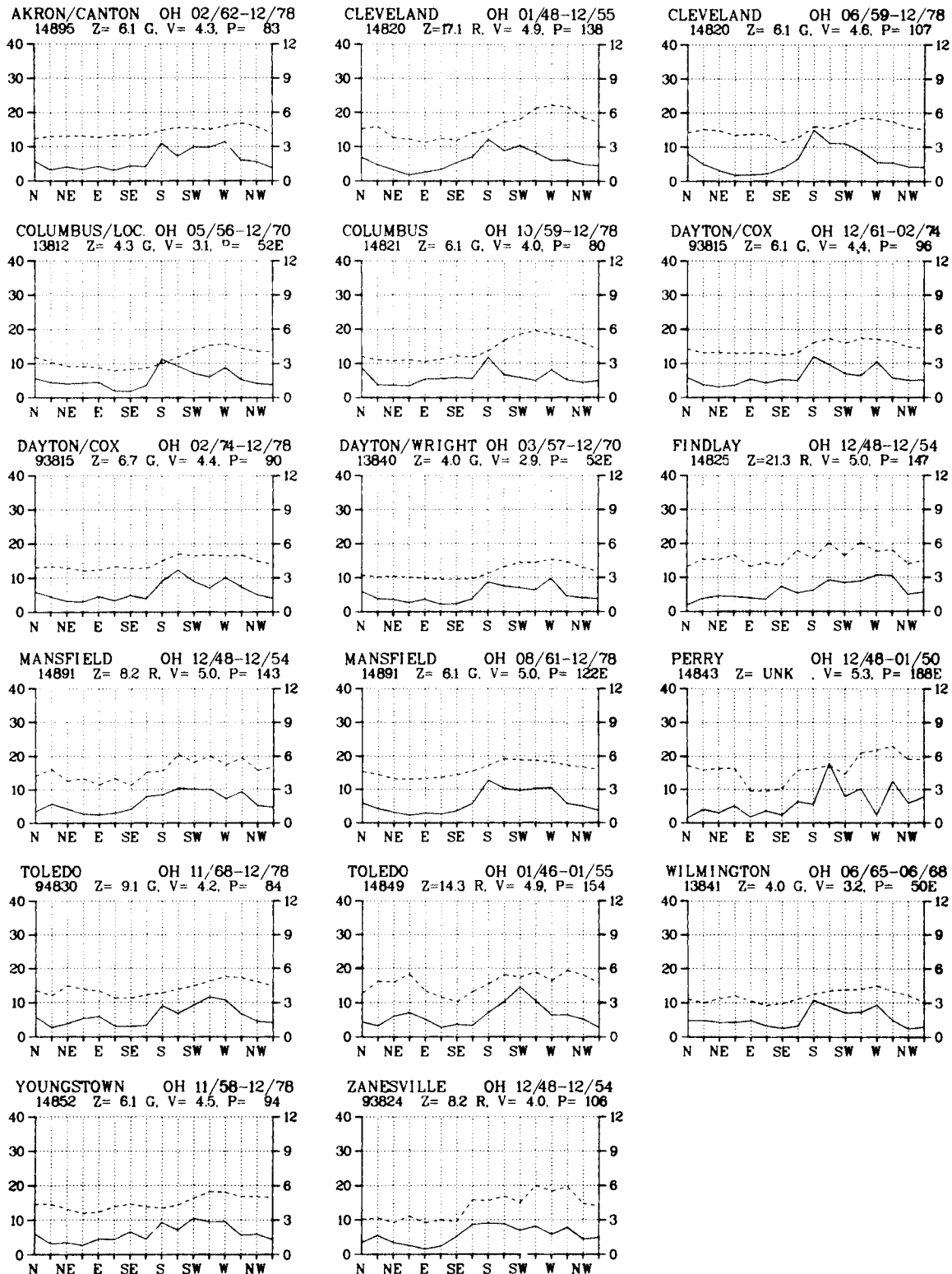
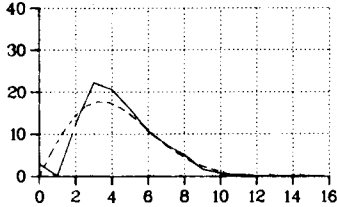


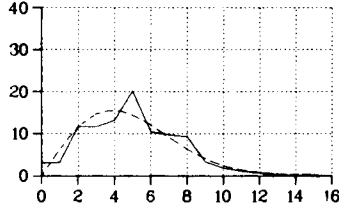
FIGURE 7.13. Directional Frequency and Average Wind Speed for Ohio

— ACTUAL DISTRIBUTION      ORDINATE - PERCENT  
 - - - RAYLEIGH DISTRIBUTION      ABSCISSA - M/S  
 PNL-3195 WERA-3

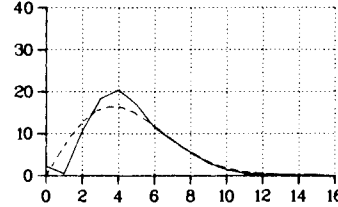
AKRON/CANTON OH 02/62-12/78  
 14895 Z= 6.1 G, V= 4.3, P= 83



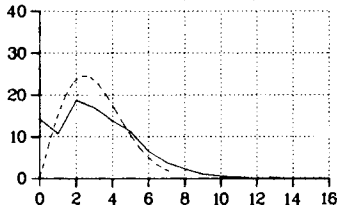
CLEVELAND OH 01/48-12/55  
 14820 Z=17.1 R, V= 4.9, P= 138



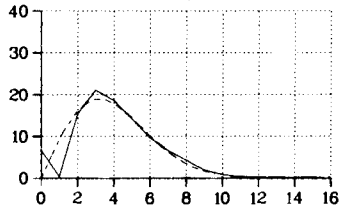
CLEVELAND OH 06/59-12/78  
 14820 Z= 6.1 G, V= 4.6, P= 107



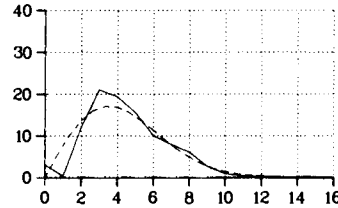
COLUMBUS/LOC. OH 05/56-12/70  
 13812 Z= 4.3 G, V= 3.1, P= 52E



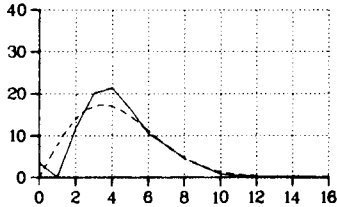
COLUMBUS OH 13/59-12/78  
 14821 Z= 6.1 G, V= 4.0, P= 80



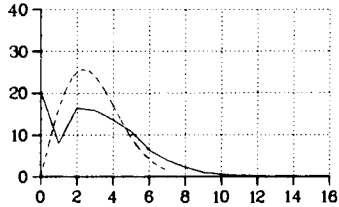
DAYTON/COX OH 12/61-02/74  
 93815 Z= 6.1 G, V= 4.4, P= 96



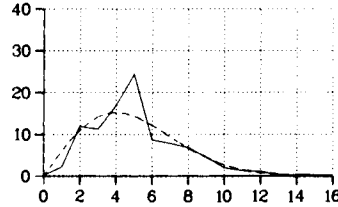
DAYTON/COX OH 02/74-12/78  
 93815 Z= 6.7 G, V= 4.4, P= 90



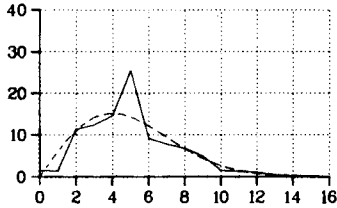
DAYTON/WRIGHT OH 03/57-12/70  
 13840 Z= 4.0 G, V= 2.9, P= 52E



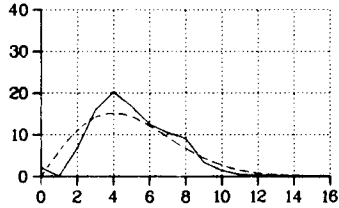
FINDLAY OH 12/48-12/54  
 14825 Z=21.3 R, V= 5.0, P= 147



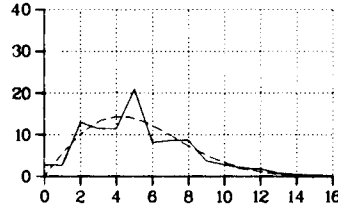
MANSFIELD OH 12/48-12/54  
 14891 Z= 8.2 R, V= 5.0, P= 143



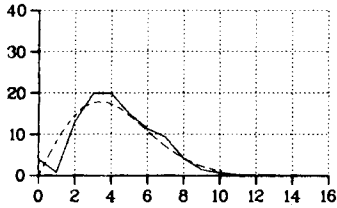
MANSFIELD OH 08/61-12/78  
 14891 Z= 8.1 G, V= 5.0, P= 122E



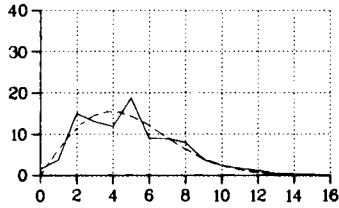
PERRY OH 12/48-01/50  
 14843 Z= UNK, V= 5.3, P= 188E



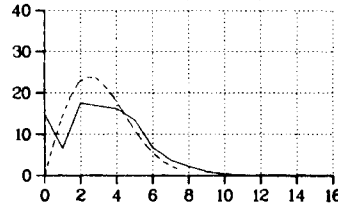
TOLEDO OH 11/68-12/78  
 94830 Z= 9.1 G, V= 4.2, P= 84



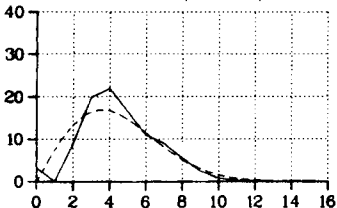
TOLEDO OH 01/46-01/55  
 14849 Z=14.3 R, V= 4.9, P= 154



WILMINGTON OH 06/65-06/68  
 13841 Z= 4.0 G, V= 3.2, P= 50E



YOUNGSTOWN OH 11/58-12/78  
 14852 Z= 6.1 G, V= 4.5, P= 94



ZANESVILLE OH 12/48-12/54  
 93824 Z= 8.2 R, V= 4.0, P= 106

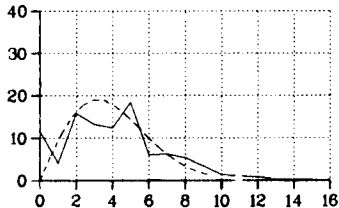
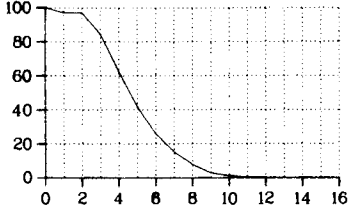


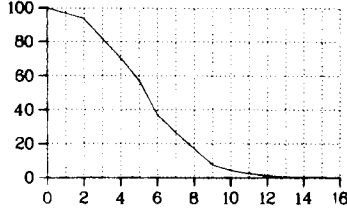
FIGURE 7.14. Annual Average Wind Speed Frequency for Ohio

ORDINATE - PERCENT  
 ABSCISSA - M/S  
 PNL-3195 WERA:3

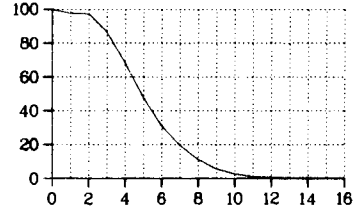
AKRON/CANTON OH 02/62-12/78  
 14895 Z= 6.1 G, V= 4.3, P= 83



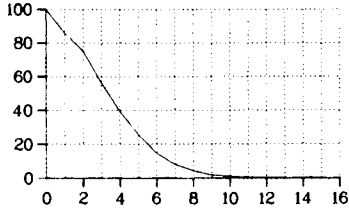
CLEVELAND OH 01/48-12/55  
 14820 Z=7.1 R, V= 4.9, P= 138



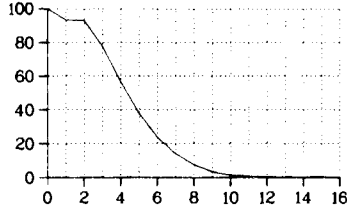
CLEVELAND OH 06/59-12/78  
 14820 Z= 6.1 G, V= 4.6, P= 107



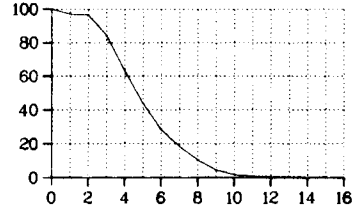
COLUMBUS/LOC. OH 05/56-12/70  
 13812 Z= 4.3 G, V= 3.1, P= 52E



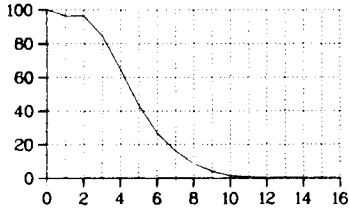
COLUMBUS OH 10/59-12/78  
 14821 Z= 6.1 G, V= 4.0, P= 80



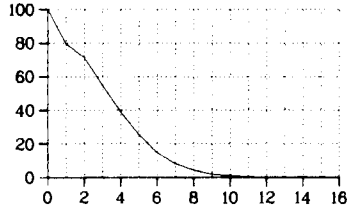
DAYTON/COX OH 12/61-02/74  
 93815 Z= 6.1 G, V= 4.4, P= 96



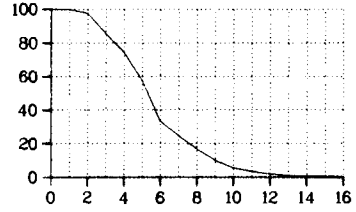
DAYTON/COX OH 02/74-12/78  
 93815 Z= 6.7 G, V= 4.4, P= 90



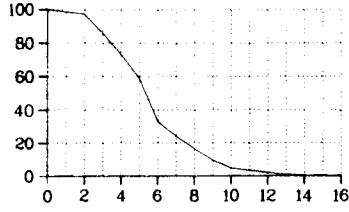
DAYTON/WRIGHT OH 03/57-12/70  
 13840 Z= 4.0 G, V= 2.9, P= 52E



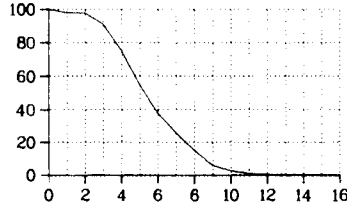
FINDLAY OH 12/48-12/54  
 14825 Z=21.3 R, V= 5.0, P= 147



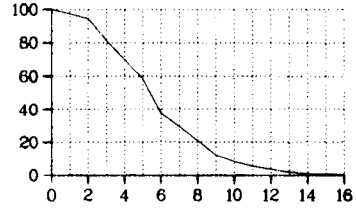
MANSFIELD OH 12/48-12/54  
 14891 Z= 8.2 R, V= 5.0, P= 143



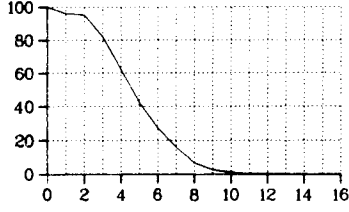
MANSFIELD OH 08/61-12/78  
 14891 Z= 6.1 G, V= 5.0, P= 122E



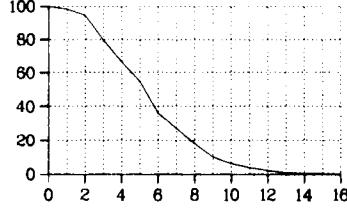
PERRY OH 12/48-01/50  
 14843 Z= UNK, V= 5.3, P= 188E



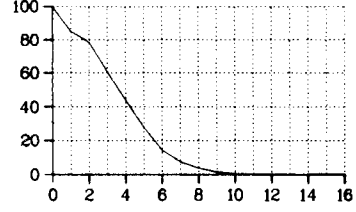
TOLEDO OH 11/68-12/78  
 94830 Z= 9.1 G, V= 4.2, P= 84



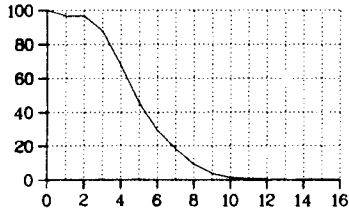
TOLEDO OH 01/46-01/55  
 14849 Z=14.3 R, V= 4.9, P= 154



WILMINGTON OH 06/65-06/68  
 13841 Z= 4.0 G, V= 3.2, P= 50E



YOUNGSTOWN OH 11/58-12/78  
 14852 Z= 6.1 G, V= 4.5, P= 94



ZANESVILLE OH 12/48-12/54  
 93824 Z= 8.2 R, V= 4.0, P= 108

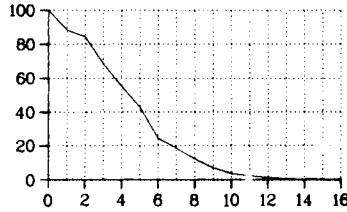


FIGURE 7.15. Annual Average Wind Speed Duration for Ohio

ORDINATE - PERCENT  
 ABSCISSA - WATTS/M<sup>2</sup>  
 PNL-3195 WERA-3

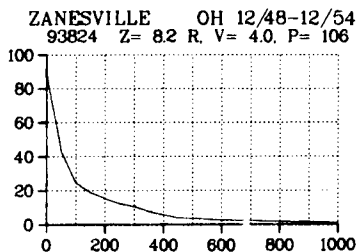
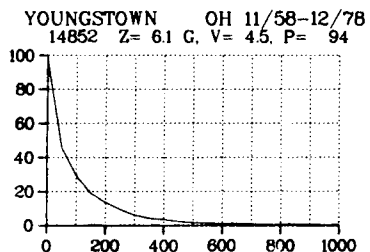
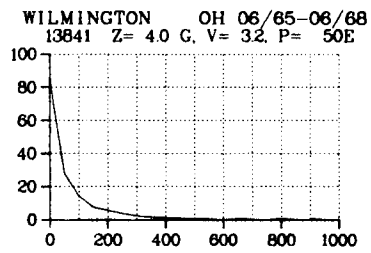
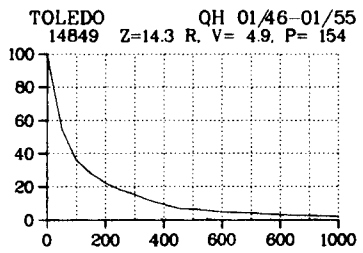
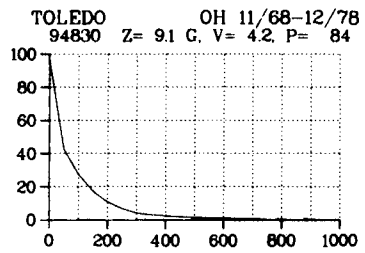
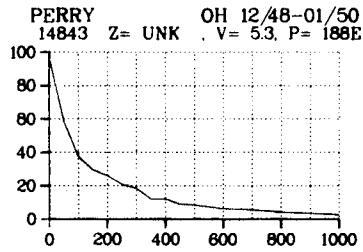
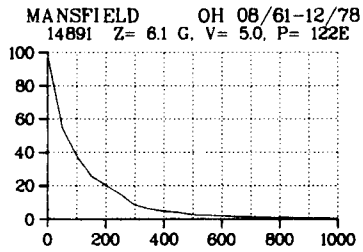
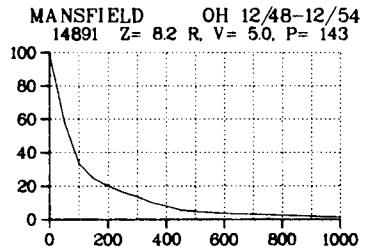
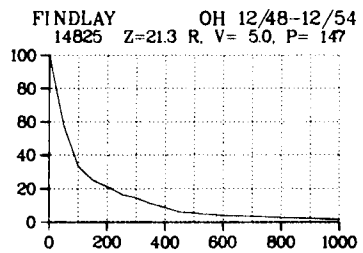
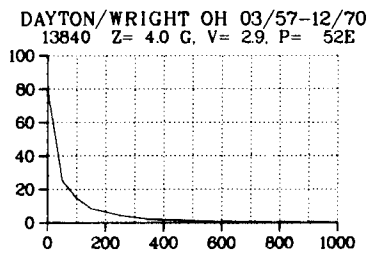
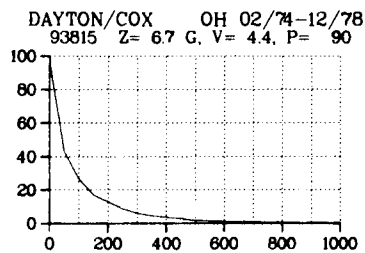
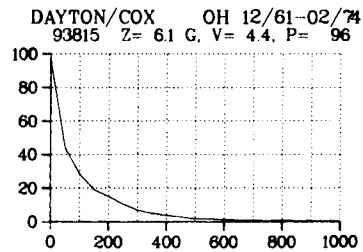
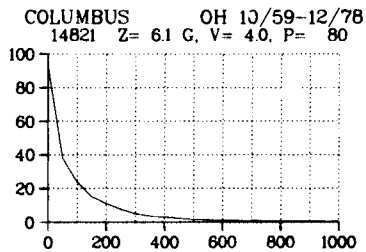
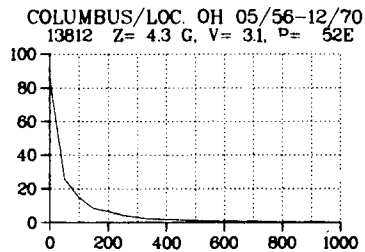
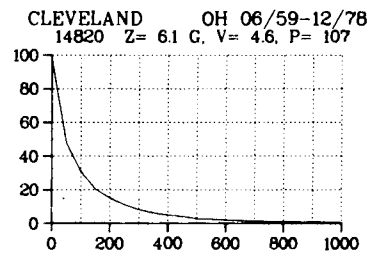
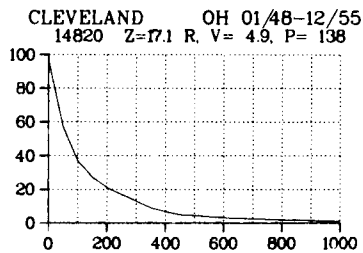
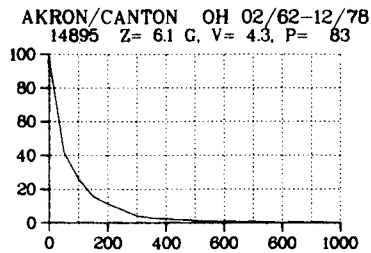


FIGURE 7.16. Annual Average Wind Power Duration for Ohio



**WISCONSIN**

Wisconsin covers an area of 145,465 km<sup>2</sup> (56,164 mi<sup>2</sup>). With a population of 4,417,933 in 1970, it is the least populated state in the Great Lakes region. Most of the inhabitants live in the eastern and southern parts of the state where the two largest cities, Madison and Milwaukee, are situated (see Figure 8.1).

Located west of Lake Michigan and southwest of the Upper Peninsula of Michigan, much of Wisconsin is characterized by rolling hills favorable to dairy farming (Figure 8.2). The only unglaciated region of considerable relief is in the southwestern part of the state (Figure 8.3). Elevations in Wisconsin range from 200 m (600 ft) above mean sea level on the shores of Lake Michigan to 595 m (1,950 ft) in the southwest. The Lake Superior Uplands in northern Wisconsin cover about 38,850 km<sup>2</sup> (15,000 mi<sup>2</sup>) and range in elevation from 300 to 640 m (1,000 to 1,800 ft).

Existing summarized or digitized wind data from the National Climatic Center (NCC) are mostly concentrated in the southern half of Wisconsin. Data-sparse regions are found in the extreme northwest and northeast. Much of the coastal data was in the form of unsummarized Coast Guard records, with unknown anemometer height and history and undetermined exposure (see Figure 8.4). Other data sources used in the Wisconsin wind assessment included nuclear facilities, universities, and private utilities (Figure 8.5). These latter three sources of wind data were both digitized and summarized.

### 8.1 ANNUAL AVERAGE WIND POWER

The annual average available wind power density in Wisconsin is shown in Figure 8.6. The analyses of mean wind power apply to terrain features that are favorably exposed to the wind, such as hilltops, uplands, and open plains (see Section 1.6). However, nearby terrain features may interact with the wind field to cause the wind power at some exposed sites to vary as much as + 50 to 100% from the assessment values. (See Wegley et al. 1980 for information on terrain features that may increase or reduce wind energy.) In forested or wooded areas, the estimates are representative of large clearings with good exposure to the prevailing strong winds, such as airports, where runways are generally aligned parallel to the prevailing wind direction(s). The percentage of land area that is favorably exposed to the

wind strongly depends on the land-surface form (Section 1.8).

The annual average wind power map for Wisconsin shows class 3 wind power at offshore and exposed sites along the coast of Lake Michigan, and class 4 wind power along the coast of Lake Superior. These estimates along the lakes represent offshore and exposed coastal areas, e.g., open shorelines that are not sheltered from the prevailing winds. The winds may be accelerated around and over capes and headlands, where exposed areas could have class 4 or 5 wind power (not indicated in Figure 8.6). The abrupt inland increase of surface roughness (because of vegetation and topography) rapidly attenuates the wind resource landward of the coast line.

The band of class 4 along Lake Superior suggests the intensity of winds striking the coast after sweeping across the water. This wind power class extends well inland due to the favorable exposure of hilltop sites in the Gogebic Mountains and to the rugged terrain to the west. The sharp decrease in wind power from class 4 to class 1 is explained by increased surface roughness and by the simpler terrain (that is, decreased exposure). The class 2 and 3 transition bands along the northern shore are too narrow and too uncertain to be resolved in this analysis.

Class 3 wind power has been assigned to the coastline of Lake Michigan from the Door Peninsula southward to the Illinois border. The potential for class 3 wind power arises when east component winds, having a long smooth fetch across Lake Michigan, impact the shoreline. The prevailing annual winds are westerly, but eastward-moving storms moving out over the lake initiate easterly flows as they pass over the coastal area. The other occasions for easterly wind arise when pressure-induced lake breezes develop during the summer and late spring.

The effect of the smooth lake surfaces is greatly reduced at inland locations. The upland plains in central and northern Wisconsin experience the very low wind speeds associated with that inland location. Northern sections of the state are extensively forested, and sites are usually unfavorably exposed. To the south of the class 1 region the wind resource increases to class 2 as the terrain becomes more complex. Channeling

is evident in the unglaciated sections of the southwest near the Mississippi River (along the Minnesota border), where the wind resource is estimated as class 2.

#### 8.1.1 Certainty Rating of the Wind Resource

Certainty ratings of the wind power estimates for Wisconsin vary from 1 to 4 (Figure 8.7). The areas with certainty rating 4 are found in central and southern sections where low spatial variability, lack of relief, and abundant, representative data combine to produce a high degree of certainty. The wind resource in this region is very low (class 1 or 2). In Wisconsin, areas of high certainty are never those of high wind power resource. Consistently, the coastal sections that border Lake Michigan and Lake Superior have very low certainty ratings. The combination of high spatial variability with questionable exposure and quality of the offshore marine and coastal data results in shoreline estimates of low certainty. The area of certainty rating 2 and 3 in central and northern Wisconsin reflect the sparsity of data in these regions.

#### 8.1.2 Areal Distribution

The influence of the large expanses of class 1 and 2 wind power over much of central Wisconsin is evident in the summary of the areal distribution of wind power classes (Table 8.1). The fractional area experiencing wind power class 3 is very small, and is primarily due to favorable exposures near Lakes Michigan and Superior. Some shoreline and offshore areas bordering Lake Superior may experience a wind power of class 5. However, this is not indicated on the annual average map since it was not supported by the data. The very large fractional area (77%) of class 1 wind power makes for featureless maps at class 4 and 5 wind power (Figure 8.8).

### 8.2 SEASONAL WIND POWER

Wind power maps for each season are shown on facing pages in Figure 8.9. With the exception of the Lake Superior coastline and northern interior sections, winter is the season of maximum wind power; summer is the season of lowest wind power throughout the entire state.

#### 8.2.1 Winter

In winter, wind power class 4 is estimated for exposed coastal and offshore areas along Lake Superior and Lake Michigan. Although most of northern

Wisconsin is heavily forested, hills and mountains along Lake Superior permit favorable exposure to winds blowing landward. The assignment of class 4 wind power to the region inland from the coast reflects the increased exposure to fetch-enhanced winds from the north and northwest. Northeasterly winds associated with winter storm systems give rise to the powerful winds recorded at exposed sites on the coast of Lake Michigan. This resource diminishes rapidly with distance from the coast as surface roughness increases. To the west in unglaciated sections, the orientation of the Mississippi River appears to channel the northwesterlies, resulting in class 2 wind power. A broad expanse of class 1 wind power exists in north-central Wisconsin, where heavy forest cover and little terrain relief combine to decrease the wind power potential.

#### 8.2.2 Spring

Except for the coast of Lake Michigan and extreme southern sections, the wind power resource in Wisconsin is maximum in the spring. The frequency and strength of cyclones over the north central United States and south central Canada (e.g., Alberta track cyclones) reach a maximum during the early spring months. The wind energy potential of northwestern sections of the Great Lakes region (i.e., northwest Wisconsin) reflects this factor with a class 2 wind power. Additionally, the land-water temperature gradient is maximized in spring and this can contribute to the available wind power via lake-breeze circulation along the Lake Superior shoreline.

Along Lake Michigan, the frequency and intensity of eastward-moving storms decreases from March to May, but the land-water temperature gradient increases, so that winter-level wind speeds are largely maintained.

#### 8.2.3 Summer

During the summer, the average wind power in Wisconsin is lowest. Wind power class 1 has been assigned throughout the state except for the coastal regions (class 2).

#### 8.2.4 Autumn

In autumn, as pressure gradients strengthen and winds shift toward the west-northwest from September to November, the wind power resource for Wisconsin begins to take on some of the

characteristics of the wintertime resource. Class 4 wind power is estimated once again for the Lake Superior shoreline and the class 3 wind power band reappears along Lake Michigan (reflecting the southward shift in storm tracks).

### 8.3 FEATURES OF SELECTED STATIONS

Graphs of the wind characteristics are shown for 9 stations in Wisconsin (Table 8.2). Eight of these stations are in central and southern sections, Grantsburg is in the northwestern corner. La Crosse and Lone Rock are the only stations located in the rough, unglaciated region of the southwest.

Camp Douglas Airport/Volks Field Airport is on a plain in central Wisconsin with small hills to the southwest. This station appears to have good exposure, but the low wind speeds recorded indicate local sheltering, possibly by the terrain.

La Crosse Municipal Airport is situated on the Wabash River in southwest Wisconsin. Surrounding terrain is quite hilly, especially in the northwest quadrant. Although the anemometer was moved from a rooftop to a ground mast in 1964, the recorded wind speeds from 1964 to 1978 are lower than those measured in the previous period. The site appears to be very well exposed to prevailing winds from the northwest and south, but the low wind power values from 1964 to 1978 suggest questionable data.

Lone Rock Tri-City Airport is located in a broad valley surrounded by rolling hills in south central Wisconsin. The anemometer height is unknown and the recorded wind speeds are moderate (3.7 m/s). This site has questionable exposure to prevailing westerlies.

Eau Claire Airport, on the Chippewa River, is situated on a mostly sandy, irregular plain. Terrain slopes upward to the south and west. It is very well exposed to the power-producing winds from the northwest quadrant.

Madison/Truax Field is located northeast of Lake Mendota in south central Wisconsin. The high wind powers obtained for 1948 to 1952 suggest good exposure. From 1959 to 1978, the anemometer was shifted from a rooftop to a ground mast, and the observed wind speeds were lower than for the previous period.

Milwaukee/Mitchell Field is situated just west of the Lake Michigan coastline in the southeastern part of the state. The topography is relatively flat and the site is estimated to be very well exposed to prevailing winds.

Wausau Municipal Airport is located near the Wisconsin River, in the central part of the state. The site is on a wide plain and apparently well exposed. The anemometer, however, is on a rooftop location which may account for the low observed wind speeds. The anemometer is estimated to be only moderately well exposed.

#### 8.3.1 Interannual Wind Power and Speed

With the exception of La Crosse, which shows a large variation from 1968 to 1975, the interannual variations appear to be moderate for most of Wisconsin (Figure 8.10). For Eau Claire, Madison, Green Bay, and La Crosse, 1968 was a year of maximum wind power, while 1969 was a "low" year. The highest wind power was recorded at Milwaukee ( $205 \text{ W/m}^2$ ) in 1960, and at Madison ( $220 \text{ W/m}^2$ ) in 1950. Milwaukee, however, displays the most consistent high values of wind power. Note that as in Madison, La Crosse, and Milwaukee, the magnitude of the interannual variations may differ for different periods of record for a given station.

#### 8.3.2 Monthly Average Wind Power and Speed

The season of minimum power for all 9 stations is summer (Figure 8.11). With the exception of Green Bay, the season of maximum power is spring. In Madison and Milwaukee the peak occurs in March; at the other stations the peak is in April. Many of the stations show a strong secondary peak in November. At Green Bay during 1949-1961, the maximum wind power occurred in November, while during 1961-1978, it occurred in January. Milwaukee, Camp Douglas, and La Crosse display only a small increase in wind power from winter to spring; La Crosse shows an almost imperceptible change and is nearly constant year round (1964-1978).

#### 8.3.3 Diurnal Wind Speed by Season

All nine stations presented for Wisconsin indicate maximum daily wind speeds during the mid-morning to afternoon period for all seasons (see Figure 8.12). Peak speeds generally occur from between 1200 and 1500 LST. Nighttime wind speeds tend to be lowest in summer, highest in spring or winter.

The magnitude of the diurnal variation with season varies with location, but is generally weakest in winter and greater in summer. The small diurnal variation is seen at La Crosse where seasonal variation is almost negligible.

#### 8.3.4 Directional Frequency and Average Speed

In many cases, the prevailing winds are not necessarily the power-producing winds. This is most evident at La Crosse where the prevailing winds are southerly, and the strongest winds are from the northwest. Some channeling effect of the terrain could contribute to the more vigorous winds observed from the northwest.

With the exception of Madison and Milwaukee, most of the power-producing winds come from the northwest. At Milwaukee the strongest winds are from the south or the north-northwest; in Madison they are from the southwest. These are also the two stations with the most consistently strong winds (Figure 8.13).

#### 8.3.5 Annual Average Wind Speed Frequency

Because observer bias and low instrument threshold speeds distort the observed frequency distribution (Figure 8.14), the representativeness of the Rayleigh speed distribution is hard to evaluate. Observer biases are readily apparent at Camp Douglas, Eau Claire (1949-1961), Grantsburg, Green Bay, La Crosse, Lone Rock, Madison (1948-1952), and Milwaukee (1948-1955). In Wisconsin and Madison (1959-1978), the Rayleigh distribution approximates the actual distribution quite well. The stronger winds (8 m/s and greater) are most frequent at Green Bay, Madison, and Milwaukee.

#### 8.3.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in Figures 8.15 and 8.16. Abrupt changes in the slope of the direction curves correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity.





FIGURE 8.1. Geographic Map of Wisconsin

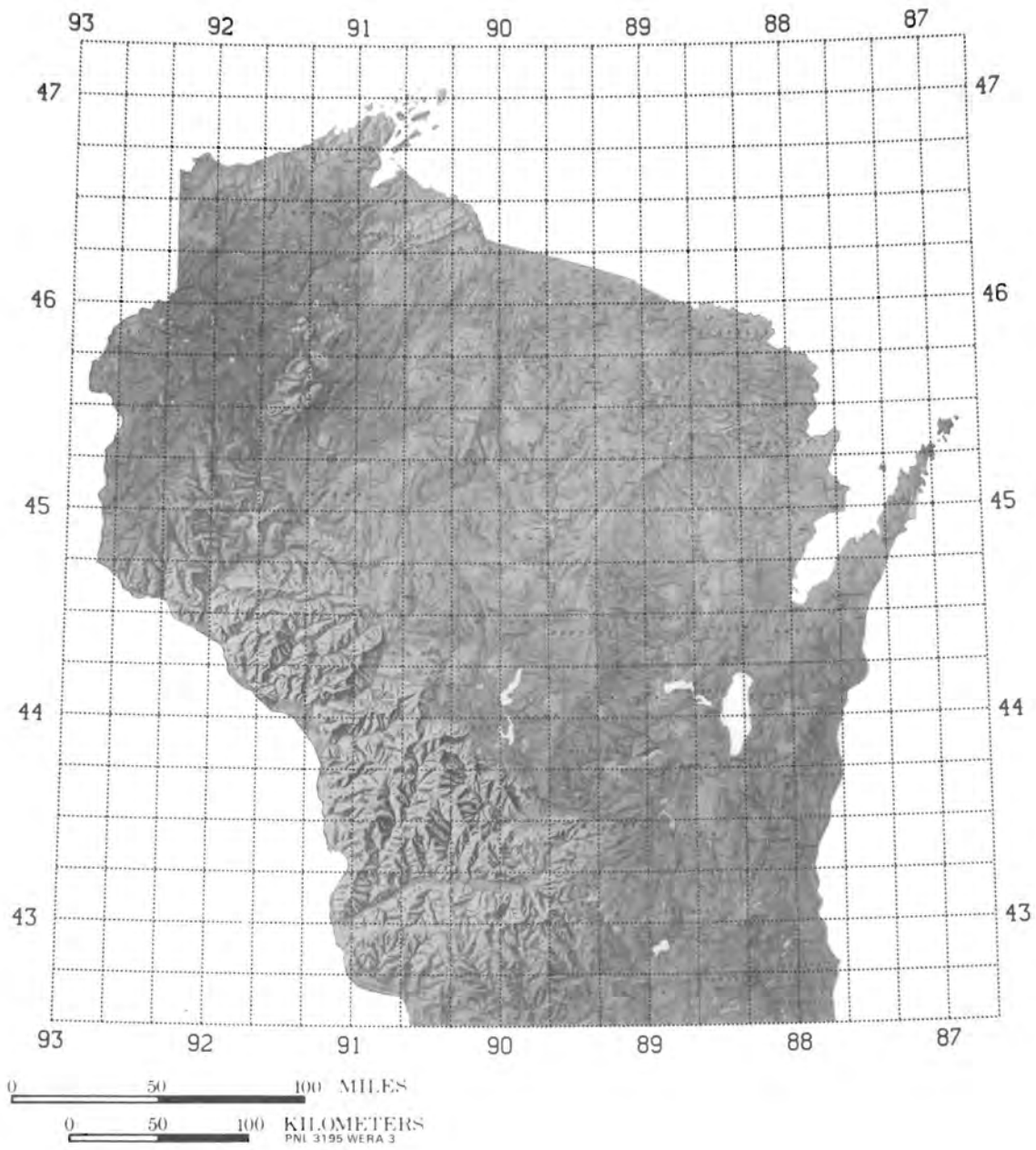


FIGURE 8.2. Topographic Map of Wisconsin

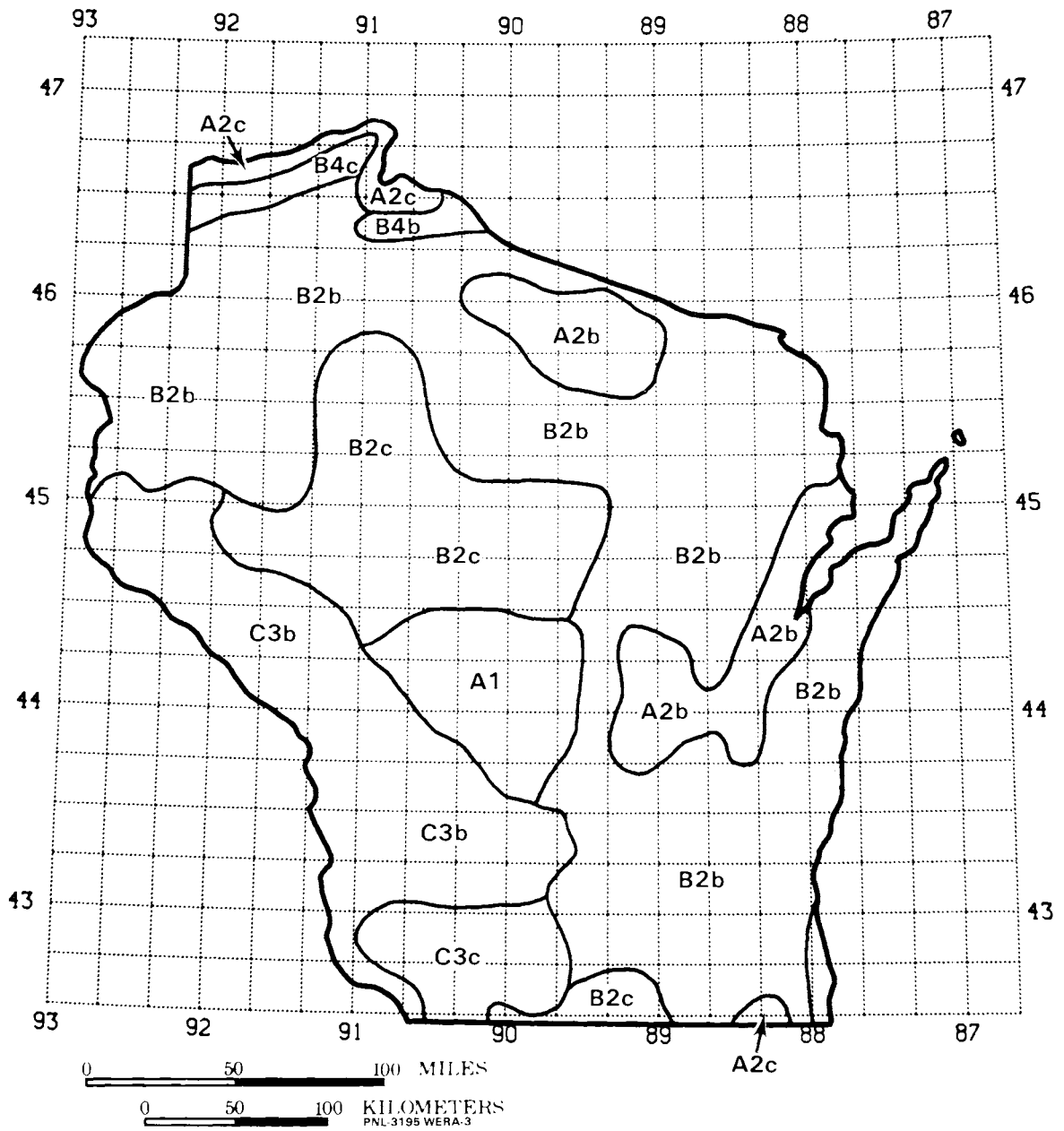


FIGURE 8.3. Land-Surface Form Map for Wisconsin

## LAND-SURFACE FORM LEGEND

### PLAINS

|    |                                 |
|----|---------------------------------|
| A1 | FLAT PLAINS                     |
| A2 | SMOOTH PLAINS                   |
| B1 | IRREGULAR PLAINS, SLIGHT RELIEF |
| B2 | IRREGULAR PLAINS                |

### TABLELANDS

|       |                                 |
|-------|---------------------------------|
| B3c,d | TABLELANDS, MODERATE RELIEF     |
| B4c,d | TABLELANDS, CONSIDERABLE RELIEF |
| B5c,d | TABLELANDS, HIGH RELIEF         |
| B6c,d | TABLELANDS, VERY HIGH RELIEF    |

### PLAINS WITH HILLS OR MOUNTAINS

|         |                            |
|---------|----------------------------|
| A,B3a,b | PLAINS WITH HILLS          |
| B4,a,b  | PLAINS WITH HIGH HILLS     |
| B5a,b   | PLAINS WITH LOW MOUNTAINS  |
| B6a,b   | PLAINS WITH HIGH MOUNTAINS |

### SCHEME OF CLASSIFICATION

#### SLOPE (1st LETTER)

|   |                               |
|---|-------------------------------|
| A | >80% OF AREA GENTLY SLOPING   |
| B | 50-80% OF AREA GENTLY SLOPING |
| C | 20-50% OF AREA GENTLY SLOPING |
| D | <20% OF AREA GENTLY SLOPING   |

### OPEN HILLS AND MOUNTAINS

|    |                     |
|----|---------------------|
| C2 | OPEN LOW HILLS      |
| C3 | OPEN HILLS          |
| C4 | OPEN HIGH HILLS     |
| C5 | OPEN LOW MOUNTAINS  |
| C6 | OPEN HIGH MOUNTAINS |

#### LOCAL RELIEF (2nd LETTER)

|   |                                |
|---|--------------------------------|
| 1 | 0 TO 30m (1 TO 100 ft)         |
| 2 | 30 TO 90m (100 TO 300 ft)      |
| 3 | 90 TO 150m (300 TO 500 ft)     |
| 4 | 150 TO 300m (500 TO 1000 ft)   |
| 5 | 300 TO 900m (1000 TO 3000 ft)  |
| 6 | 900 TO 1500m (3000 TO 5000 ft) |

### HILLS AND MOUNTAINS

|    |                |
|----|----------------|
| D3 | HILLS          |
| D4 | HIGH HILLS     |
| D5 | LOW MOUNTAINS  |
| D6 | HIGH MOUNTAINS |

#### PROFILE TYPE (3rd LETTER)

|   |                                      |
|---|--------------------------------------|
| a | >75% OF GENTLE SLOPE IS IN LOWLAND   |
| b | 50-75% OF GENTLE SLOPE IS IN LOWLAND |
| c | 50-75% OF GENTLE SLOPE IS ON UPLAND  |
| d | >75% OF GENTLE SLOPE IS ON UPLAND    |

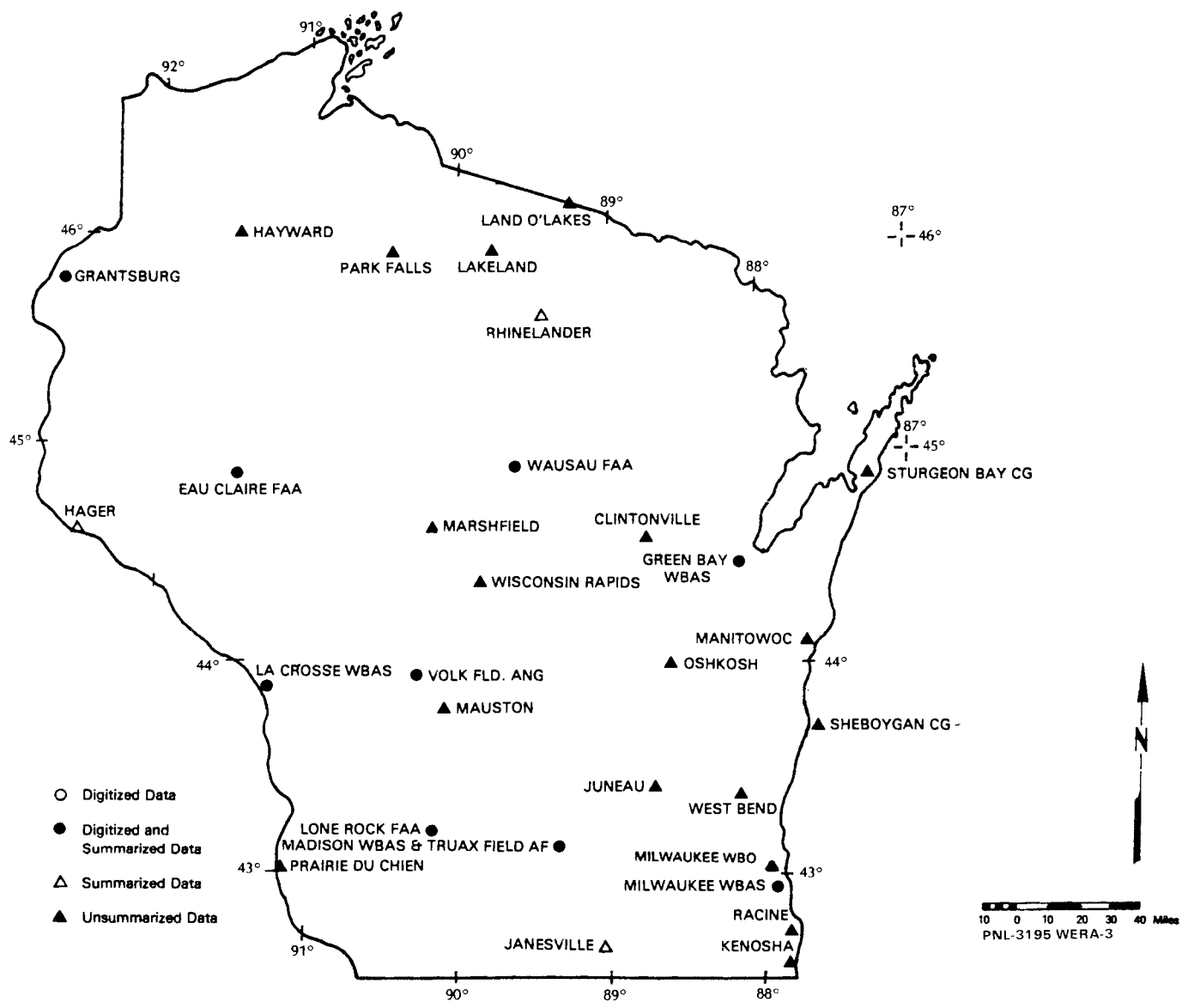


FIGURE 8.4. NCC Station Locations in Wisconsin

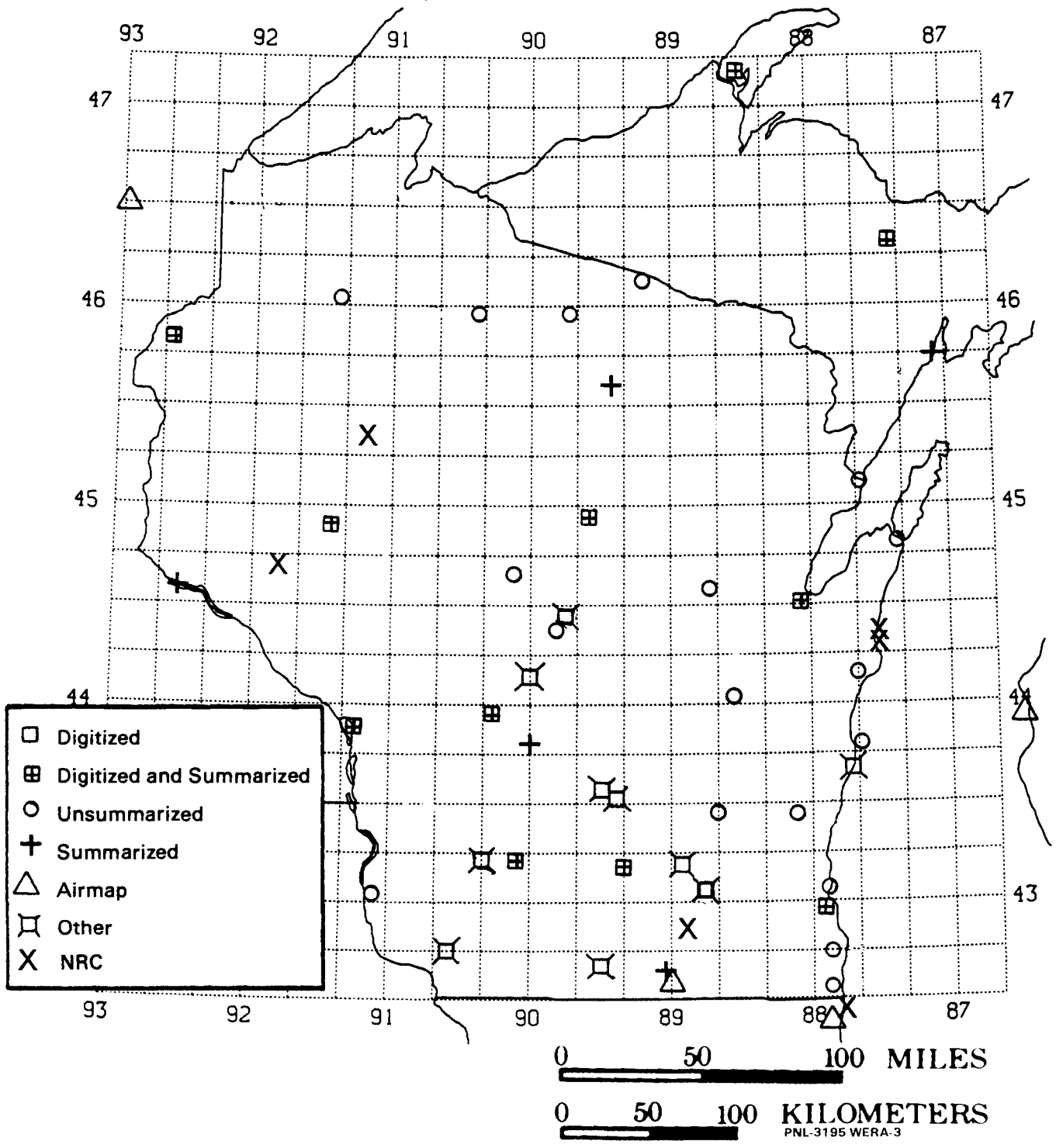


FIGURE 8.5. Location of Stations Used in Wisconsin Resource Assessment

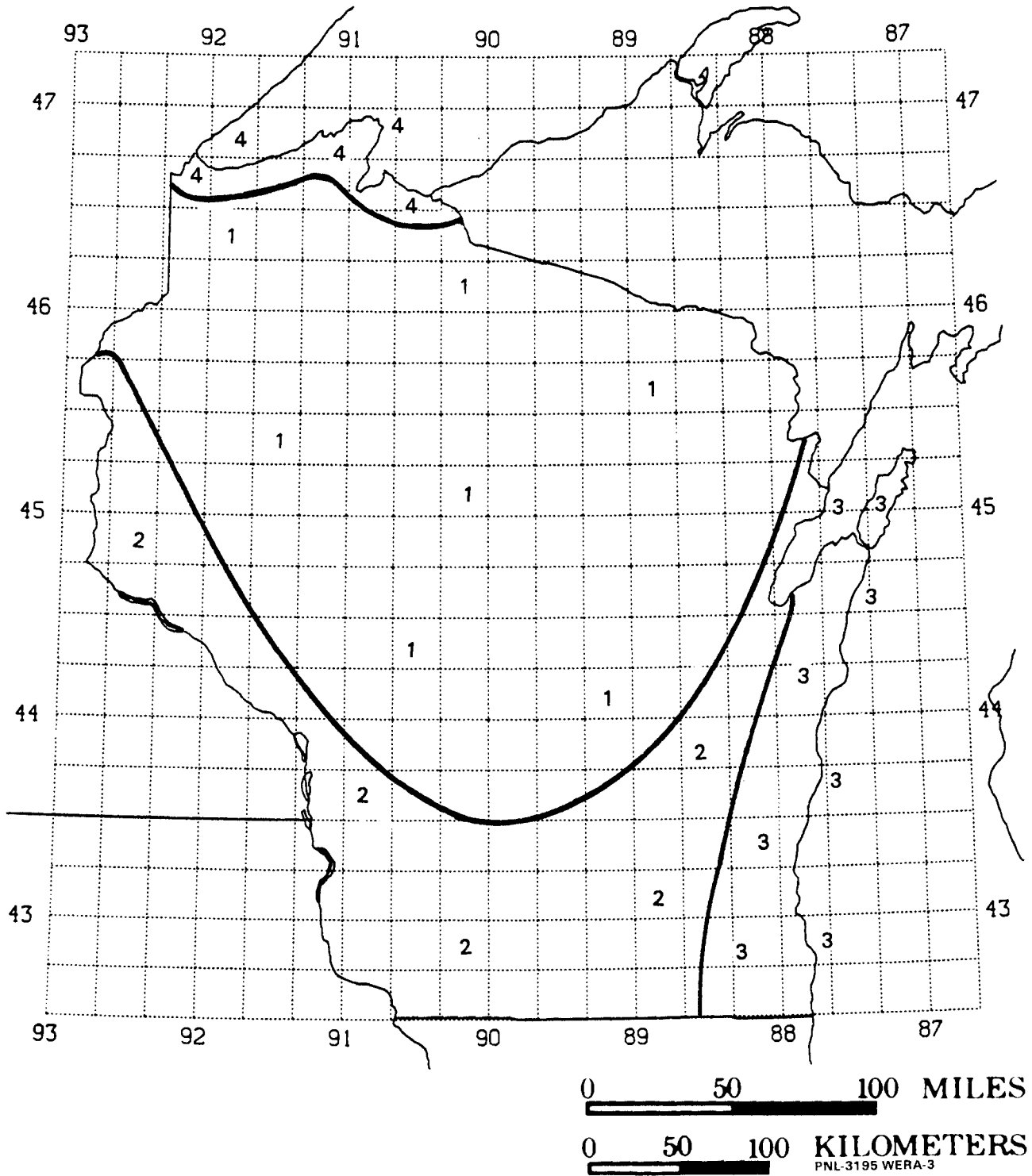


FIGURE 8.6. Wisconsin Annual Average Wind Power

Classes of Wind Power Density at 10 m and 50 m<sup>(a)</sup>

| Wind Power Class | 10 m (33 ft)                             |                                 | 50 m (164 ft)                            |                                 |
|------------------|--|---------------------------------|--|---------------------------------|
|                  | Wind Power Density, watts/m <sup>2</sup> | Speed, <sup>(b)</sup> m/s (mph) | Wind Power Density, watts/m <sup>2</sup> | Speed, <sup>(b)</sup> m/s (mph) |
|                  | 0  | 0                               | 0  | 0                               |
| 1                | 100                                      | 4.4 (9.8)                       | 200                                      | 5.6 (12.5)                      |
| 2                | 150                                      | 5.1 (11.5)                      | 300                                      | 6.4 (14.3)                      |
| 3                | 200                                      | 5.6 (12.5)                      | 400                                      | 7.0 (15.7)                      |
| 4                | 250                                      | 6.0 (13.4)                      | 500                                      | 7.5 (16.8)                      |
| 5                | 300                                      | 6.4 (14.3)                      | 600                                      | 8.0 (17.9)                      |
| 6                | 400                                      | 7.0 (15.7)                      | 800                                      | 8.8 (19.7)                      |
| 7                | 1000                                     | 9.4 (21.1)                      | 2000                                     | 11.9 (26.6)                     |

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 8.1. Areal Distribution (km<sup>2</sup>) of Wind Power Classes in Wisconsin

| Power Class | Land Area | Percent Land Area | Cumulative Land Area | Percent Cumulative Land Area |
|-------------|-----------|-------------------|----------------------|------------------------------|
| 1           | 104,000   | 77.0              | 135,000              | 100.0                        |
| 2           | 20,000    | 15.0              | 31,200               | 23.0                         |
| 3           | 7,800     | 5.8               | 10,800               | 8.0                          |
| 4           | 3,000     | 2.2               | 3,000                | 2.2                          |
| 5-7         | 0.        | 0.00              | 0.                   | 0.00                         |

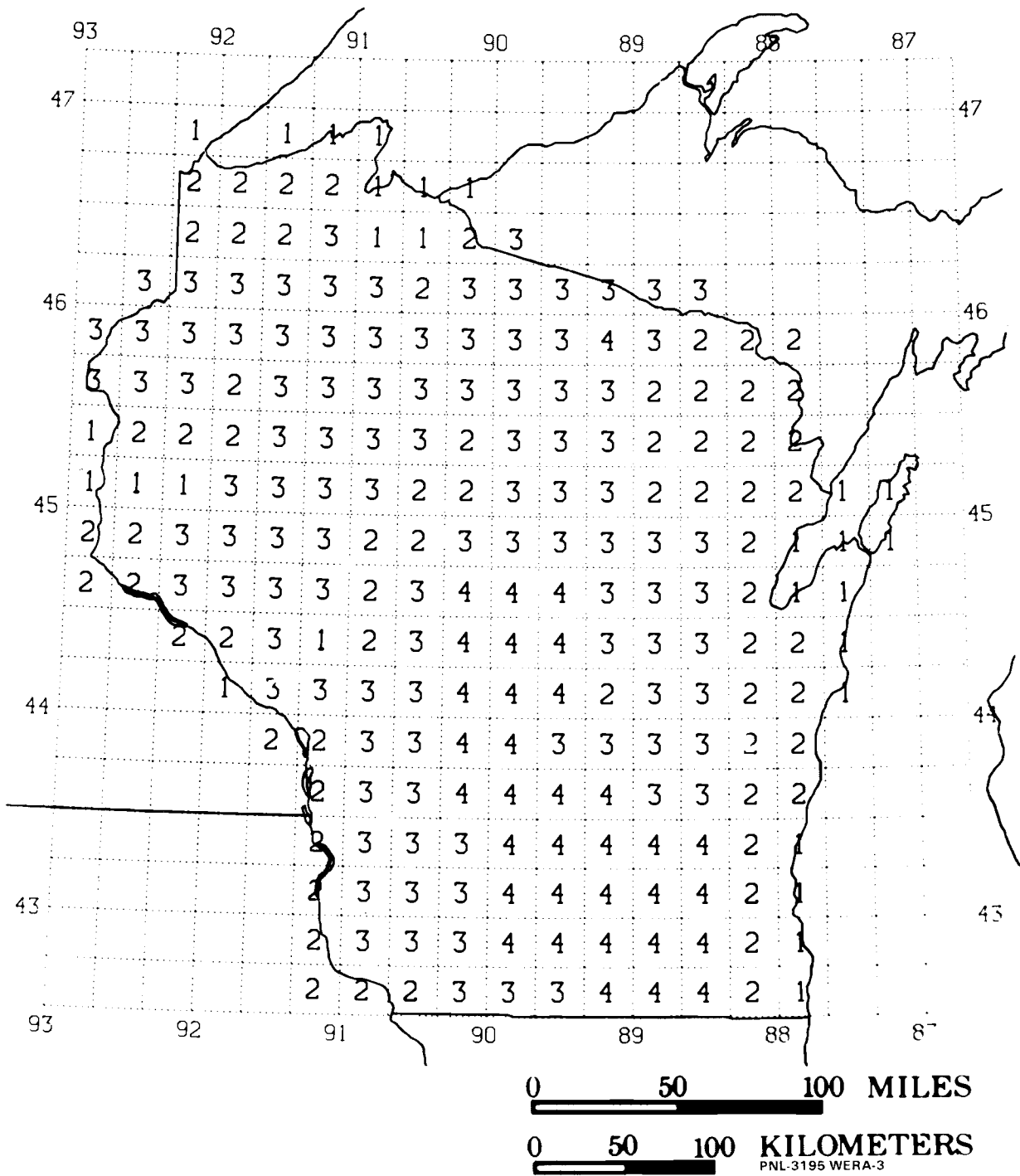


FIGURE 8.7. Certainty Rating of Wisconsin Wind Resource

### CERTAINTY RATING LEGEND

| Rating | Definition   |
|--------|--|
| 1      | <p>The lowest degree of certainty. A combination of the following conditions exists:</p> <ol style="list-style-type: none"><li>1) No data exist in the vicinity of the cell.</li><li>2) The terrain is highly complex.</li><li>3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.</li></ol>   |
| 2      | <p>A low-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"><li>1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data.</li><li>2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.</li></ol> |
| 3      | <p>A high-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"><li>1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data.</li><li>2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.</li></ol>       |
| 4      | <p>The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.</p>   |



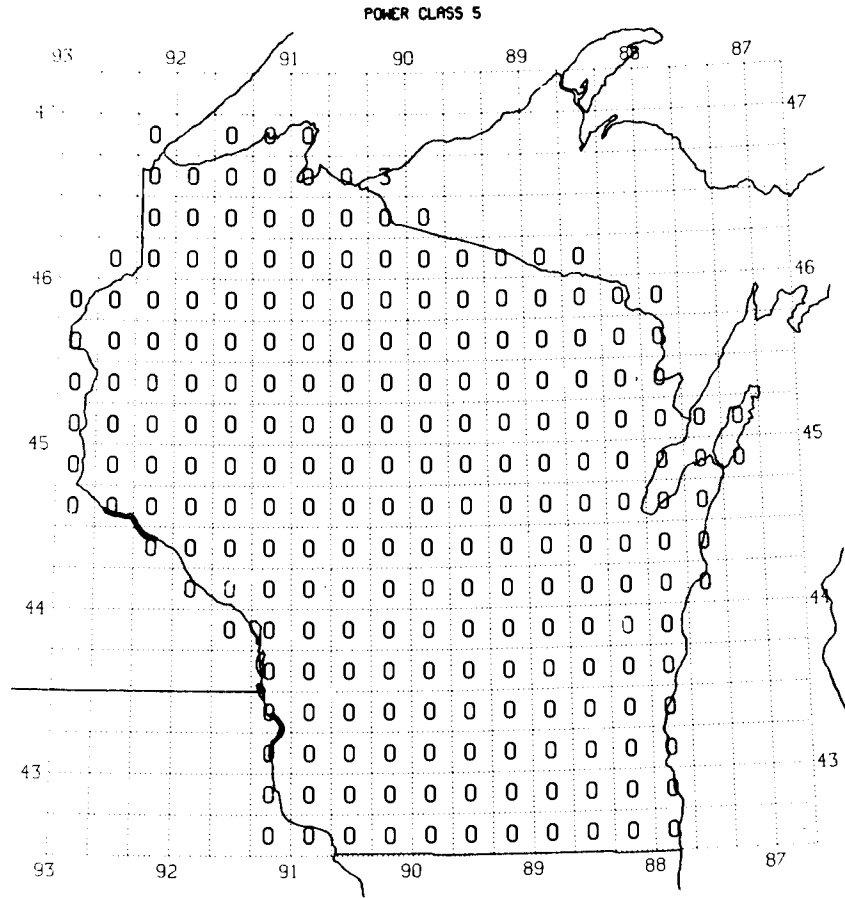
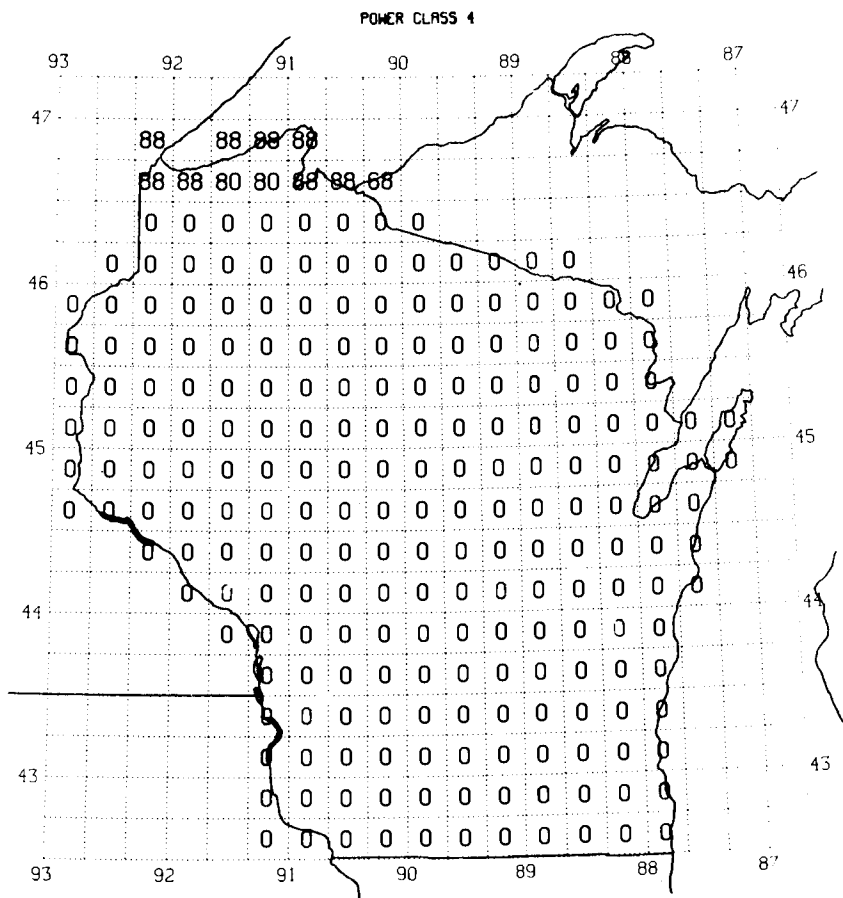


FIGURE 8.8 (Continued). Areal Distribution of Wind Resource in Wisconsin (Power Classes 4 and 5); Percent of Land Area With or Exceeding Power Class Shown.

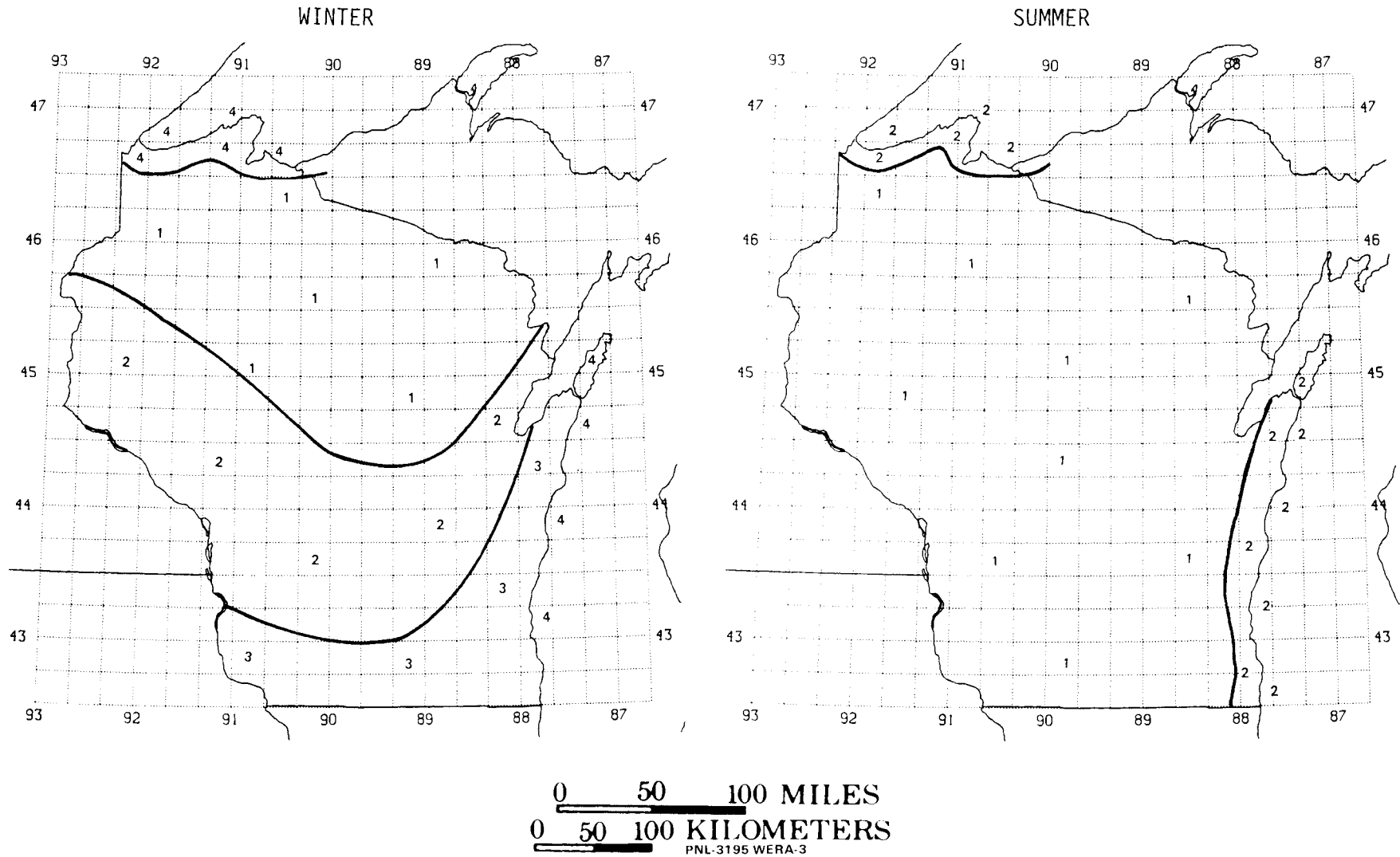


FIGURE 8.9. Seasonal Average Wind Power in Wisconsin

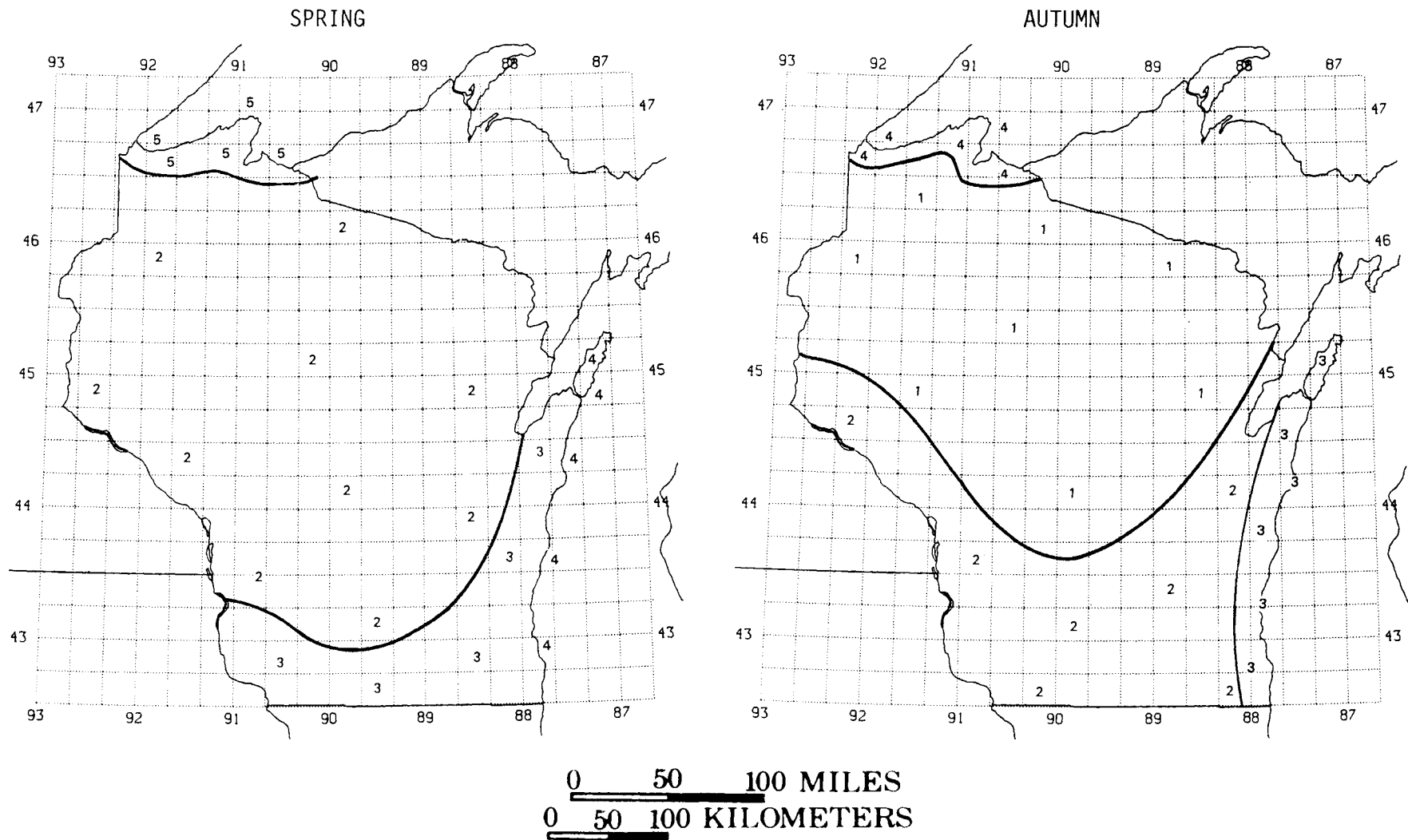


FIGURE 8.9 (Continued). Seasonal Average Wind Power in Wisconsin

TABLE 8.2. Wisconsin Stations with Graphs of the Wind Characteristics

| Station      | Station Name <sup>(a)</sup> | Latitude,<br>Degrees North | Longitude,<br>Degrees West | Elevation of<br>Station, m | Period of<br>Record,<br>mm/yy | Anemometer<br>Height, m | Annual Average<br>Wind Speed, m/s |            |            | Annual Average<br>Wind Power<br>Watts/m <sup>2</sup> |            |            |
|--------------|-----------------------------|----------------------------|----------------------------|----------------------------|-------------------------------|-------------------------|-----------------------------------|------------|------------|--|------------|------------|
|              |                             |                            |                            |                            |                               |                         | At<br>Anemometer<br>Height        | At<br>10 m | At<br>50 m | At<br>Anemometer<br>Height                           | At<br>10 m | At<br>50 m |
| Camp Douglas | Volk Field ANG              | 43.93                      | 90.26                      | 280                        | 10/66-12/70                   | 3.7                     | 3.1                               | 3.5        | 4.5        | 48   | 74         | 147        |
| Eau Claire   | Municipal Airport           | 44.86                      | 91.48                      | 292                        | 10/49-07/61                   | 7.9                     | 3.8                               | 4.0        | 5.0        | 87   | 96         | 192        |
| Eau Claire   | Municipal Airport           | 44.86                      | 91.48                      | 272                        | 07/61-12/78                   | 8.5                     | 4.3                               | 4.4        | 5.6        | 101  | 108        | 215        |
| Grantsburg   |                             | 45.80                      | 92.67                      | 284                        | 07/50-12/54                   | 7.3                     | 3.7                               | 3.8        | 4.8        | 64   | 73         | 146        |
| Green Bay    | Austin Straubel<br>Airport  | 44.48                      | 88.13                      | 212                        | 09/49-11/61                   | 14.3                    | 4.8                               | 4.5        | 5.7        | 143  | 122        | 244        |
| Green Bay    | Austin Straubel<br>Airport  | 44.48                      | 88.13                      | 212                        | 11/61-12/78                   | 6.1                     | 4.4                               | 4.7        | 6.0        | 102  | 126        | 351        |
| La Crosse    | Municipal Airport<br>WBAS   | 43.86                      | 91.24                      | 201                        | 08/52-11/64                   | 11.9                    | 4.4                               | 4.3        | 5.4        | 115  | 107        | 213        |
| La Crosse    | Municipal Airport<br>WBAS   | 43.86                      | 91.24                      | 201                        | 11/64-12/78                   | 6.4                     | 3.5                               | 3.7        | 4.7        | 63   | 76         | 152        |
| Lone Rock    | Tri-County Airport<br>WBAS  | 43.19                      | 90.18                      | 219                        | 12/48-12/54                   | UNK                     | 3.7                               | 3.7        | 4.7        | 86   | 86         | 171        |
| Madison      | Truax Field WBAS            | 43.13                      | 89.33                      | 265                        | 01/48-08/52                   | 12.2                    | 5.1                               | 5.0        | 6.2        | 198  | 182        | 363        |
| Madison      | Truax Field WBAS            | 43.13                      | 89.33                      | 265                        | 10/59-12/78                   | 6.4                     | 4.2                               | 4.5        | 5.6        | 92   | 111        | 222        |
| Milwaukee    | Mitchell Field WBAS         | 42.94                      | 87.89                      | 211                        | 01/48-06/55                   | 20.1                    | 5.4                               | 4.9        | 6.1        | 186  | 138        | 275        |
| Milwaukee    | Mitchell Field WBAS         | 42.94                      | 87.89                      | 211                        | 07/58-12/78                   | 6.1                     | 5.0                               | 5.4        | 6.7        | 136  | 168        | 335        |
| Mausau       | Municipal Airport           | 44.91                      | 89.61                      | 367                        | 01/54-12/64                   | 8.8                     | 3.9                               | 3.9        | 4.9        | 76   | 80         | 160        |

<sup>a</sup>WBAS - Weather Bureau Airport Station; ANG - Air National Guard.

+---+ WIND POWER  
 ◆---◆ WIND SPEED  
PNL-3195 WERA-3

LEFT ORDINATE - WATTS/M<sup>2</sup>  
 RIGHT ORDINATE - M/S  
 ABSCISSA - YEAR

V AND P ADJUSTED FROM Z TO 10 M BY 1/7 POWER LAW

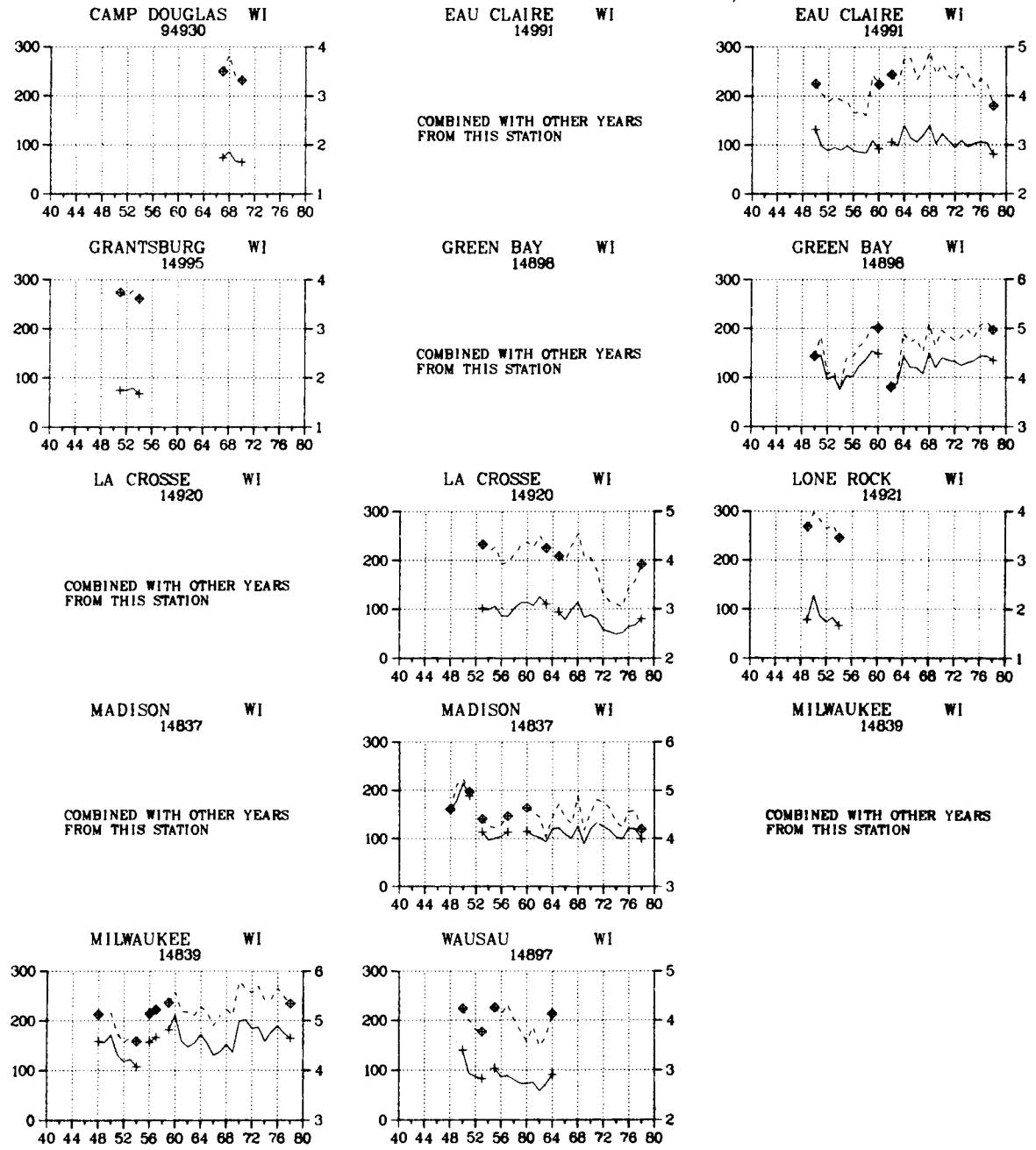


FIGURE 8.10. Interannual Wind Power and Speed for Wisconsin

— WIND POWER  
 - - - WIND SPEED  
 PNL-3195 WERA-3

LEFT ORDINATE - WATTS/M<sup>2</sup>  
 RIGHT ORDINATE - M/S  
 ABSCISSA - MONTH

V AND P ADJUSTED FROM Z TO 10 M BY 1/7 POWER LAW

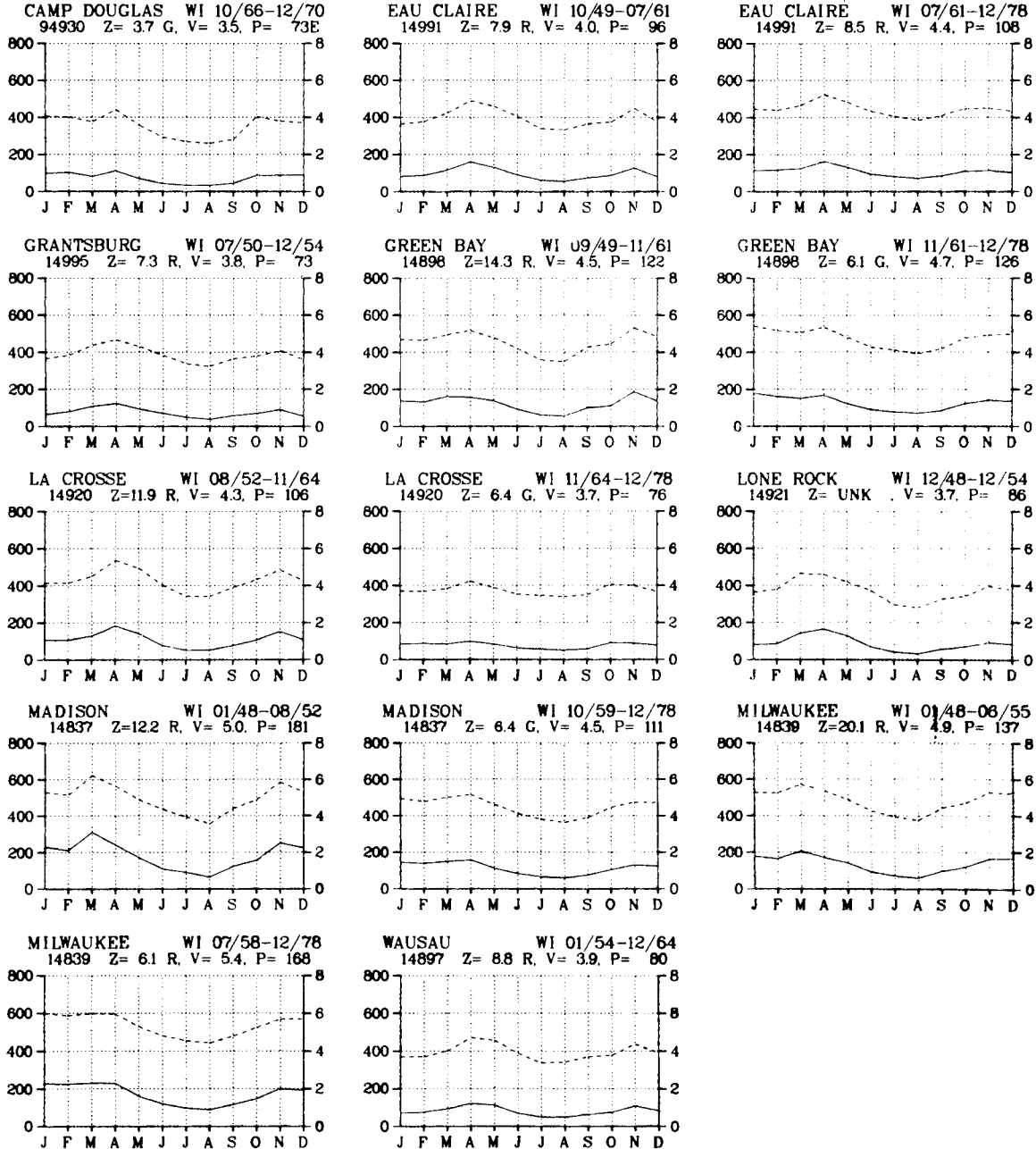
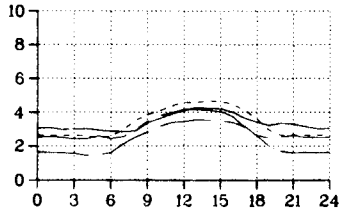


FIGURE 8.11. Monthly Average Wind Power and Speed for Wisconsin

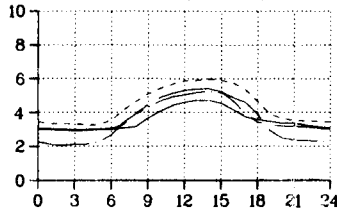
——— WINTER  
 ⊕ — ⊕ SUMMER  
 PNL 3195 WERA-3  
 ◆ - - - ◆ SPRING  
 ⊞ - - ⊞ AUTUMN

ORDINATE - M/S  
 ABSCISSA - HOUR

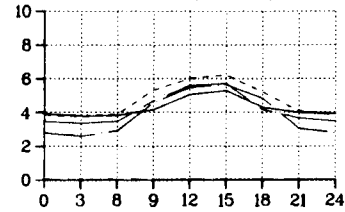
CAMP DOUGLAS WI 10/66-12/70  
94930 Z= 3.7 G, V= 3.1, P= 48E



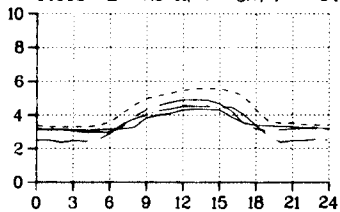
EAU CLAIRE WI 10/49-07/61  
14991 Z= 7.9 R, V= 3.8, P= 87



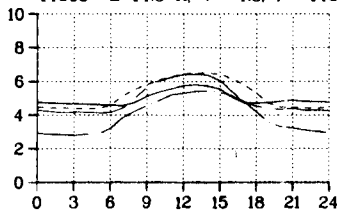
EAU CLAIRE WI 07/61-12/78  
14991 Z= 8.5 R, V= 4.3, P= 101



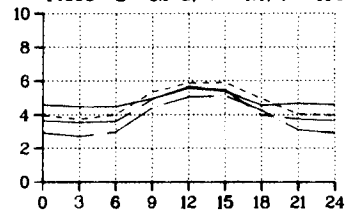
GRANTSBURG WI 07/50-12/54  
14995 Z= 7.3 R, V= 3.7, P= 64



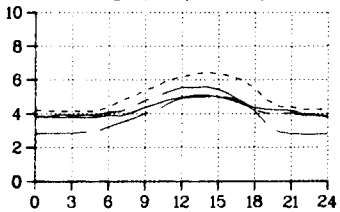
GREEN BAY WI 09/49-11/61  
14898 Z=14.3 R, V= 4.8, P= 143



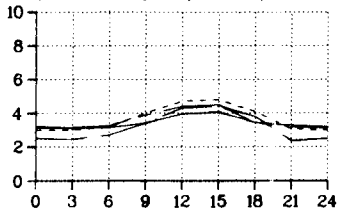
GREEN BAY WI 11/61-12/78  
14898 Z= 6.1 G, V= 4.4, P= 102



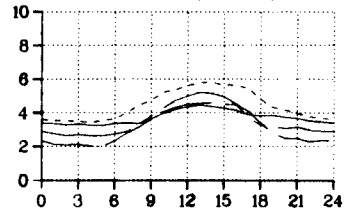
LA CROSSE WI 08/52-11/64  
14920 Z=11.9 R, V= 4.4, P= 115



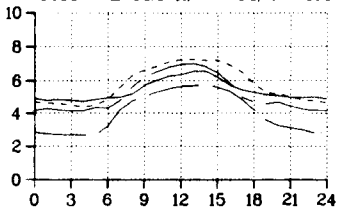
LA CROSSE WI 11/64-12/78  
14920 Z= 6.4 G, V= 3.5, P= 63



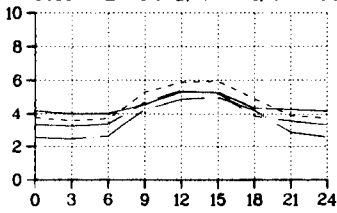
LONE ROCK WI 12/48-12/54  
14921 Z= UNK, V= 3.7, P= 86



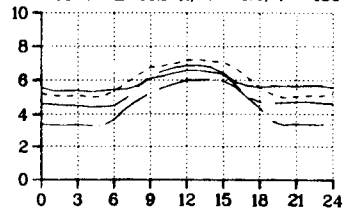
MADISON WI 01/48-08/52  
14837 Z=12.2 R, V= 5.1, P= 198



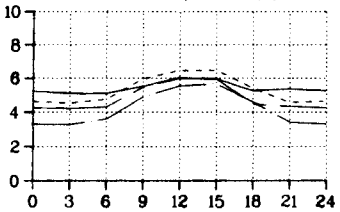
MADISON WI 10/59-12/78  
14837 Z= 6.4 G, V= 4.2, P= 92



MILWAUKEE WI 01/48-08/55  
14839 Z=20.1 R, V= 5.4, P= 186



MILWAUKEE WI 07/58-12/78  
14839 Z= 8.1 R, V= 5.0, P= 136



WAUSAU WI 01/54-12/64  
14897 Z= 8.8 R, V= 3.9, P= 78

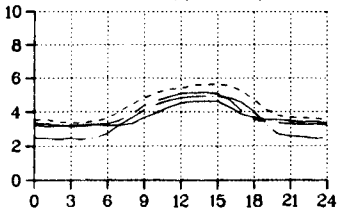


FIGURE 8.12. Diurnal Wind Speed by Season for Wisconsin

— PERCENT FREQUENCY LEFT ORDINATE - PERCENT  
 - - - - WIND SPEED RIGHT ORDINATE - M/S  
 PNL 3195 WERA-3  
 ABSCISSA - WIND DIRECTION

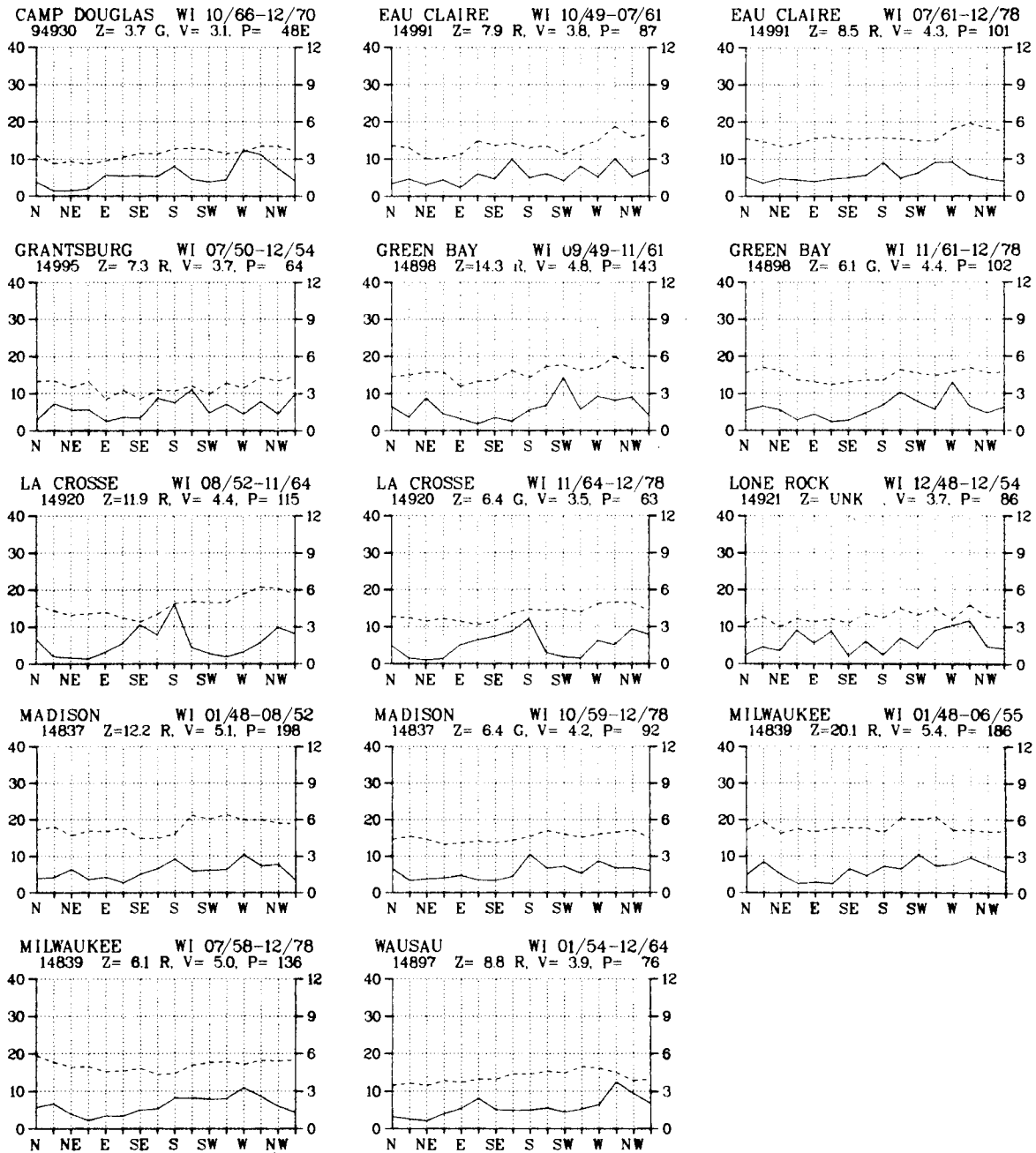


FIGURE 8.13. Directional Frequency and Average Wind Speed for Wisconsin

— ACTUAL DISTRIBUTION      ORDINATE - PERCENT  
 - - - RAYLEIGH DISTRIBUTION      ABSCISSA - M/S  
 PNL 3195 WERA-3

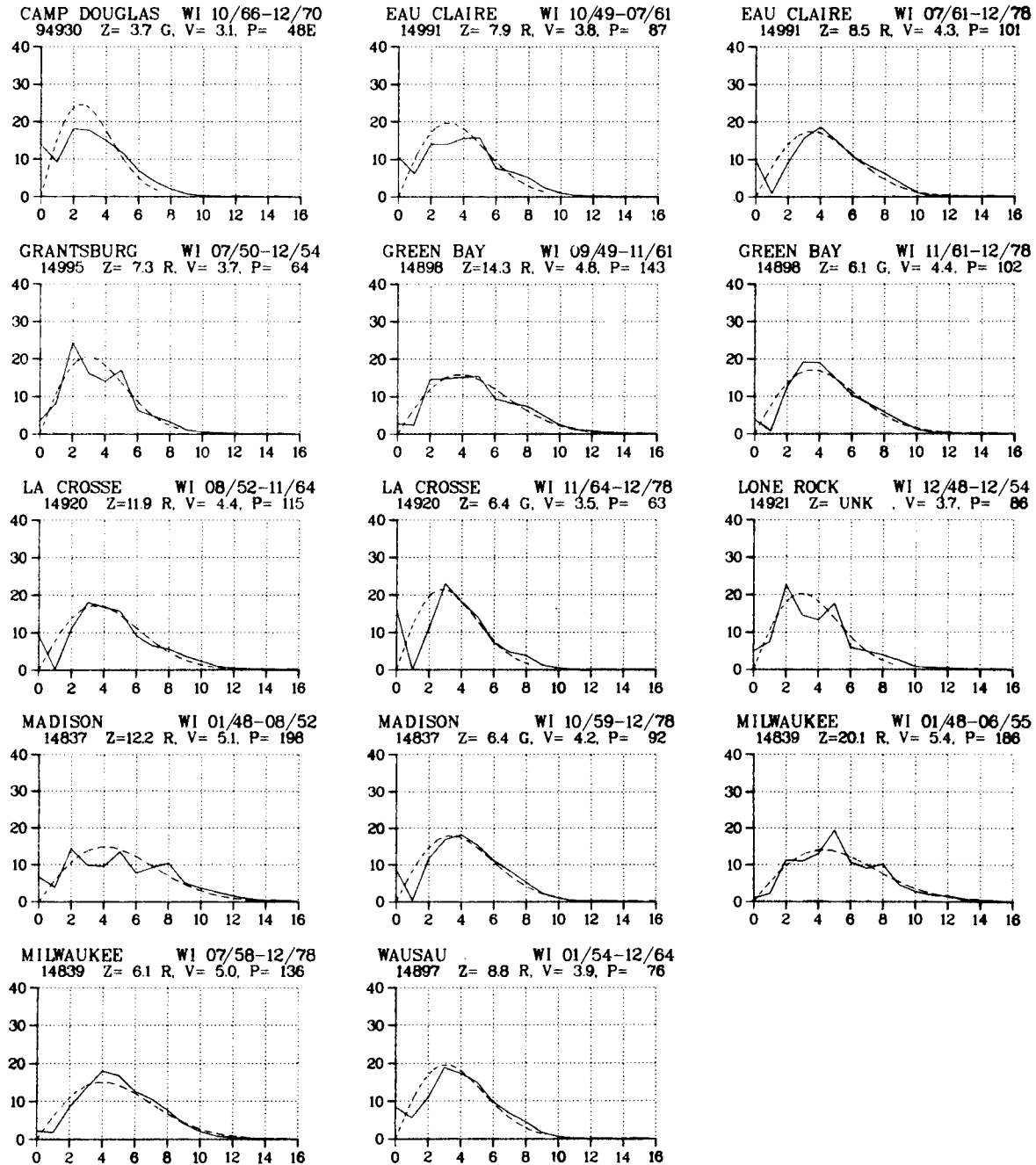


FIGURE 8.14. Annual Average Wind Speed Frequency for Wisconsin

ORDINATE - PERCENT  
 ABSCISSA - M/S  
 PNL 3195 WERA-3

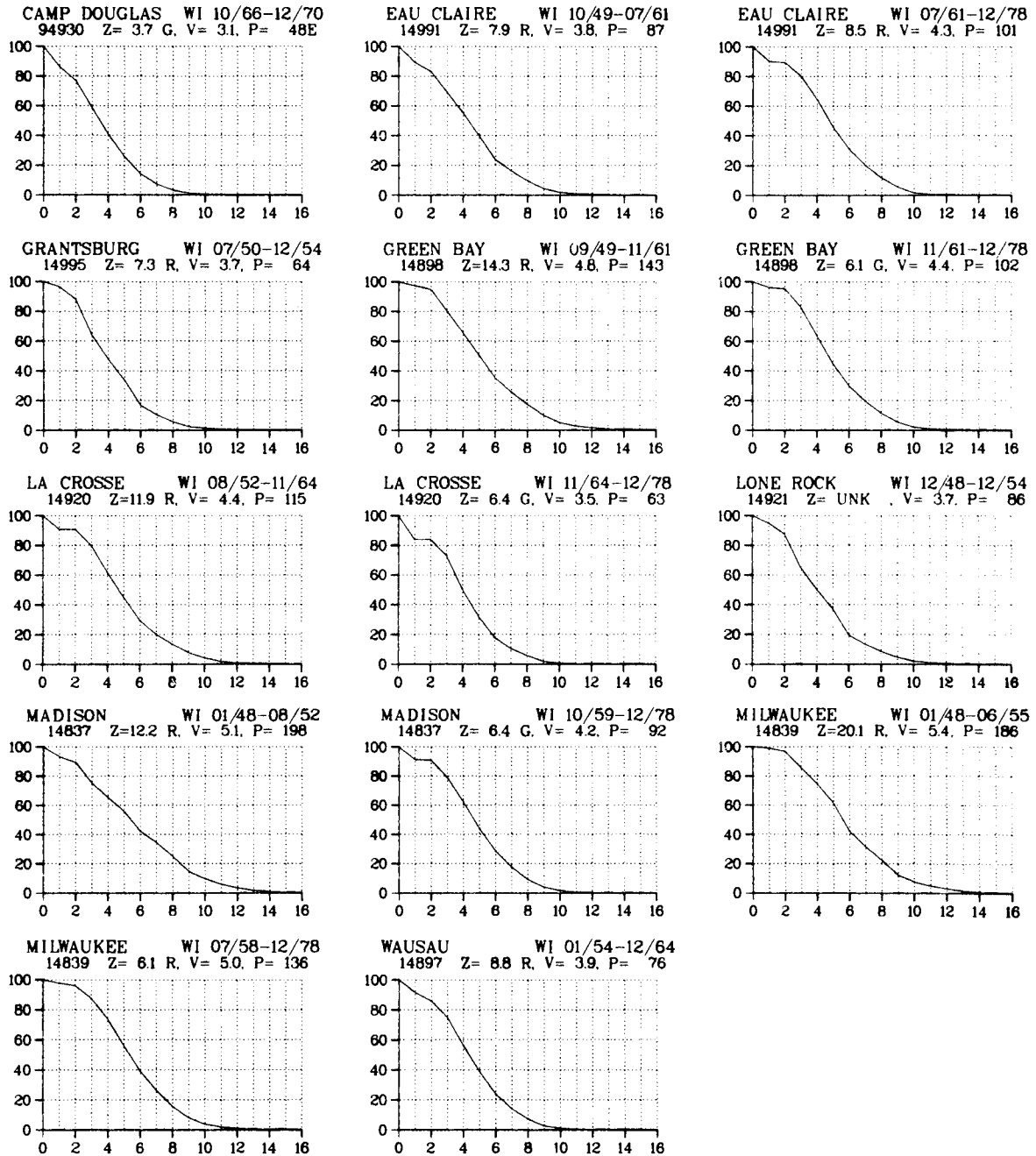
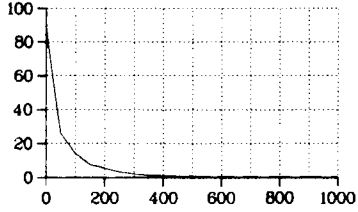


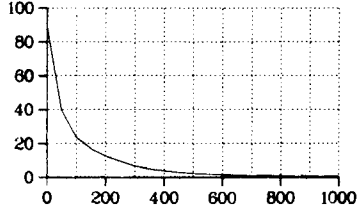
FIGURE 8.15. Annual Average Wind Speed Duration for Wisconsin

ORDINATE - PERCENT  
 ABSCISSA - WATTS/M<sup>2</sup>  
 PNL 3195 WERA-3

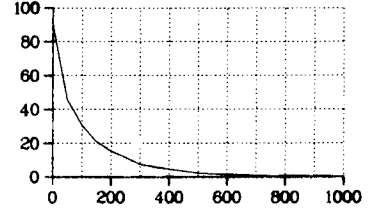
CAMP DOUGLAS WI 10/66-12/70  
 94930 Z= 3.7 G, V= 3.1, P= 48E



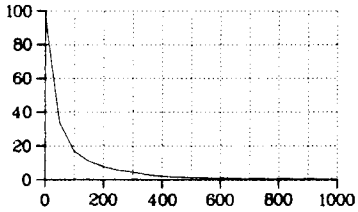
EAU CLAIRE WI 10/49-07/61  
 14991 Z= 7.9 R, V= 3.8, P= 87



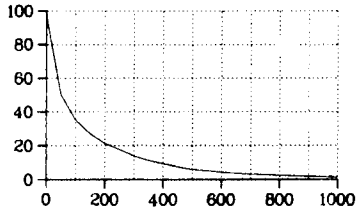
EAU CLAIRE WI 07/61-12/78  
 14991 Z= 8.5 R, V= 4.3, P= 101



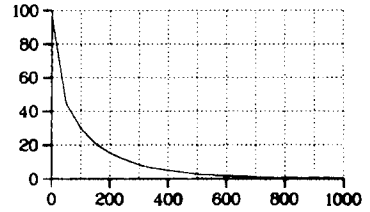
GRANTSBURG WI 07/50-12/54  
 14995 Z= 7.3 R, V= 3.7, P= 64



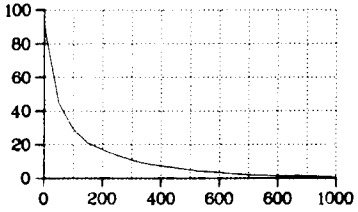
GREEN BAY WI 09/49-11/61  
 14898 Z=14.3 R, V= 4.8, P= 143



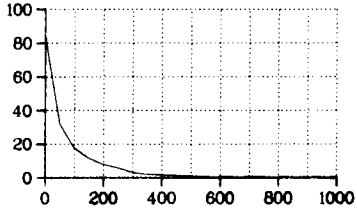
GREEN BAY WI 11/61-12/78  
 14898 Z= 6.1 G, V= 4.4, P= 102



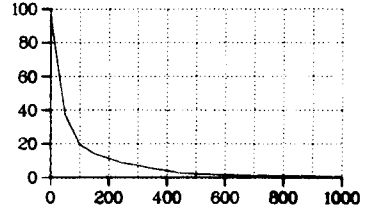
LA CROSSE WI 08/52-11/64  
 14920 Z=11.9 R, V= 4.4, P= 115



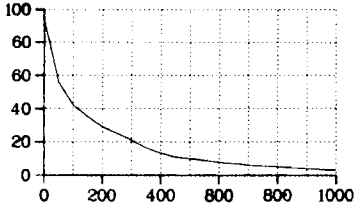
LA CROSSE WI 11/64-12/78  
 14920 Z= 6.4 G, V= 3.5, P= 63



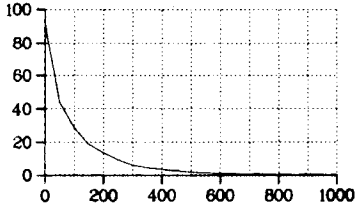
LONE ROCK WI 12/48-12/54  
 14921 Z= UNK, V= 3.7, P= 86



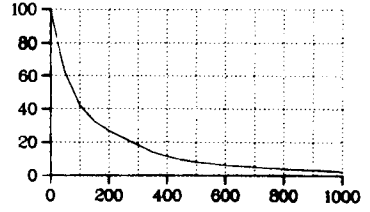
MADISON WI 01/48-08/52  
 14837 Z=12.2 R, V= 5.1, P= 198



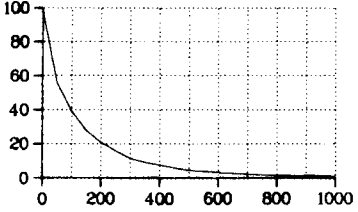
MADISON WI 10/59-12/78  
 14837 Z= 6.4 G, V= 4.2, P= 92



MILWAUKEE WI 01/48-08/52  
 14839 Z=20.1 R, V= 5.4, P= 186



MILWAUKEE WI 07/58-12/78  
 14839 Z= 6.1 R, V= 5.0, P= 136



WAUSAU WI 01/54-12/64  
 14897 Z= 8.8 R, V= 3.9, P= 76

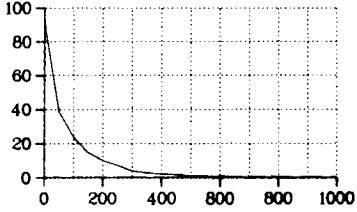


FIGURE 8.16. Annual Average Wind Power Duration for Wisconsin



## REFERENCES

- Chang, Jen-hu 1972. Atmospheric Circulation Systems and Climates. The Oriental Publishing Company, Honolulu, Hawaii.
- Changery, M. J. 1975. Initial Wind Energy Data Assessment Study. NSF/NOAA, NSF-RA-11-75-020, National Climatic Center, Asheville, North Carolina.
- Changery, M. J., W. T. Hodge, and J. V. Ramsdell 1977. Index-Summarized Wind Data. BNWL-2220 WIND-11, NOAA/Pacific Northwest Laboratory, National Climatic Center, Asheville, North Carolina.
- Changery, M. J. 1978. National Wind Data Index. NCO/T1041-01, DOE/NOAA, E(49-26)-1041, National Climatic Center, Asheville, North Carolina.
- Cliff, W. C. 1977. The Effect of Generalized Wind Characteristics on Annual Power Production Estimates from Wind Turbine Generators. PNL-2436, Pacific Northwest Laboratory, Richland, Washington.
- Climates of the States, Vol. 1, 1974, National Oceanic and Atmospheric Administration, Port Washington, New York.
- Coty, U. A. 1976. Wind Energy Mission Analysis. SAN/1075-1/1,2,3; Lockheed-California Company, Burbank, California.
- Elliott, D. L. 1977. Synthesis of National Wind Energy Assessments. BNWL-2220 WIND-5, Pacific Northwest Laboratory, Richland, Washington.
- Elliott, D. L. 1979a. "Meteorological and Topographical Indicators of Wind Energy for Regional Assessments." Proceedings of the Conference on Wind Characteristics and Wind Energy Siting. PNL-3214, Pacific Northwest Laboratory, Richland, Washington.
- Elliott, D. L. 1979b. "Adjustment and Analysis of Data for Regional Wind Energy Assessments." Paper presented at the Workshop on Wind Climate, Asheville, North Carolina, November 12-13, 1979.
- Furman, R. W. and G. E. Brink 1975. The National Fire Weather Data Library. USDA For. Ser. Gen. Tech. Rep. RM-19, RMFRES, Fort Collins, Colorado.
- Garate, J. A. 1977. Wind Energy Mission Analysis. COO/2578-1/1,2,3, General Electric Company, Philadelphia, Pennsylvania.
- Hammond, E. H. 1964. "Analysis of Properties in Landform Geography: An Application to Broad-scale Landform Mapping," Annals, Association of American Geographers, 54:11-19, Map Supplement Number 4.
- Hewson, E. W. et al. 1979. A Handbook on the Use of Trees as an Indicator of Wind Power Potential. RLO/2227-79/3. Available from National Technical Information Service, Springfield, Virginia.
- Holzworth, G. C. 1972. Mixing Heights, Wind Speeds, and Potential For Urban Air Pollution Throughout the Contiguous United States. EPA, Research Triangle Park, North Carolina.
- Marlatt, W. E., P. Tierney, P. Meikle, M. Baer, and J. Childs. 1979. Assessment of the Applicability of the National Fire Weather Library to Wind Energy Analysis. PNL-2538, Pacific Northwest Laboratory, Richland, Washington.
- National Climatic Center (NCC) 1970. Winds Aloft Summaries, by Month. Available from National Weather Records Center, Federal Building, Asheville, North Carolina.
- National Climatic Center (NCC) 1975. TDF-14: Surface Observations. Available from the National Climatic Center, Asheville, North Carolina.
- Reed, J. W. 1975. Wind Power Climatology of the U.S. SAND 74-0348, Sandia Laboratories, Albuquerque, New Mexico.
- Verholek, M. G. 1977. Summary of Wind Data from Nuclear Power Plant Sites. BNWL-2220 WIND-4, Pacific Northwest Laboratory, Richland, Washington.

Voelker, A. H. et al. 1979. A Systematic Method for Resource Rating with Two Applications to Potential Wilderness Areas. ORNL/TM-6759, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Wegley, H. L. et al. 1980. A Siting Handbook for Small Wind Energy Conversion Systems. PNL-2521, Rev. 1, Pacific Northwest Laboratory, Richland, Washington.

## INDEX

- Annual average wind power,
  - discussion of,
    - regional, 12
    - Illinois, 27
    - Indiana, 55
    - Michigan, 83
    - Ohio, 111
    - Wisconsin, 139
  - maps of,
    - regional, 20
    - Illinois, 38
    - Indiana, 66
    - Michigan, 94
    - Ohio, 122
    - Wisconsin, 150
- Areal distribution of wind power,
  - defined, 7
  - discussions of,
    - regional, 12
    - Illinois, 28
    - Indiana, 55
    - Michigan, 84
    - Ohio, 112
    - Wisconsin, 140
  - maps of,
    - Illinois, 42
    - Indiana, 70
    - Michigan, 98
    - Ohio, 126
    - Wisconsin, 154
- Certainty rating for wind power,
  - basis, 6
  - discussions of,
    - Illinois, 28
    - Indiana, 55
    - Michigan, 84
    - Ohio, 111
    - Wisconsin, 140
  - maps of,
    - Illinois, 40
    - Indiana, 68
    - Michigan, 96
    - Ohio, 124
    - Wisconsin, 152
- Directional frequency and average speed at selected stations,
  - discussions of,
    - Illinois, 30
    - Indiana, 57
    - Michigan, 87
    - Ohio, 114
    - Wisconsin, 142
  - graphs of,
    - Illinois, 50
    - Indiana, 78
    - Michigan, 106
    - Ohio, 134
    - Wisconsin, 162
- Diurnal wind speed by season at selected stations,
  - discussion of,
    - Illinois, 30
    - Indiana, 57
    - Michigan, 87
    - Ohio, 114
    - Wisconsin, 141
  - graphs of,
    - Illinois, 49
    - Indiana, 77
    - Michigan, 105
    - Ohio, 133
    - Wisconsin, 161
- Evaluation of wind data,
  - method, 2
- Interannual wind power and speed, at selected stations,
  - discussion of,
    - Illinois, 29
    - Indiana, 57
    - Michigan, 86
    - Ohio, 113
    - Wisconsin, 141
  - graphs of,
    - Illinois, 47
    - Indiana, 75
    - Michigan, 103
    - Ohio, 131
    - Wisconsin, 159
- Land-surface form classes,
  - defined, 5
  - maps of,
    - regional, 18
    - Illinois, 34
    - Indiana, 62
    - Michigan, 91
    - Ohio, 118
    - Wisconsin, 146
- Monthly average wind power and speed at selected stations,
  - discussion of,
    - Illinois, 30
    - Indiana, 57
    - Michigan, 87
    - Ohio, 113
    - Wisconsin, 141
  - graphs of,
    - Illinois, 48
    - Indiana, 76
    - Michigan, 104
    - Ohio, 132
    - Wisconsin, 160
- Qualitative indicators, used in data-sparse areas, 4
- Seasonal variations in wind power, in the Great Lakes Region,
  - discussion of, 13

- map of, 22
- at selected stations, discussion of,
  - Illinois, 28
  - Indiana, 56
  - Michigan, 84
  - Ohio, 112
  - Wisconsin, 140
- at selected stations, maps of,
  - Illinois, 44
  - Indiana, 72
  - Michigan, 100
  - Ohio, 128
  - Wisconsin, 156

Sources of wind data,

- general, 2
- discussion of,
  - Illinois, 29
  - Indiana, 56
  - Michigan, 85
  - Ohio, 113
  - Wisconsin, 141
- maps of,
  - Illinois, 37
  - Indiana, 65
  - Michigan, 93
  - Ohio, 121
  - Wisconsin, 149
- table describing,
  - Illinois, 46
  - Indiana, 74
  - Michigan, 102
  - Ohio, 130
  - Wisconsin, 158

Wind power density classes,

- table defining, 9
- relationship to wind speed, 5

Wind resource,

- greatest potential in the Great Lakes Region, 13

Wind speed and power duration, annual average, at selected stations,

- discussion of,
  - Illinois, 30
  - Indiana, 58
  - Michigan, 87
  - Ohio, 114
  - Wisconsin, 142
- graphs of,
  - Illinois, 52,53
  - Indiana, 80,81
  - Michigan, 108,109
  - Ohio, 136,137
  - Wisconsin, 164,165

Wind speed frequency, annual average, at selected stations,

- discussion of,
  - Illinois, 30
  - Indiana, 58
  - Michigan, 87
  - Ohio, 114
  - Wisconsin, 142
- graphs of,
  - Illinois, 51
  - Indiana, 79
  - Michigan, 107
  - Ohio, 135
  - Wisconsin, 163

DISTRIBUTION

| <u>No. of<br/>Copies</u>   | <u>No. of<br/>Copies</u>  |
|--|---|
| A. A. Churm<br>DOE Chicago Patent Group<br>9800 S. Cass Ave.<br>Argonne, IL 60439  | Tunis Wentink<br>University of Alaska<br>Geophysical Institute<br>Fairbanks, AK 99701   |
| D. F. Ancona<br>Department of Energy<br>600 E St. NW<br>Washington, DC 20545   | J. L. Wise<br>Arctic Environmental Information and<br>Data Center<br>University of Alaska<br>707 A St.<br>Anchorage, AK 99501 |
| Ted Ankrum<br>Office of Commercialization<br>Department of Energy<br>Room 6A081, M/S 6B025<br>Washington, DC 20585                               | Richard Katzenburg<br>American Wind Energy Association<br>2820 Upton St. NW<br>Washington, DC 20008                           |
| 5 C. I. Aspliden<br>Department of Energy<br>600 E. St. NW<br>Washington, DC 20545  | Ben Wolff<br>American Wind Energy Association<br>1621 Connecticut Ave. NW<br>Fifth Floor<br>Washington, DC 20009              |
| Ernie Chabot<br>Department of Energy<br>GMTA, CS-74, M/S 2H027<br>Forrestal Building<br>Washington, DC 20585                                     | AWEA Windletter<br>1609 Connecticut Ave. NW<br>Washington, DC 20009   |
| 5 L. V. Divone<br>Department of Energy<br>600 E St. NW<br>Washington, DC 20545   | Bruce B. Hicks<br>Argonne National Laboratory<br>9700 S. Cass Ave.<br>Argonne, IL 60439                                       |
| 5 W. C. Reddick<br>Department of Energy<br>600 E St. NW<br>Washington, DC 20545  | D. L. Sisterson<br>Argonne National Laboratory<br>9700 S. Cass Ave.<br>Argonne, IL 60439                                      |
| Robert San Martin<br>Department of Energy<br>600 E St. NW<br>Washington, DC 20545  | P. A. Taylor<br>Atmospheric Environmental Service<br>4505 Dufferin St.<br>Downsview, Ontario, CANADA                          |
| 20 G. P. Tennyson<br>Department of Energy<br>Albuquerque Operations<br>Office<br>Suite 151<br>4501 Indian School Rd. NE<br>Albuquerque, NM 87110 | Wayne Wiesner<br>Boeing Engineering and Construction<br>P.O. Box 3707<br>Seattle, WA 98124                                    |
| 27 DOE Technical Information Center  | M. J. Berger<br>Bonneville Power Administration<br>P.O. Box 3621<br>Portland, OR 97208  |
| 50 U.S. Government Printing Office<br>Documents Warehouse<br>8610 Cherry Ln.<br>Laurel, MD 20810   | Edgar De Meo<br>Electric Power Research Institute<br>3412 Hillview Ave.<br>Palo Alto, CA 94303                                |
| 30 Doug Smith<br>Environmental Research<br>and Technology, Inc.<br>696 Virginia Road<br>Concord, MA 01742  | Ken Bosley<br>Energy Unlimited<br>2 Aldwin Center<br>Villanova, PA 19085  |

No. of  
Copies

No. of  
Copies

Stanley Macklis  
General Electric Company  
P.O. Box 8661  
Philadelphia, PA 19101

Ken Pickering  
GEOMET, Inc.  
15 Firstfield Rd.  
Gaithersburg, MD 20760

Joe Zabransky  
GEOMET, Inc.  
15 Firstfield Rd.  
Gaithersburg, MD 20760

G. T. Norman  
Global Weather Consultants, Inc.  
2301 Hanover St.  
Palo Alto, CA 94306

Alain Streicher  
Hagler, Bailly and Co.  
Suite 350  
2020 K St. NW  
Washington, DC 20006

T. A. Schroeder  
Department of Meteorology  
University of Hawaii  
2525 Correa Rd.  
Honolulu, HI 96822

Leon Graves  
Institute for Storm Research  
4104 Mt. Vernon  
Houston, TX 77006

J. B. Knox  
Lawrence Livermore Laboratory  
P.O. Box 808  
Livermore, CA 94550

Barbara Luxemburg  
Library of Congress/CRS  
Washington, DC 20540

R. J. Templin  
National Research Council  
Montreal Rd.  
Ottawa, Ontario, CANADA  
K1A 0R6

J. Estes  
NASA Lewis Research Center  
21000 Brookpark Rd.  
Cleveland, OH 44135

Ron Thomas  
NASA Lewis Research Center  
21000 Brookpark Rd.  
Cleveland, OH 44135

Phillip French  
NASA Scientific and Technical  
Information Facility  
P.O. Box 8757  
Baltimore/Washington International  
Airport  
Baltimore, MD 21240

Tom Potter  
National Oceanic and Atmospheric  
Administration/EDIS  
National Climatic Center  
Federal Building  
Asheville, NC 28801

Malcom Reid  
National Oceanic and Atmospheric  
Administration  
EDIS/CEAS  
Room 416 Page 1  
Washington, DC 20235

M. J. Changery  
National Oceanic and Atmospheric  
Administration  
National Climatic Center  
Federal Building  
Asheville, NC 28801

5 Daniel Mitchell  
National Oceanic and Atmospheric  
Administration  
National Climatic Center  
Federal Building  
Asheville NC 28801

Roger Brode  
NUS Corporation  
4 Research Pl.  
Rockville, MD 20850

Ron Stoner  
NUS Corporation  
4 Research Pl.  
Rockville, MD 20850

R. L. Simon  
Pacific Gas and Electric  
Rm 455  
215 Market St.  
San Francisco, CA 94106

E. L. Luther  
PRC Energy Analysis Co.  
7600 Old Springhouse Rd.  
McLean, VA 22102

R. Cingo  
Rockwell International  
Rocky Flats Plant  
P.O. Box 464  
Golden, CO 80401

No. of  
Copies

C. Hansen  
Rockwell International  
Rocky Flats Plant  
P.O. Box 464  
Golden, CO 80401

Terry Healy  
Rockwell International  
Rocky Flats Plant  
P.O. Box 464  
Golden, CO 80401

R. Moment  
Rockwell International  
Rocky Flats Plant  
P.O. Box 464  
Golden, CO 80401

J. Sherman  
Rockwell International  
Rocky Flats Plant  
P.O. Box 464  
Golden, CO 80401

Ted Kornreich  
SAI  
1710 Goodridge Dr.  
McClellan, VA 22102

Richard Braasch  
Division 4715  
Sandia Laboratory  
Albuquerque, NM 87185

E. Kadlec  
Division 5443  
Sandia Laboratory  
Albuquerque, NM 87115

J. A. Bereny  
Solar Energy Information Service  
P.O. Box 204  
San Mateo, CA 94401

Roland Hulstrom  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401

Information Library  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401

Ken Olsen  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401

No. of  
Copies

Irwin Vas  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401

C. M. Bhumralker  
SRI International  
333 Ravenswood Ave.  
Menlo Park, CA 94025

A. Rothstein  
TRC  
125 Silas Deane Highway  
Wethersfield, CT 06109

Billy Owen  
TVA  
360 TVA Credit Union Bldg.  
Chattanooga, TN 37401

Noland Clark  
U.S. Department of Agriculture  
Agriculture Research Service  
Bushland, TX 79012

R. Case  
U.S. Bureau of Land Management  
Building 50, Dept. D-440  
Denver Federal Center  
Denver, CO 80225

S. Hightower  
U.S. Bureau of Reclamation  
Building 67, Code 254  
Denver Federal Center  
Denver, CO 80225

S. Jennings  
U.S. Department of Justice/INS  
Room 6307, COENG  
425 I St. NW  
Washington, DC 20534

Steve Anderson  
Western Scientific Services, Inc.  
328 Airpark Dr., P.O. Box 1965  
Ft. Collins, CO 80522

Dan Freeman  
Western Scientific Services, Inc.  
328 Airpark Dr., P.O. Box 1965  
Ft. Collins, CO 80522

Farrell Smith Seiler  
Wind Energy Report  
Box 14  
104 X. Village Ave.  
Rockville Centre, NY 11571

No. of  
Copies

Earl Davis  
Wind Farms Ltd.  
639 Front St.  
San Francisco, CA 94111

R. G. Pratt  
The Detroit Edison Company  
2000 2nd Avenue  
Detroit, MI 48226

Michael Hohmann  
Mid-America Solar Energy Complex  
Alpha Business Center  
8140 26th Ave. South  
Minneapolis, MN 55420

R. A. Cappalletti  
Business and Renewable Resources  
Section  
Michigan Department of Commerce  
Energy Administration  
P.O. Box 30228  
Lansing, MI 48909

No. of  
Copies

R. K. Woodruff  
R. Zengerle  
Technical Information (5)  
Publishing Coordination (2)

ONSITE

- 2 DOE Richland Operations Office  
P.O. Box 550  
Richland, WA 99352

H. E. Ransom  
R. K. Stewart

- 75 Pacific Northwest Laboratory  
Battelle Boulevard  
Richland, WA 99352

W. R. Barchet (10)  
J. C. Barnard  
N. J. Cherry  
J. R. Connell  
J. C. Doran  
R. L. Drake  
K. Drumheller  
C. E. Elderkin  
D. L. Elliott (20)  
R. L. George  
D. Hadley  
S. K. Heflick  
T. R. Hiester  
G. A. Jensen  
A. H. Miller  
E. L. Owzarski  
W. T. Pennell  
E. H. Phinney  
D. C. Powell  
J. M. Proud (15)  
J. V. Ramsdell  
D. S. Renne  
H. L. Wegley  
L. L. Wendell