EOLIAN LANDFORMS AND WIND POWER PROSPECTING IN THE CENTRAL COLUMBIA RIVER BASIN

by

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I would like to thank Charles Rosenfeld, Peter Maule, and John Wade for their encouragement, guidance, and financial help during my work on this research. Sand dunes have special and intriguing qualities whose appreciation we have shared.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EOLIAN LANDFORMS AND WIND POWER PROSPECTING IN THE CENTRAL COLUMBIA RIVER BASIN

ABSTRACT. Sand dunes are used as indicators of wind power potential and examples are presented of their application as a prospecting technique at four study sites in the Central Columbia River Basin. Aerial reconnaissance is combined with interpretation of photography and topographic maps as a basis of sand dune analysis. Sand samples from each site are subjected to sieve analysis and grain size statistical parameters are determined. Wind speed and direction data are presented from calculations based on dune field measurements and from weather station records. Dune morphometry figures and study area maps illustrate sand dune characteristics. Techniques are briefly critiqued indicating problems and limitations.

INTRODUCTION

Increased demand has prompted a call for more ways of finding energy and for more ways to utilize its less exploited forms. Wind energy has become a viable source, but what is needed is a means of finding wind power resources, especially in regions of sparse wind data.

Various strategies have been developed by wind energy prospectors. Biological indicators of wind power, such as wind-flagged trees, are now a valuable prospecting tool.[1] Arid regions have fewer biological techniques available, but other appropriate wind indicators have been investigated including eolian landforms. This paper applies wind power prospecting techniques to eolian landforms (sand dunes) in semi-arid areas of the Pacific Northwest.

Sand dunes as geomorphological wind indicators may be studied at a variety of scales from entire dune fields, to individual dunes, to the sand grains themselves (Table 1). The prevailing wind direction over an entire dune field usually follows its long axis, assuming relatively flat terrain, and often parallel to it are sand streaks downwind and elongated deflation areas upwind. The orientation of dune fields to obvious sand source areas of loose fluvial deposits may be another indicator of the direction of wind flow.

Often an area of dunes consists of a predominant dune form which characteristically reflects the dominant wind regime. Unimodal, bimodal, and complex wind regimes are responsible for specific dune forms as Fryberger has shown.[2] Major eolian landforms can be detected from satellite imagery to determine dominant wind flow patterns.[3]

Wind speed is more difficult to determine when dune fields as a whole are observed; however, inferences can be made as to wind speed relative to other dune fields and as to areas of wind convergence or divergence within a dune field. Studies at this scale also often include areas with some weather station data.

Individual dunes can be studied on the ground or from mid- to low-level platforms. Many dune form classification systems have been created to deal with the nearly infinite variations in form that sand may take when blown by wind. Hack presented an early classification of sand dunes in the North American Southwest.[4] Wilson has developed a bedform hierarchy applicable to all wavelengths of dune form phenomena.[5] However, the most appropriate classification system for this paper is presented by Dean which he developed for California desert sand dune areas and which is slightly modified for use herein (see Appendix A for definitions of dune forms and their illustration).[6]

Wind direction can be determined from individual dune forms since avalanche slopes, or slipfaces, always form in specific orientation to the prevailing wind (most often perpendicular to the wind for the dunes studied in this paper). Another way to determine wind direction is to follow dune movement over several years using maps, aerial photos, or ground measurements.

Limited information related to wind speed can be implied from dune form type since specific wind regimes usually cause similar dune form response. The classification above by Dean presents typical wind speed inferences (see Appendix A).

Individual dunes may be intertwined as several different forms within a single dune field as wind and sand respond to local controlling factors. Seasonal changes in moisture, temperature, wind direction and speed in turn cause changes in dune activity. Also important in some areas are vegetation, changes in topography, and changes in sand sources. The relative importance of these controlling factors is difficult to determine without detailed study, but at times they are critical to dune activity.

Ripple marks on the surfaces of sand dunes represent response to short-term, very localized winds and they are less reliable indicators than the others mentioned here, especially to an untrained observer.[7]

Analysis of sand samples by sifting through sieves is a common technique in sediment study. Sieves can be used to determine the size distribution of sand grains and this data in turn can be plotted on graph paper to find statistical characteristics of the distribution.

Wind speed may also be inferred from sand grain size since stronger winds are required to move larger grains. The mechanics of sand transport by wind has been thoroughly studied in wind tunnels and in the field.[8] Equations have been developed which approximate the processes of wind acting on sand and this is now used as a basis of wind power prospecting. Two separate methods (hereafter referred to as Method I and Method II as defined below), one based on grain size distribution and the other on dune migration rates, are used in this paper. These techniques were presented by Heister and Pennell (see Appendix B for detail of formula usage).[9]

Method I can be briefly presented as:

$$U_{(z)} = \frac{U_*}{k} \ln \frac{Z}{Z_o}$$

where: U = the wind speed at height Z

U_* = friction velocity

k = 0.35, von Karmen constant

Z = height above ground

Z_o = surface roughness

Method II can be briefly presented as:

$$V_{10} = V_T + \frac{\bar{U}_*}{k} \ln \frac{10}{k'}$$

where: V_{10} = wind velocity at 10 meters

V_T = threshold velocity

$\bar{U}_*$ = long-term average friction velocity

k = as above

k' = roughness of the sand bed (1 cm)

Threshold wind speeds are important in understanding dune movement and sand activity. The finest particles making up sand dunes may be blown away in suspension while the midsize range of sand moves by bouncing near the surface, known as saltation. Saltation in turn causes the largest sand grains to creep along the surface as they absorb the impact of the saltating grains. The wind speed at which sand movement is initiated due to direct pressure is known as the fluid threshold velocity, whereas the slower wind speed known as the impact threshold velocity reflects sustained sand movement due to a continuous rain of saltating grains.[10]

Table 1 - Summary of Wind Speed and Wind Direction Data Obtainable From Sand Dune Study.

SCALE	WIND DIRECTION	WIND SPEED
DUNE FIELD	Relation to sand source areas	Dune migration rates, topographic controls
INDIVIDUAL DUNES	Slipface orientation	Dune form type
DUNE SAND	Relative amounts of sorting, rounding, heavy minerals, or color change from mineral coatings	Grain size calculations

OBJECTIVES

This paper strives to meet several objectives beginning with identification of four different study sites within the Central Columbia River Basin of Oregon and Washington. These sites contain areas of active sand dunes. The dune areas are evaluated using techniques presented by J. Wade, et al., and the techniques themselves are critiqued as to their limitations and the problems encountered in their use.[11] This information is presented in a form intended to be useful to wind power prospectors and to those responsible for the dune study sites.

For each study site the more common dune forms are described as to type, typical dimensions, orientation to wind, and relative activity. Maps of each study site are presented showing dune movement. Total dune field area calculations are given as are sand grain size and density data from analysis of samples taken at each study site. Wind speeds are calculated from sand dune data and presented with data from local weather stations for comparison.

TECHNIQUES

The five major techniques used in this research are: (1) low-level flights in a small plane, (2) gathering information from USGS topographical maps, (3) field work done on each site, (4) aerial photo interpretation, and (5) general lab work and calculations including sediment analysis. Several separate tasks are accomplished using these techniques and summary of tasks and the appropriate techniques are presented below (Table 2).

Low-level flights in a small plane allow close observation of eolian landforms and the surrounding environment. Two separate flights were taken over potential study sites on October 15 and October 16, 1980, and on August 18 and August 19, 1981. Field notes were taken in flight and vertical and oblique aerial photography were obtained using hand-held 35mm cameras with color slide film. Notes and photography recorded dune form type, relative activity, dune orientation to wind, estimates of dune dimensions, and some ideas about possible dune movement controlling factors. Also noted were access roads for ground field trips.

Aeronautical charts and topographic maps of various scales were referred to in order to locate potential sites (see Appendix C). Further analysis of 1:24,000 United States Geological Survey (USGS) topographic maps permitted their use as aides in mapping study sites, in defining township and range location of sites, in area calculations of entire dune fields (some area calculations done at 1:250,000), and in assessment of dune movement controlling factors. Topographic maps were also interpreted for individual sand dune information such as: dune orientation to wind, dune location at time of mapping, and dune dimensions.

Field work later verified aerial observations and allowed on-site sand sampling and dune evaluation. Sand samples were taken from the most active sand surfaces for lab analysis. Ground photography and field notes recorded observations of dune form type, relative dune activity, dune dimension estimates, and detailed views of dune movement controlling factors.

Interpretation of aerial photography purchased from the US Department of Agriculture and the US Army Corps of Engineers is a fourth research technique. This black and white vertical photography was often used in conjunction with large scale topographic maps and low-level oblique color slides. This technique provided additional information on dune forms present at the study sites, dune dimensions, dune orientation to wind, and assessment of dune movement controlling factors. Aerial photos were also used for mapping and as a record of dune location at specific times in order to determine dune movement. (See Appendix D for photography used.)

Sand samples obtained in the field at each study site were mechanically sieved to determine grain size distributions and significant statistical parameters (mean, mode, and maximum grain sizes) using one-half phi (ø) interval sieves and samples of about 40 grams. Sand sample density was also estimated using pre-weighed samples and a graduated cylinder.

Finally, calculations of wind speeds were made using the techniques of Heister and Pennell as described in J. Wade, et al. (see Appendix B).[12]

TABLE 2. RESEARCH TECHNIQUES AND TASKS ACCOMPLISHED.

TECHNIQUE / TASK	AIRPLANE OBSERVATION	TOPOGRAPHIC MAPS	FIELD WORK	AERIAL PHOTOS	CALCULATIONS & LAB WORK
IDENTIFY POTENTIAL STUDY SITES	■	■		■	
IDENTIFY DUNE FORMS AND RELATIVE ACTIVITY	■		■	■	
DUNE-TO-WIND ORIENTATION	■	■		■	
ASSESS CONTROLLING FACTORS	■	■	■	■	
DEFINE DUNE LOCATION AT SPECIFIC TIME		■		■	
MAPPING AND EXACT LOCATION DESCRIPTION		■		■	
AREA CALCULATIONS		■			
DUNE MOVEMENT		■		■	■
DUNE DIMENSIONS	■	■	■	■	
SAND SAMPLING AND ANALYSIS			■		■
WIND SPEED					■

ANALYSIS

Four study sites were chosen within the Central Columbia River Basin. The Vantage study site is located just north of the Vantage substation near Wanapum Dam in Grant County, Washington. The Moses Lake study site is located just south of the town of Moses Lake and east of Potholes Reservoir in Grant County, Washington. The Pasco study site is northeast of Pasco, Washington, in Franklin County. The fourth study site is east of The Dalles, Oregon, adjacent to Interstate Highway Eighty-four in Wasco County (Figure 1). (See Appendix D for specific locations of sections mapped.)

The Vantage study site is a dune field of 0.45 square miles consisting of barchan dunes moving eastward singly and in groups. The dunes are located on level ground above the rimrock along Wanapum Reservoir, and several other small dune areas are nearby. The overall shape of the dune field is similar to a large-scale parabolic dune about 2.25 miles long with a cluster of dunes at its apex (Figure 2). Aerial reconnaissance of this area showed center-pivot irrigation nearby with runoff influencing dune activity at least seasonally, especially at the northwestern edge of the dunes. Vegetation seems to have no hold on these dunes

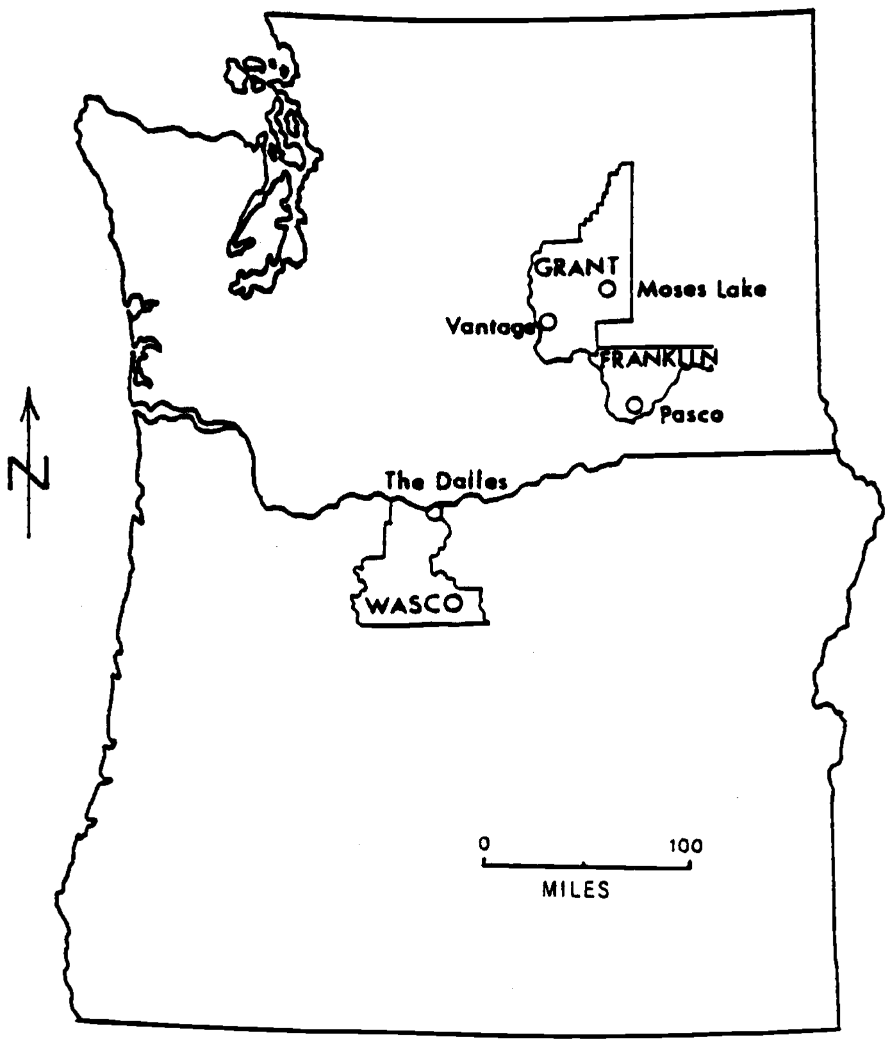


FIGURE 1. Key Map to Study Sites

and no topographical obstacles are in their immediate path.

Dunes at the Vantage site range in size from 123-490 feet long by 70-403 feet wide. The only height estimate available is 16.4 feet. Dune movement is estimated at 98 feet per year from 1969 to 1973, the fastest moving dunes of the four study sites. One sand sample was taken here which appears to be predominantly quartz and has a mode diameter of 2.5ø (Table 3, part A and B).

Wind speed calculations at Vantage are 13 miles per hour for Method I and 11.8 miles per hour for Method II. Weather station data at the Vantage Substation has a mean annual wind speed of 13.4 miles per hour.[13] Prevailing winds implied from dune orientation are 285° (clockwise from 0° true north), and weather station data show prevailing winds from 270° for more than 27% of the year (Table 3, part C).[14]

The Moses Lake study site is located at the eastern extreme of large dune field of about 41 square miles which extends east and west of Potholes Reservoir (Figure 3). These dunes consist of several minerals including dark sand derived apparently from basalt rock. Parabolic dunes in several stages of activity are

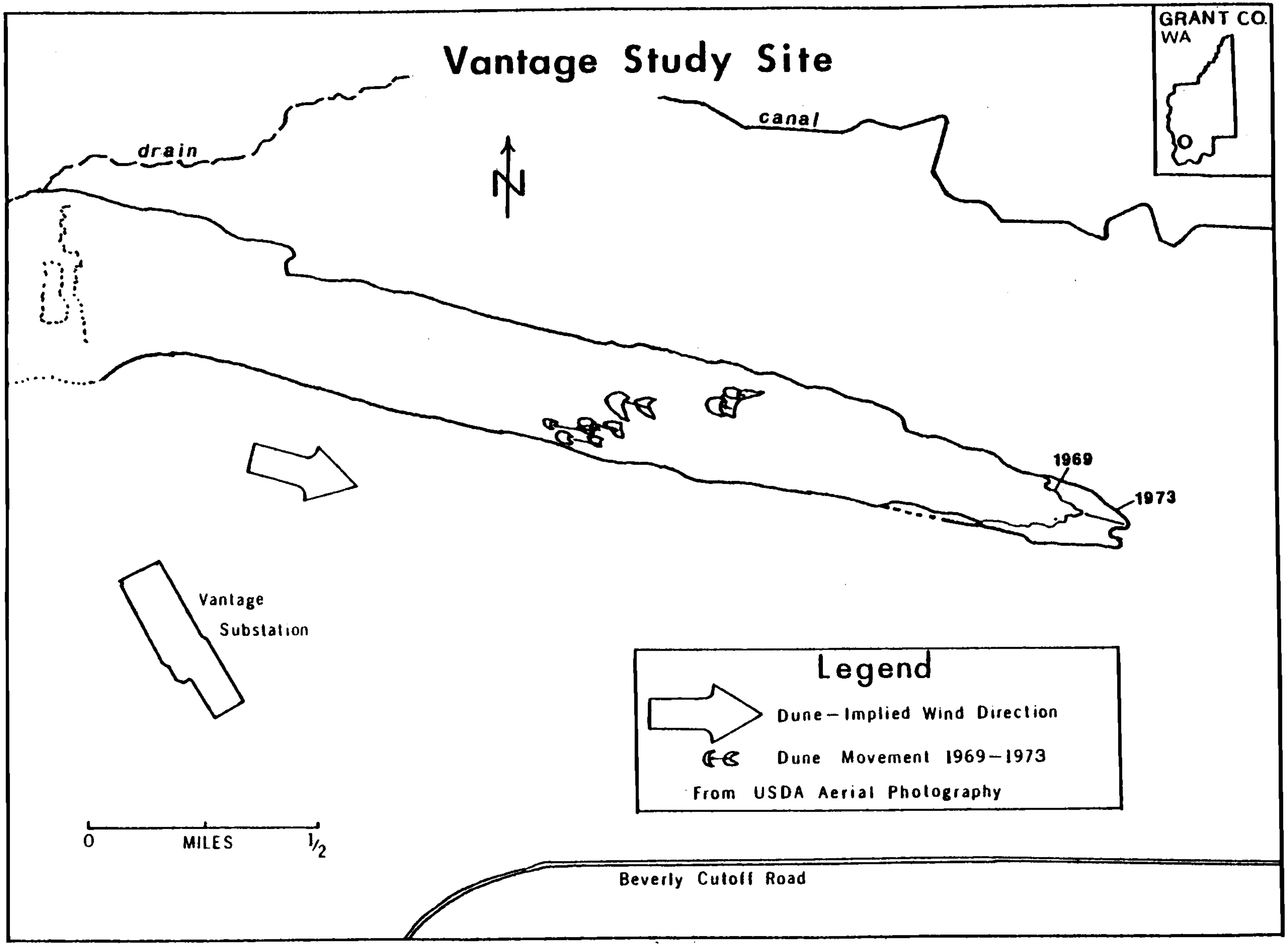


FIGURE 2. Vantage Study Site Map.

TABLE 3. VANTAGE STUDY SITE DUNE DATA.

A) DUNE MORPHOMETRY DATA

Total Dune Field Area: 0.45 mile^2 (1.18 km^2)

Elevation - Average: 1120 ft

Dune Form Types Present: barchan

Dune Dimensions:	Average	Range
Length n = 10	208 ft (63.4 m) σ n - 1 = 78 ft	123-490 ft (37-149 m)
Width n = 10	161 ft (49 m) σ n - 1 = 77 ft	70-403 ft (21-123 m)
Height	16.4 ft (5m)	———

Dune Movement Rate: 98.4 ft/year (30m/year)
n = 7 σ n - 1 = 39 ft

(ft = feet, m = meters)

B) SAND GRAIN DATA

	mm	ϕ
Mean ($\bar{x}$)	0.159	2.66
Mode	0.177	2.50
Maximum ($\bar{x}$ + 2s)	0.50	0.99
Density (g/cm^3)	2.5	

C) WIND DATA

Wind Speed	miles/hour	meters/second
Method I	13.0	5.8
Method II	11.8	5.3
Weather Station	13.4	6.0

Prevailing Wind Direction (clockwise from 0° true north)

Dune-implied	285°
Weather Station	270°

present here with relict dunes in places being overridden by active forms. Some dune slipfaces are evolving into transverse and barchan shapes as parabolic dune arms become stabilized and buried under advancing dunes. Parabolic dunes are the predominant form present, however. Seasonally high water influences much of this dune field, especially near Potholes Reservoir which inundates part of it. Also inhibiting dune movement are grass and shrub vegetation and in places volcanic ash from the Mount St. Helens eruption coating low-lying interdune areas.

Dunes at the Moses Lake study site range in width from 260 to 1240 feet with slipfaces of several dunes sometimes merging into wide fronts of advancing sand. Heights of dunes range from 10 to 50 feet, and dune advances are estimated at 6.8 feet per year from 1954 to 1976 (Table 4, part A).

Three sand samples were taken near Moses Lake; one east of Potholes Reservoir, and two within the mapped study site (Figure 3). The mode grain size is 2.5ϕ and the density is 2.71g/cm^3, relatively high (Table 4, part B).

Moses Lake wind speed calculations for Method I are 13.4 miles per hour and for Method II, 10.8 miles per hour. Weather station records have a wind speed of 7.2 miles per hour annually.[15] Prevailing wind is from 245-255° according to dune orientation and weather records show winds from 225° for 14% of the year and 270° for only 9% of the year (Table 4, part C).[16] This weather data is the poorest match of dune data to weather data of the four sites, but this particular anemometer data may not be truly representative of actual conditions.[17]

The Pasco study site is part of a sand dune area of 27.5 square miles located north of Ice Harbor Dam. This area is sometimes referred to as the Juniper Dunes and has unique botanical and recreational values.[18] This site contains the largest dunes of the four areas studied and probably the most vegetated. Slipfaces and lower slopes of these dunes support grasses and in interdune areas are brush and an occasional juniper tree. Seasonally high water affects some specific areas within the dune field and irregular topography exists beneath the dunes which are invading former drainages.

Large parabolic dunes predominate in the Pasco dune field. The highest dune slipfaces and most active sand surfaces are located at the northeastern extreme of the dunes which is the leading edge and the location of the study site map (Figure 4). The width of dunes

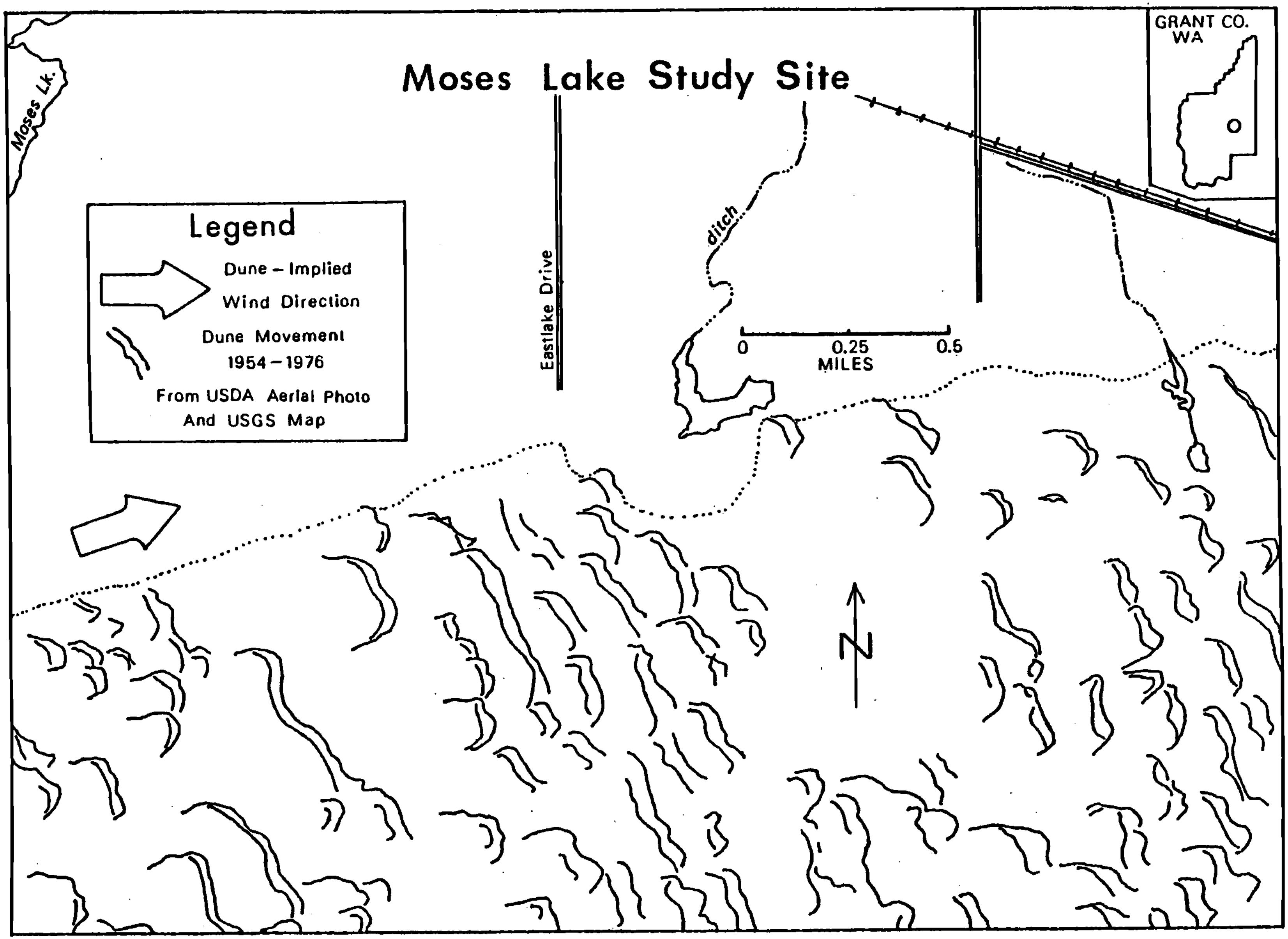


FIGURE 3. Moses Lake Study Site Map.

TABLE 4. MOSES LAKE STUDY SITE DUNE DATA.

A) DUNE MORPHOMETRY DATA

Total Dune Field Area: 41.0 $mile^2$ (106.2 km^2)

Elevation - Average: 1140 ft

Dune Form Types Present: parabolic, transverse, barchan

Dune Dimensions:	Average	Range
Width n = 20	798 ft (243 m) $\sigma n - 1 = 156$ ft	260-1240 ft (79-378m)
Height n = 20	23 ft (7m) $\sigma n - 1 = 9$ ft	10-50 ft (3-15m)

Dune Movement Rate: 6.8 ft/year (2.1m/year)
n = 25 $\sigma n - 1 = 2$ ft

(ft = feet, m = meters)

B) SAND GRAIN DATA

	mm	ø
Mean ($\bar{x}$)	0.196	2.35
Mode	0.177	2.50
Maximum ($\bar{x}$ + 2s)	0.435	1.20
Density (g/cm^3)	2.71	

C) WIND DATA

Wind Speed	miles/hour	meters/second
Method I	13.4	6.0
Method II	10.8	4.8
Weather Station	7.2	3.2

Prevailing Wind Direction (clockwise from 0° true north)

Dune-implied	245-255°
Weather Station	225° (14% annually)

here range from 200 to 1200 feet with one slipface, representing several merged dunes, advancing as a continuous front about one mile long (1.16 km). Dune height ranges from 30 to 130 feet. The Bureau of Land Management reports dunes here of 200-300 feet high, but this seems to be too high.[19] Dune movement is estimated to be 7.0 feet per year from 1959 to 1978 (Table 5, part A). The Bureau of Land Management estimates dune movement at only 18 inches per year.[20]

Sand was sampled at four locations within the study site. This was the finest sand of the four study areas with a modal size of 3.5ø (Table 5, part B).

Wind speed calculations using Method I yield 10.1 miles per hour and using Method II, 8.8 miles per hour. Weather station data on wind speed show an annual speed of 7.8 miles per hour.[21] Dune-implied prevailing winds are from 225-235° and weather data indicate 225° for 28% of the year (Table 5, part C).[22]

The Dalles study site is the smallest dune field of the areas studied at 0.33 square miles. This sand has long been a plague to the maintenance crews of Interstate Highway Eighty-four since it constantly intrudes onto the roadway.[23] The main body of sand rests on a terrace roughly 200 feet above the roadway at 400

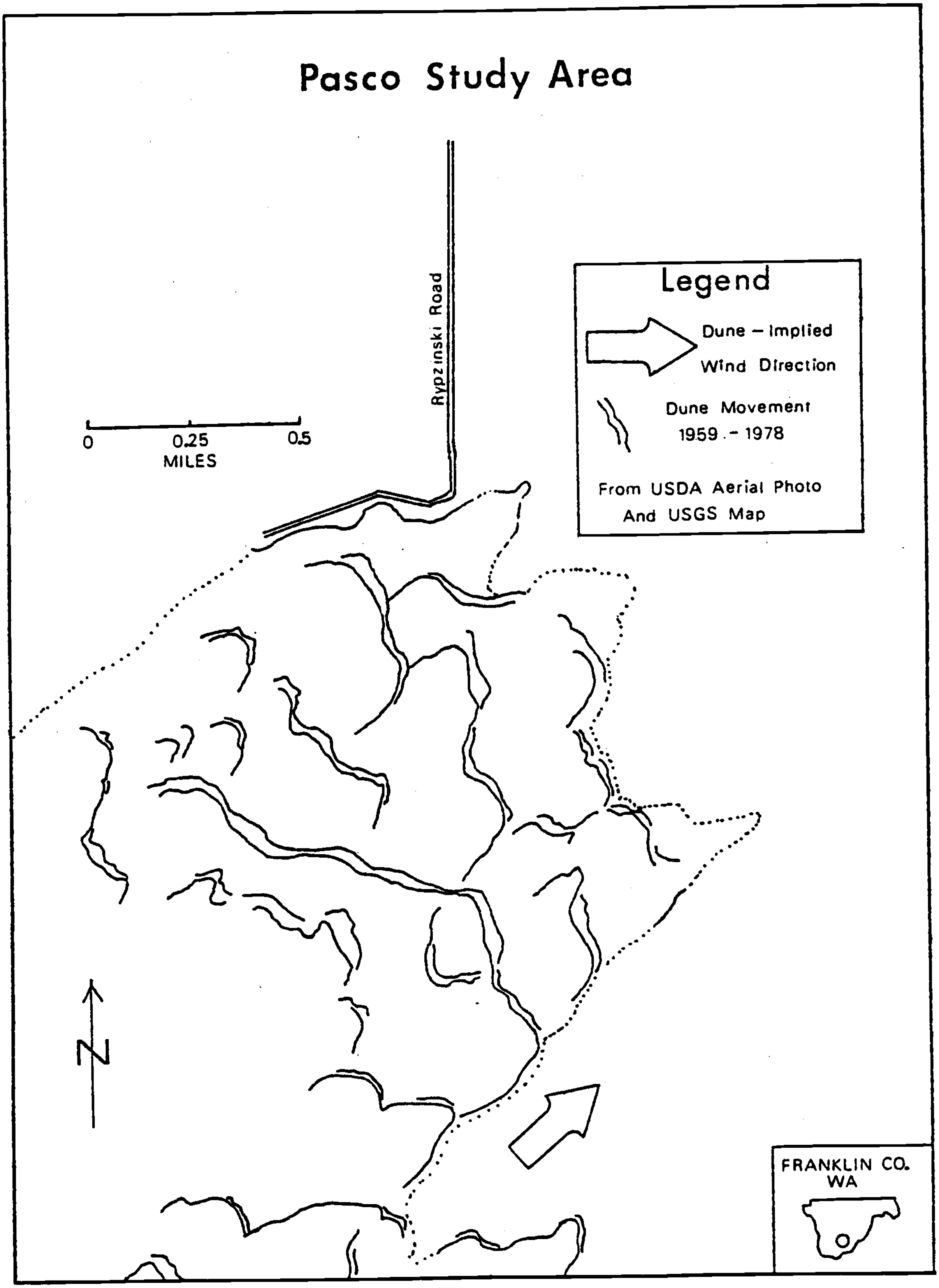


FIGURE 4. Pasco Study Site Map.

TABLE 5. PASCO STUDY SITE DUNE DATA.

A) DUNE MORPHOMETRY DATA

Total Dune Field Area: 27.5 mile^2 (71.2 km^2)

Elevation - Average: 950 ft Range: 850-1070 ft

Dune Form Types Present: parabolic, transverse

Dune Dimensions:	Average	Range
Width n = 20	749 ft (243m) σ_{n-1} = 216 ft	200-1200 ft (61-366m)
Height n = 20	64 ft (20m) σ_{n-1} = 14 ft	30-130 ft (9-40m)

Dune Movement Rate: 7.0 ft/year (2.1 m/year)
n = 25 σ_{n-1} = 3 ft

(ft = feet, m = meters)

B) SAND GRAIN DATA

	mm	ø
Mean	0.125	3.00
Mode	0.088	3.50
Maximum ($\bar{x}$ + 2s)	0.215	2.22
Density (g/cm^3)	2.63	

C) WIND DATA

Wind Speed	miles/hour	meters/second
Method I	10.1	4.5
Method II	8.8	3.9
Weather Station	7.8	3.5

Prevailing Wind Direction (clockwise from 0° true north)

Dune-implied	225-235°
Weather Station	225°

feet above sea level, but several stringers of sand including small dunes have climbed upward to 1160 feet near Kaser Ridge (Figure 5). Seasonally high water influences the upwind portion of this dune area. The wind here appears to be topographically controlled by canyon walls, rising and falling slopes, and the influence of the nearby Columbia River Gorge.

Dune types here are less easily defined than at the other study sites but consist of transverse slipfaces which almost reach barchan form in the center of the dune field. Slipfaces range from 5 to 30 feet in height with the largest at the center of the field where sand advances toward the highway. Small areas of climbing and falling dunes can be found here as well as sand-scoured bedrock. Dune movement is estimated at 37.5 feet per year from 1975-1979 (Table 6, part A).

Sand samples were taken at five locations. This sand has a mode of 2.5ø and a variety of minerals including micas, and along the dune field margins, large basalt grains forming large ripples. These sand components were not sampled in the sieving procedure (Table 6, part B).

Wind speed calculations obtained 13.4 miles per hour for Method I and 11.1 for Method II. A speed of 9.2 miles per hour is the annual rate according to

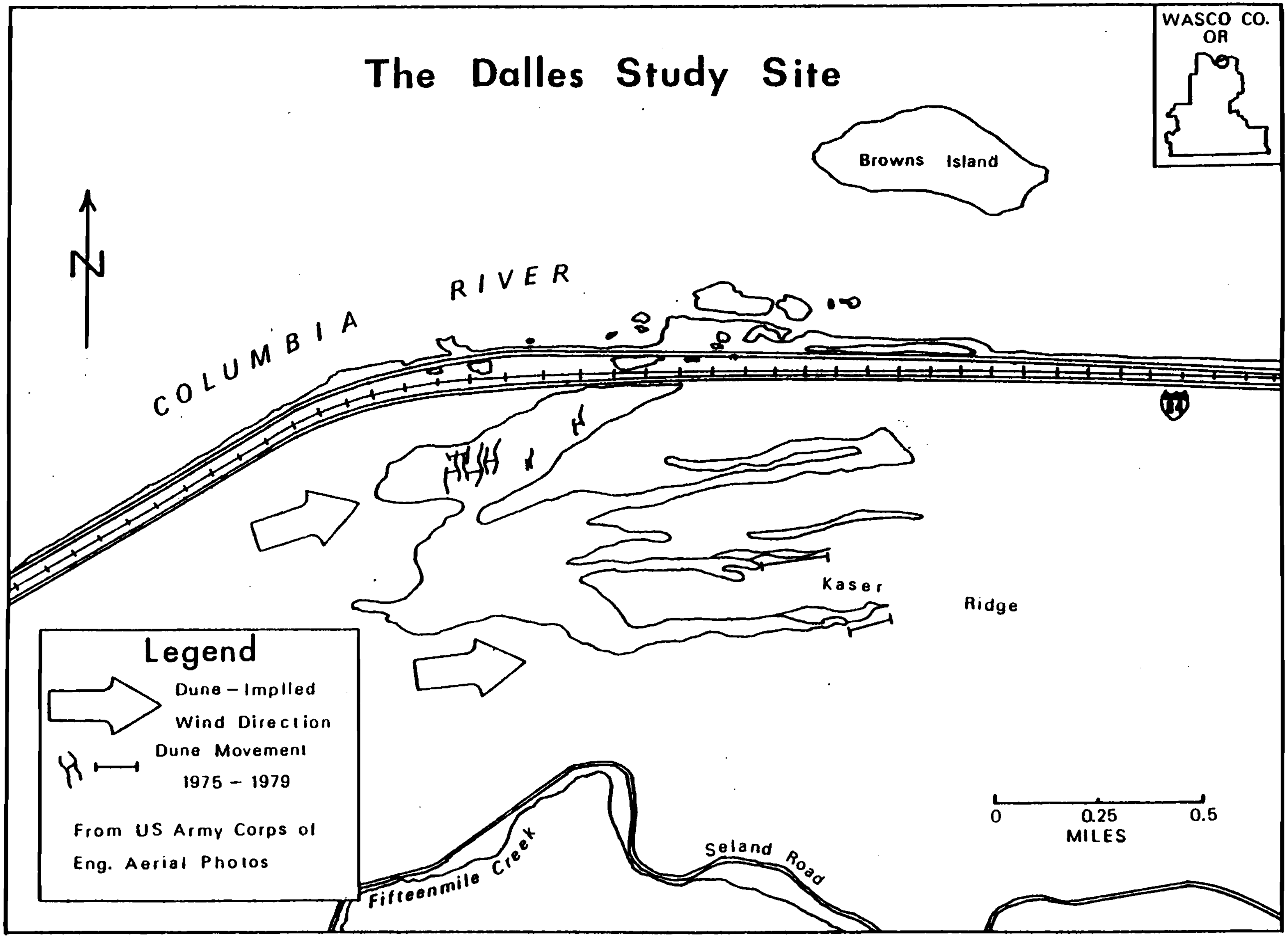


FIGURE 5. The Dalles Study Site Map.

TABLE 6. THE DALLES STUDY SITE DUNE DATA.

A) DUNE MORPHOMETRY DATA

Total Dune Field Area: 0.33 mile^2 (0.86 km^2)		
Elevation - Average: 400 ft Range: 200-1160 ft		
Dune Form Types Present: transverse, falling/climbing		
Dune Dimensions:	Average	Range
Width	______	20-633 ft (6-193m)
Height n = 7	16.4 ft (5m) σn - 1 = 9 ft	5-30 ft (1.5-9m)
Dune Movement Rate: n = 6	37.5 ft/year (11.4 m/year) σn - 1 = 16 ft	

(ft = feet, m = meters)

B) SAND GRAIN DATA

	mm	ø
Mean	0.197	2.34
Mode	0.177	2.50
Maximum ($\bar{x}$ + 2s)	0.366	1.45
Density (g/cm^3)	2.53	

C) WIND DATA

Wind Speed	miles/hour	meters/second
Method I	13.4	6.0
Method II	11.1	5.0
Weather Station	9.2	4.1

Prevailing Wind Direction (clockwise from 0° true north)

Dune-implied	245-265°
Weather Station	270°

weather station data.[24] Dune-implied prevailing winds range from 245 to 265°. Prevailing winds are 270° for 39% of the year according to weather data recorded locally (Table 6, part C).[25]

EVALUATION

Each technique used is briefly critiqued below indicating problems encountered in their use and possibilities for improvements.

Airplane observation allowed quick coverage of a wide area which included many potential study sites. Observation notes and photographs were useful memory aides and added to later study of specific sites. Dune forms of average size were easily discernible from the air in a small plane. Disadvantages of this technique, other than moderate to high cost, were difficulty in assessing controlling factors like the amount of vegetation on active sand surfaces, such as at the Pasco study site, and difficulty in estimating dune dimensions such as height.

Topographic maps proved accurate for determining dune orientation to wind and in identifying general controlling factors such as topographic control of wind flow and intermittent drainages. However, area calculations and the location of dune field perimeters may vary in accuracy according to the season of the photography used to construct the map itself. Another drawback is estimating slipface location or dune dimensions when contour lines do not define the outline of each dune and when contour interpretation varies among observers. Dune locations were drawn from topographic maps for the Pasco and Moses Lake study sites in this manner and compared to more recent aerial photography printed at the same scale to determine movement. Topographic map publication dates often do not reflect the date of the aerial photography or surveys used to construct the map. However, the dates of the photography used at the Pasco and Moses Lake sites are given on the topographic maps used (see Appendix C).

Field work at each study site was valuable in confirming aerial observations and map information. Controlling factors such as vegetation present and seasonal ponding of water in deflation areas were better understood when observed at ground level. Large dunes are difficult to see in their entirety on the ground, and views from a high point were helpful in gaining a good perspective.

More sand samples, especially from the Vantage site, would add to the credibility of the sieve analysis data. One-quarter phi (ø) interval sieves would allow more interpretation of sand data. Many workers in sedimentology now prefer settling tube analysis to sieving, but sieves are usually more readily available and the data obtained more easily interpreted for wind speed estimates.

Aerial photography provided the most information of any of the techniques used including data on dune orientation to wind, dune dimension estimates, and sand movement controlling factors. Timing of photography is critical since slipfaces without shadows can be very difficult to see and since seasonal differences in albedo may also hamper interpretation of dune areas. Distorted photographic images make overlay mapping difficult and less accurate. Dune movement as an average would be most accurate with as many different years as possible represented in photography taken over a long period, but this effort may not be justified if only approximate wind speed estimates are desired.

Wind speed calculations from Method I are generally higher and less in accordance with local weather station data than are those for Method II. One reason for this is the allowance for more variables in Method II. Both methods are limited to only a partial representation of actual processes and should be used in conjunction with all other available wind data to determine areas of high wind power potential.

Heister and Pennell suggest that sand analysis by sieve methods should be adjusted as Bagnold did to account for sand grain shape variation and for sieve-to-sieve mean grain size.[26] However, this increases calculated wind speeds about 30% and appears to be a less accurate estimate than using unadjusted sieve data.

Changes in sand density values from those measured to a standard density for quartz of 2.65 g/cm^3 and an estimated density of basalt of 2.75 g/cm^3 (for the Moses Lake sand), changes wind speed values by less than 2% for both Method I and II.

Estimates of maximum grain size values are subject to variation depending on accuracy of graphing and the method of determination. The maximum grain size is computed herein as the mean size plus two standard deviations ($\bar{x} + 2s$), and this seems to be a consistently more conservative value than using the ninety-fifth percentile as read directly from graph paper.

Changing dune heights to minimum possible values for the study areas changes the wind speed values for Method II by less than 1% (using height values of 3 meters for Vantage, Moses Lake, and The Dalles and of 5 meters for Pasco). By changing dune migration rates to lower values, changes in Method II wind speeds are also little changed (less than 3% if rates are: Vantage, 16 m/year; Moses Lake, 1.1 m/year; Pasco, 0.6 m/year; and The Dalles, 4.5 m/year).

Weather station wind speeds are the lowest at Moses Lake and at Pasco with the highest speeds at Vantage. The highest calculated wind speed is 13.4 miles per hour both at Moses Lake and at The Dalles using Method I. The lowest calculated wind speed is 8.8 miles per hour at Pasco using Method II. Method I and Method II calculations differ from each other by 1.2 to 2.6 miles per hour (0.5 to 1.2 m/sec) with the largest difference at Moses Lake and The Dalles. The largest difference between calculated and recorded wind speeds is at Moses Lake using Method I which is a 6.2 miles per hour (2.8 m/sec) difference.

SUMMARY

The techniques presented here for wind power prospecting via sand dune study are meant to be used in data-poor regions and in conjunction with other methods of wind resource evaluation. These methods may prove especially helpful in developing countries in arid regions with little or no local weather information and with a need for wind power. Aerial photography interpretation by a trained observer of eolian landforms may be the most useful technique of the five presented to gain general information on local wind characteristics. Field work and map use may also add important information.

In comparing the four study sites, The Dalles represents the smallest area and the one most influenced by topography. The Moses Lake site is the largest in area and, in places, the most affected by seasonally high water. Vantage is the only site predominated by barchan dunes and they were the fastest moving of the four areas. The largest dunes are within the Pasco site, both in height and width. Pasco also has the finest-grained sand and probably slowest dune movement, even though Moses Lake was estimated as slightly slower.

Method II wind speed calculations are more similar to weather station records than Method I, which seem to be too high. Prevailing wind direction seems to be readily determined by analysis of dune slipface orientation at each site.

FOOTNOTES

[1]J. E. Wade and E. W. Hewson. A Guide to Biological Wind Prospecting. DOE Contract NO. EY-76-506-2227, 1980.

[2]S. G. Fryberger and G. Dean, "Dune forms and wind regime," in A Study of Global Sand Seas. E. D. McKee, ed. USGS Professional Paper 1052, 1979, pp. 137-170.

[3]Ibid., also several other works using LANDSAT imagery such as: W. Carlisle, R. Marrs, and J. Marwitz. Airflow Near Richland, Washington Inferred From Eolian Features. ERDA Contract NO. EY-765-06-2343, 1977.

[4]J. T. Hack, "Dunes of the western Navajo country." Geographical Review, vol. 31, 1941, pp. 240-263.

[5]I. G. Wilson, "Aeolian bedforms - their development and origins." Sedimentology, vol. 19, 1972, pp. 173-210.

[6]L. E. Dean. The California Desert Sand Dunes. NASA/BLM, Grant NO. NSG 7220, 1978.

[7]Work on this has been presented in: R. P. Sharp, "Wind Ripples." Journal of Geology, vol. 71, 1963, pp. 617-637.

[8]R. A. Bagnold. The Physics of Blown Sand and Desert Dunes. London: Methuen and Co., 1941. Also: H. Lettau, ed. Exploring the World's Driest Climate. University of Wisconsin Press, 1978.

[9]T. R. Heister and W. T. Pennell. The Meteorological Aspects of Siting Large Wind Turbines. Draft DOE Report PNL-2522, 1980.

[10]Bagnold, op. cit., pp. 32-33.

[11]J. Wade, et al. Remote Sensing For Wind Power Potential A Prospector's Handbook. DOE/ET/20316-81-1. To be published during 1982.

[12]Ibid., pp. 81-90.

[13]Ibid., p. 95. Other local wind speeds given in this source are: 4.1 meters/second annually at Vantage Farms and 5.3 meters/second annually at Wanapum.

[14]E. W. Hewson, et al. Network Wind Power Over The Pacific Northwest. Bonneville Power Administration Report 78-3, 1978, p. 124.

[15]Wade, loc. cit.

[16]Bonneville Power Administration. Addendum to 1964 BPA Report, "Distribution of Extreme Winds in the BPA Service Area."

[17]J. Wade. Personal communication, 1982.

[18]G. Yeager. Bureau of Land Management District Office, Spokane, Washington. Personal communication, 1981. And BLM Land Use Plan for the Juniper Dunes Area.

[19]Ibid.

[20]Ibid.

[21]Wade, Remote Sensing For Wind Power Potential A Prospector's Handbook. p. 95.

[22]Hewson, loc. cit.

[23]R. Hawkins. Oregon State Highway Department District Office No. 9, The Dalles, Oregon. Personal communication, 1981. See also: A. B. Muzzall, "Trouble-making sand dune," American Association of State Highway and Transportation Officials, vol. 61, 1982, p. 17.

[24]J. W. Reed. Wind Power Climatology of the United States - Supplement. NTIS, SAND 78-1620, 1979, p. 89.

[25]Hewson, loc. cit.

[26]Heister and Pennell, op. cit., pp. 7-8, 7-9.

APPENDICES

APPENDIX A

Below are presented definitions of dune forms based on classifications by L. E. Dean in The California Desert Sand Dunes (NASA/BLM Grant No. 7220, 1978), and in part by A Study of Global Sand Seas, edited by E. D. McKee (USGS Professional Paper 1052, 1979, pp. 1-21, 137-170.). The most common dune forms observed by the author in the Central Columbia River Basin include: transverse, parabolic, obstacle, and barchan. A figure is presented to further clarify dune form definitions and it should be noted that dune dimensions are often difficult to determine, as are the correct categories in which to place a sand dune. Dunes can take an infinite variety of shapes and may coalesce indistinguishably, but often one or two dominant dune form types are present within any one area.

A. Barchan: Isolated crescent-shaped dune with "horns" pointing downwind and a single slipface. Forms frequently on a bare, smooth and non-sandy surface. Often reflects unimodal wind regime.

B. Transverse: Asymmetrical ridge perpendicular to the sand-moving wind with one slipface. Forms on a base of bare, loose sand of relatively unlimited surface area and depth. Occurs in a variety of directional wind regimes.

C. Longitudinal: A symmetrical ridge with two slipfaces, one on each side. Forms in relatively high-velocity, bi-directional winds from within the same quadrant. Often appear as long, parallel ridges with their long axis following the dominant sand-moving winds. Forms in areas of abundant sand sources. Also known as seif dune.

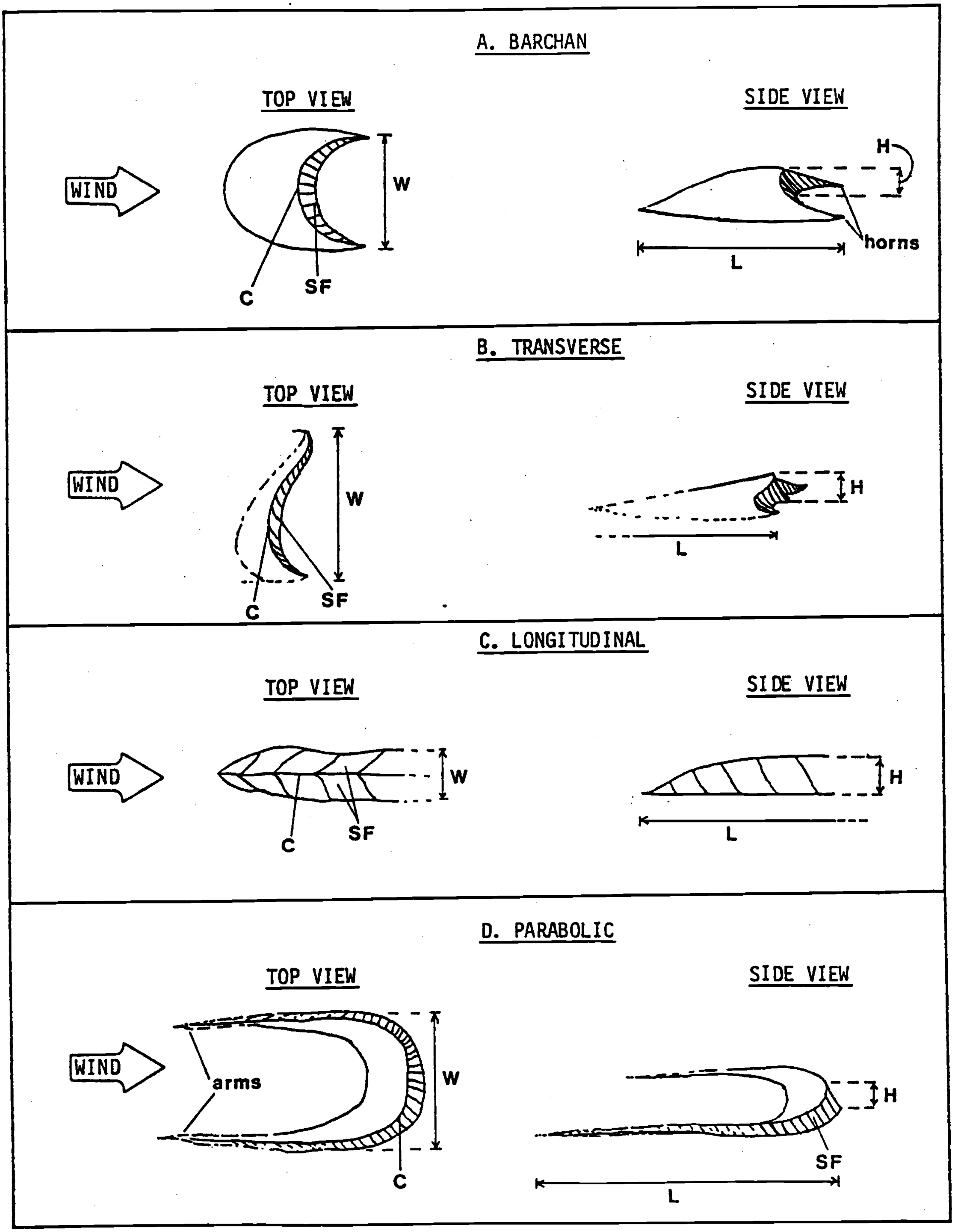
D. Parabolic: "U" shape to "V" shape with one or more slipfaces. "Arms" often partially anchored by vegetation and higher "nose" migrates downwind. Inner surfaces represent a bowl-shaped deflation area. Forms in deep sand where gentle winds tend to create "U" shape and stronger winds tend to create "V", or hairpin, shape.

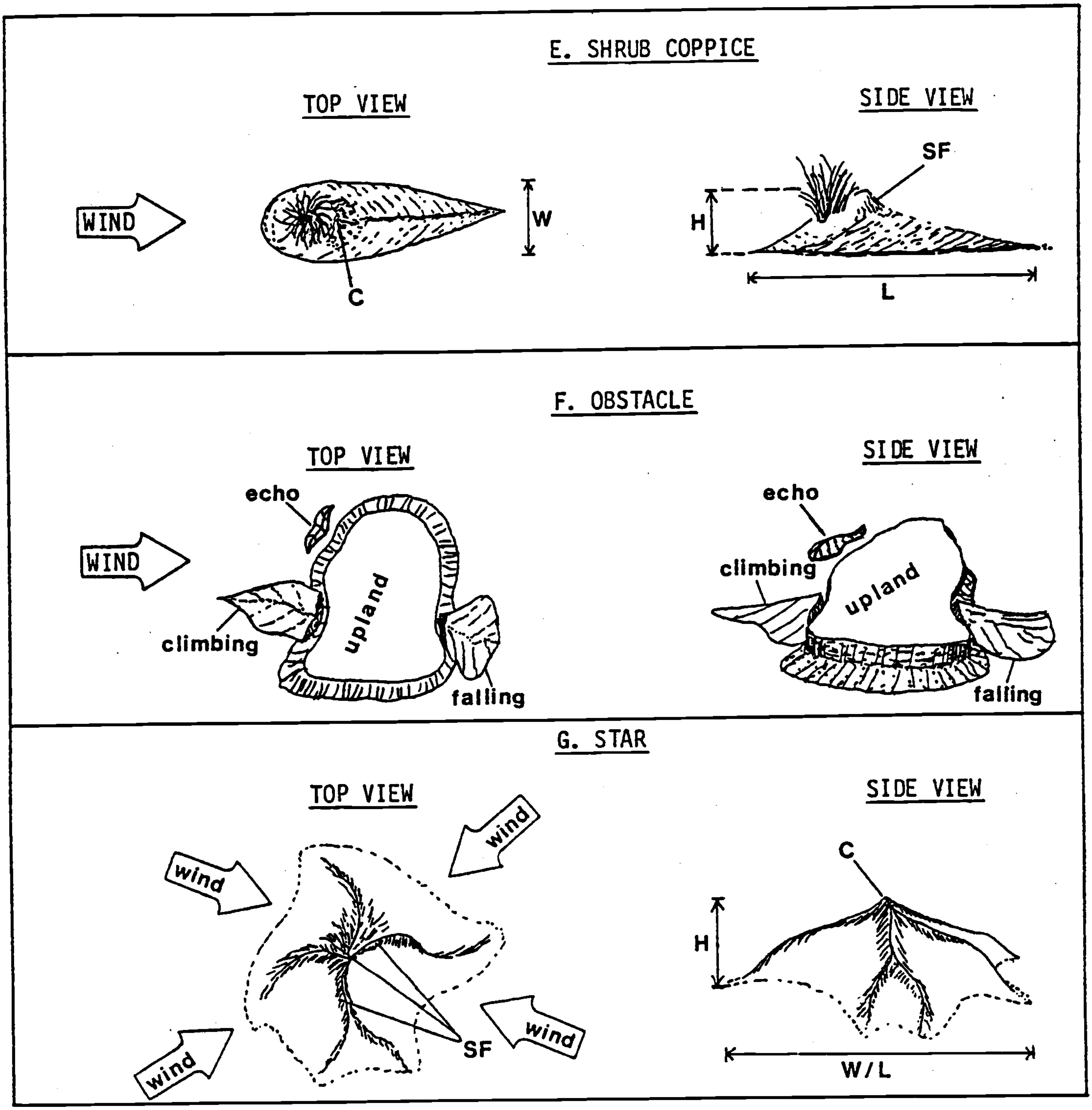
E. Shrub Coppice: Sand mounds partially stabilized by bunch or clump vegetation which interrupts wind flow. Forms on smooth surface in shallow sand. Relatively small-scale feature compared to most dune forms.

F. Obstacle: Includes wide variety of sand deposits forming on windward or leeward sides of topographic obstacles. Climbing dunes pile up on windward sides and falling dunes on leeward sides of sand/wind flow obstructions. Echo dunes form on windward sides as sand is dumped out of slowed airflow near steep slopes; may parallel contour of obstacle and not climb its side. Obstacle dunes may have several slipfaces and limited sand supply.

G. Star: Large "sand mountain", often relatively isolated with multiple slipfaces and a central peak with three or more radial arms. Forms in unlimited sand from multidirectional and often strong winds. Grows vertically rather than migrating laterally as other forms do. Also known as pyramid or rhourd dunes.

(See Figure: "Simple Sand Dune Forms" for illustration of each dune form type defined here.)


A. BARCHAN
TOP VIEW
SIDE VIEW
WIND
W
C
SF
H
horns
L
B. TRANSVERSE
TOP VIEW
SIDE VIEW
WIND
W
C
SF
H
L
C. LONGITUDINAL
TOP VIEW
SIDE VIEW
WIND
W
C
SF
H
L
D. PARABOLIC
TOP VIEW
SIDE VIEW
WIND
arms
W
C
H
SF
L



SIMPLE SAND DUNE FORMS

H height
L length
W width

C crest
SF slipface

APPENDIX B

The following is taken from examples in J. Wade, et al. Remote Sensing For Wind Power Potential A Prospector's Handbook (DOE/ET/20316-81-1. To be published during 1982) which is in part based on the work of T. R. Heister and W. T. Pennell in The Meteorlogical Aspects of Siting Large Wind Turbines (Draft DOE Report PNL-2522, 1980).

These are Method I and Method II calculations presented above but in more detail.

Method I - Wind Speed Estimates From Sand Size Distribution

When the wind speed equals the impact threshold velocity (defined above according to Bagnold), the following equation describes the wind profile (in CGS units):

$$U_{(z)} = \frac{U_*}{k} \ln \frac{Z}{Z_o} \qquad (1)$$

where: U = the wind speed at height Z

U_* = friction velocity which represents a velocity scale of turbulence

k = 0.35, von Karmen constant

Z = height above ground (10 meters used)

Z_o = surface roughness which can be determined by:

$Z_o = d/30$

where: d = coarsest sand grain diameter

1/30 = proportionality constant

A threshold friction velocity, U_{*T}, may be used in equation (1) for U_*. U_{*T}, based on sand grain density and diameter, can be determined using:

$$U_{*T} = A\sqrt{\frac{\sigma - p}{p} gd} \qquad (2)$$

where: U_{*T} = threshold friction velocity

A = a proportionality constant that equals 0.08 for the impact threshold velocity and 0.1 for the fluid threshold velocity (0.08 used)

σ = density of the sand

p = density of air (1.2×10^{-3} g/cm^3)

d = modal grain size

So to solve equation (1) requires use of U_{*T} for U_* and the companion calculations for $Z_\circ$, σ, and d.

Method I Results:

STUDY SITE	VANTAGE	MOSES LAKE	PASCO	THE DALLES
U_{*T} (cm/sec)	15.2	15.8	11.0	15.3
$U_{(z)}$ (cm/sec) z = 10 meters	578	607	445	595

METHOD II - Wind Speed Estimates From Dune Migration

Wind speed above the ground can be estimated using the following (MKS units):

$$\bar{V}_{(z)} = V_T + \frac{\bar{U}_*}{k} \ln \frac{z}{k'} \qquad (3)$$

where: $\bar{V}_{(z)}$ = mean wind speed at height z

k = as previously defined

k' = wind profile upper limit of threshold velocity, 0.01 meter for typical dune sands

z = as previously defined

$$V_T = \frac{A}{k} \sqrt{\frac{\sigma - p}{p} gd} \ln \frac{30k'}{d} \qquad (4)$$

(A,k,k',p,g,d,σ are defined above) this may be shortened to:

$$V_T = \frac{U_{*T}}{0.35} \ln \frac{0.3}{d}$$

$\bar{U}_*$ = long-term average friction velocity which equals β times U_{*T}

To determine $\bar{U}_*$, several more steps are required:

$$\bar{U}_* = \beta U_{*T} \qquad (5)$$

where: U_{*T} = results of equation (2), Method I

$$f(\beta) = \frac{\langle \vec{q} \rangle}{a\ U_{*T}} \qquad (6)$$

to find $f(\beta)$ a figure is used (given below) and the following:

$$\langle \vec{q} \rangle = \frac{x \sigma H}{T} \qquad (7)$$

where: $\langle \vec{q} \rangle$ = average sand transport rate

x = distance of dune migration

σ = sand density

H = dune height

T = time interval between dune observations

and

$$a = C \frac{p}{g} \sqrt{\frac{d}{D}} \qquad (8)$$

where: a = from Bagnold's mass transport rate of wind blown sand (q), where $q = a\, U_*^3$

C = 1.8, for typical dune sands

D = 2.5×10^{-4} meter, a standard grain size diameter

(d, g, p are defined above)

Method II Results:

STUDY SITE	VANTAGE	MOSES LAKE	PASCO	THE DALLES
$\langle\vec{q}\rangle$ (Kg/msec)	0.01188	0.00126	0.00350	0.00457
a ($Kgsec^2m^{-4}$)	0.185	0.185	0.131	0.185
$f(\beta)$ (m^2sec^{-2})	0.42	0.04	0.24	0.16
β (from fig.)	0.69	0.47	0.62	0.57
$\bar{U}_*$ ($msec^{-1}$)	0.1049	0.0743	0.0682	0.0872
V_T ($msec^{-1}$)	3.22	3.35	2.59	3.24
V_{10} ($msec^{-1}$)	5.29	4.82	3.94	4.96

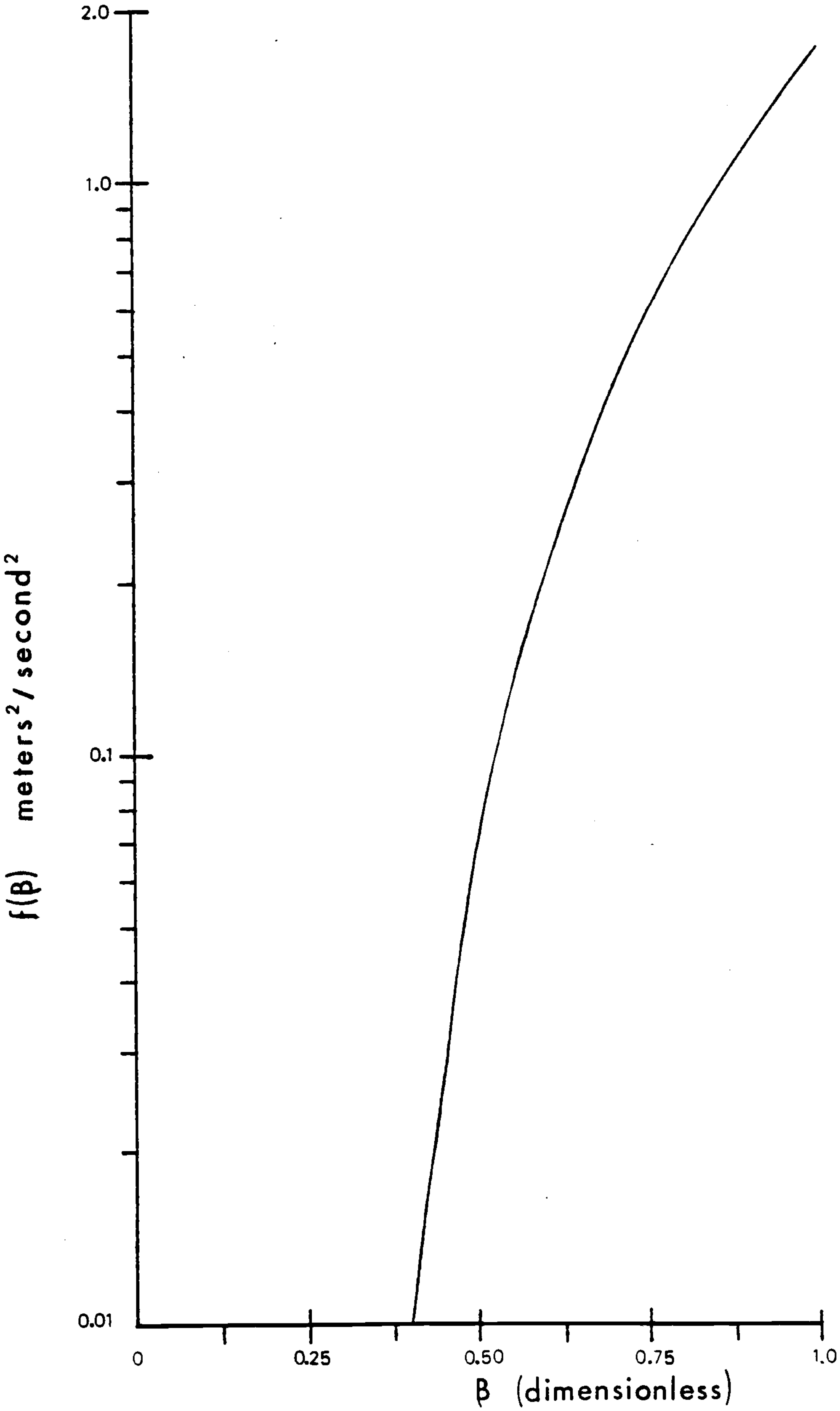


FIGURE FOR β DETERMINATION FROM f(β).

APPENDIX C

EXACT STUDY SITE LOCATIONS

FROM U.S. GEOLOGICAL SURVEY (USGS) MAPS

STUDY SITE / USGS MAP	Vantage	Moses Lake	Pasco	The Dalles
Map Title (year)	Beverly,Wash. (1965)	Moses Lake South,Wash. (1956,Revised 1978)	Levey NE,Wash. (1964	Stacker Butte,Wash.-Oreg. (1974
Map Scale	1:62,500	1:24,000	1:24,000	1:24,000
Township /Range	16N /23E	18N /28E	11N /32E	2N /14E
Sections	9,10,11,14, 15,16	9,10,11,12 13,14,15,16	19,20,21,28 29,30,31,32 33	21,22,23
Map Title (year)		Seiler,Wash. (1956,Revised 1978)		
Map Scale		1:24,000		
Township /Range		18N /28E		
Sections		R28E-Sec. 1, 12		

APPENDIX D

AERIAL PHOTOGRAPHY USED

SITE	PHOTO SOURCE	ID.NO./ FRAME NO.	DATE
Vantage	USDA	AAR-IKK-69	8/24/69
	USDA	S20-53025-173 S20-53025-156 S20-53025-83	10/3/73
Pasco	USDA	40-53021-278-164	7/22/78
Moses Lake	USDA	A40-53025-276-32	6/18/76
The Dalles	USACE	75-1185-2-47	6/12/75
		79-624-2-47	5/20/79

USDA = U.S. Department of Agriculture
ASCS Aerial Photography Field Office
Salt Lake City, Utah

USACE = U.S. Army Corps of Engineers
Portland District
Portland, Oregon