Prospecting for Wind: Windmills and Wind Characteristics[a]

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(Reviewed by the Aerospace Division)

Introduction

The windmill, that familiar if not always reliable workhorse of mankind, seems headed back into the whirl again. Visions of wind-driven power sources have tantalized mankind for centuries; however, only recently has anyone considered seriously producing by such means a significant fraction of mankind's electrical power (say 6.6 quads of energy by the year 2020). To reach this optimistic goal requires careful consideration of the characteristics and availability of the energy source itself, i.e., the wind. Effective utilization of wind energy will require estimates of wind characteristics related to: (1) Wind turbine aerodynamics, hardware, and tower design; (2) energy, climatology, and resource estimates over large mesoscale size regions; (3) dependable and cost-effective methodologies for pre-evaluating specific sites; and (4) forecasting wind conditions for large turbine system operations. A review of the history of wind characteristics research prior to 1970 has been prepared by the writer (13). Since 1976 the Wind Characteristics Program Element of the Federal Wind Energy Program has been coordinated by the Pacific Northwest Laboratory (PNL) at Richland, Washington (18).

Past experience with power generation by large windmills suggests that among the most important factors controlling success or failure of these systems is site selection and presiting evaluation—the subject of the second and third areas previously listed. Incorrect placement on a site sheltered by buildings, terrain, or agricultural growth may drop performance to one third of the original expectations. Conversely, the appropriate hill or ridge shape may amplify power available at a given height by an order of magnitude above that over flat terrain! Recent insights on the influence of terrain suggest that there is significant wind energy available in coastal regions and over complex mountain topography.

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Site selection procedures in such instances include statistical climatology, numerical simulation, and physical simulation in meteorological wind tunnels. A review of "wind prospector" methodologies is the subject of this paper.

The second section considers historical siting insights which persist from previous Wind Energy Conversion System (WECS) experience. A third section is concerned with the analysis of wind energy potential over mesoscale size regions (1,000 km × 1,000 km). The development of accurate presiting methodologies is considered in the concluding discussion.

Historical Perspectives

Some 500,000 small wind-electric systems are known to have been built in the United States, most prior to 1945. These electric generating systems were sited on the basis of rough "rules of thumb," generally a minimum height above obstacles within a specified radius. Installations were encouraged where there was an "intuitively understood 'minimal availability' of wind energy" (1).

World-wide experience prior to 1970 with some ten large wind turbines exceeding nominal capacities of 100 kW resulted in a qualitative consensus on wind-site evaluation over low-to medium-height ridges or hills (11).

1. Ridges should be athwart the principal wind direction, but high velocities are not likely on upwind foothills.
2. Hill tops should not be too flat, slopes should extend all the way to the summit.
3. A hill on the coast as opposed to an inland hill surrounded by other hills is more likely to provide high winds, i.e., unobstructed upwind.
4. Speed up is greater over a ridge of given slope than over a conical hill of the same slope.
5. Speed up over a steep hill decreases rapidly with height.
6. The optimum hill slope is probably between 1:4 and 1:3 with 1:3.5 best (h/L between 0.5 and 0.67).
7. Topographical features in the vicinity of the hill produce the structure of the flow over it.
8. Frenkiel (Ref. 5) ranks sites based on the uniformity of the summit and profile (see Table 1).

TABLE 1.—Rank of Sites Based on Uniformity of Summit and Profile

Quality (1)	$R = {}^{u}40\text{ m}/u_{10\text{ m}}$ (2)	α (3)	Slope (4)	h/L (5)
Optimum	$R < 1.05$	0.0	1:3.5	0.57
Very good	$1.05 < R < 1.10$	0.07	1:6 smooth regular	0.35
Good	$1.1 < R < 1.15$	0.1	1:10	0.20
Fair	$1.15 < R < 1.21$	0.14	1:20 smooth 1:6 regular	0.10
Avoid	$1.21 < R$	>0.14	>1.20 <1:2	<0.05 >1.0

ogy: (1) Full primitive equation (PE) models; (2) objective analysis (OA) models; and (3) shallow fluid (SF) or Lavoie models (4,7,8,15,16). Typical primitive equation models solve the conservation equations for momentum, energy, and moisture transport. The equations usually account for advection, Coriolis forces,

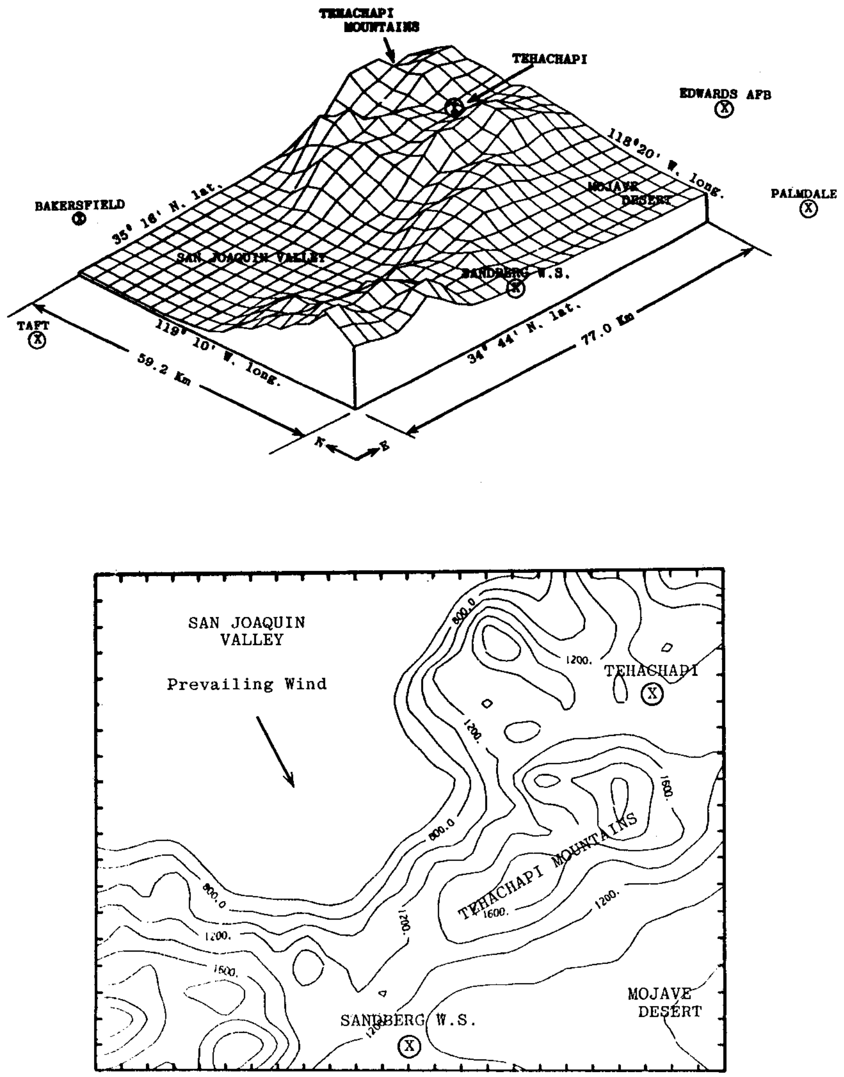


FIG. 3.—Terrain Perspective of Tehachapi Region Traci et al. (15)

turbulent heat, momentum and moisture transport, and radiation. The most sophisticated versions utilize turbulent models which account for density stratification, turbulence nonequilibrium, and history effects. Typically they use a terrain following grid system with expanded grid resolution near the surface.

Various approximations do not usually permit prediction of separation or reduction of resolution to turbine-size scales.

Validation of PE methods has been difficult. Vukovich (16) found that data-type inconsistencies inherently present in the field experiments chosen for validation forestalled positive conclusions of simulation (16). The model tested explained between 47%–81% of the total variations in wind speed and direction measured. Traci et al. (15) report their PE model ran in 10 min of CDC 7600 cpu time/simulation (10 × 30 × 30 grid), which is approximately 20 times slower than their objective analysis model (15).

A case study application of a PE model has been prepared for the Tehachapi Mountains, 100 km NNW of Los Angeles, Calif. (15). This area is of current interest because of recent proposals that wind energy conversion systems (WECS) could be used to economically pump California aqueduct water over the mountains into the Southwest basin. Fig. 3 is a perspective of the Tehachapi region incremented at the 3-km resolution used by the PE model. Using climatological data for boundary and initial conditions, the model predicts velocity vectors, temperature, water vapor, mean-square turbulent-velocity fluctuation, and wind-energy content (see Fig. 4).

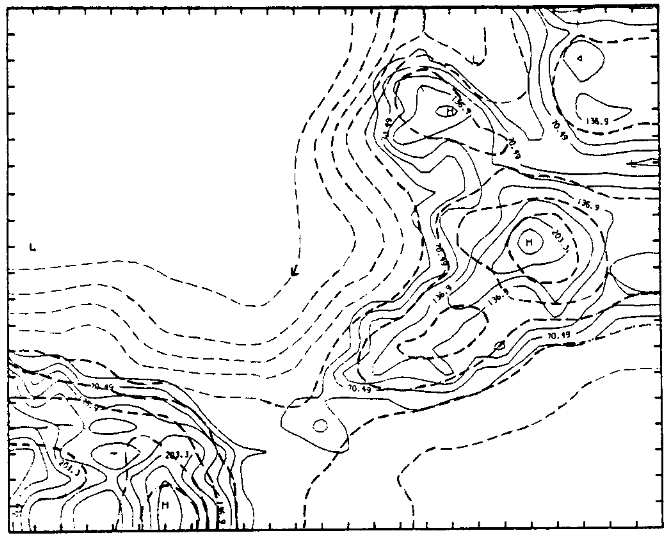
The desire to make siting methodologies more economical while retaining physical accuracy has prompted the investigation of simpler objective analysis (OA) and shallow fluid (SF) models. A number of OA codes are available (15,8). The codes are three dimensional and produce terrain dependent, divergence-free windfields given observed data as input. Input data are extrapolated and interpolated horizontally and vertically to computational mesh points. Horizontal and vertical components of the velocity field are simultaneously adjusted in a manner consistent with topography and atmospheric stratification considerations to produce a nondivergent wind field. The methodology is generally very fast; however, it does not allow for separation or turbulent diffusion of momentum.

A variety of validation experiments have been performed primarily against field measurements of atmospheric tracer trajectories which are not very sensitive to local wind velocity values. Hardy (8) has compared OA calculations and field measurements over Oahu, Hawaii. Traci et al. (15) performed validation tests against measured wind fields over Los Angeles.

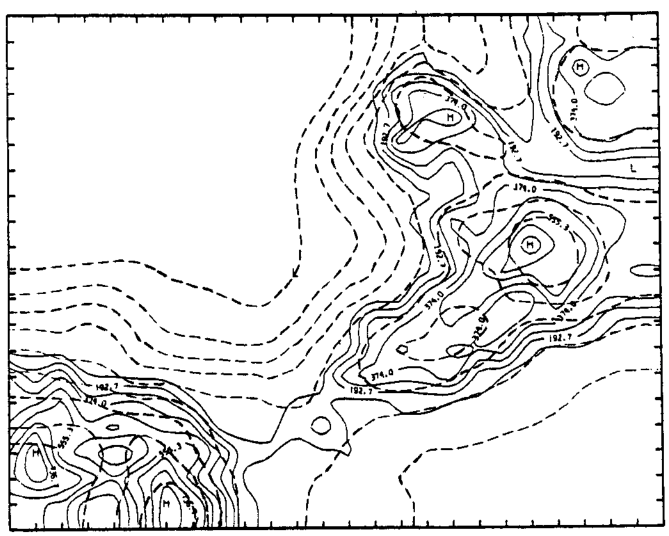
While the OA models are extremely economical to run when compared to PE models, it is known that their accuracy is dependent on initial windfield data. Fig. 5 compares Los Angeles wind fields calculated utilizing 26 input sites versus seven sites. The OA method predicted correct wind direction at 50% of the sites within one sector (22.5°) and tends to underpredict winds substantially for this test case.

When a large number of OA calculations are combined to produce long-term wind summaries over the Tehachapi region, it was found that the reference input station at Sandberg was reproduced exactly, while stations at Techachapi and Bakersfield were reproduced very well and poorly, respectively. In retrospect, this was not surprising since valley input data was limited.

The other class of simple meteorological models considered is the shallow fluid (SF) model. The active part of the atmosphere is represented by a single computational layer. Terrain shape, roughness, and thermal forcing can be treated at small expense. The method has an inherent lack of vertical resolution; however, combinations of OA and SF models look attractive (15).



a. Wind Energy Content (m^3/sec^3)
at ~42 m to 63 m AGL



b. Wind Energy Content (m^3/sec^3)
at ~131 m to 196 m AGL

FIG. 4.—Near Surface Wind Energy Content Contours: Tehachapi Flow Field Computation (1230 GMT, 11/15/74)

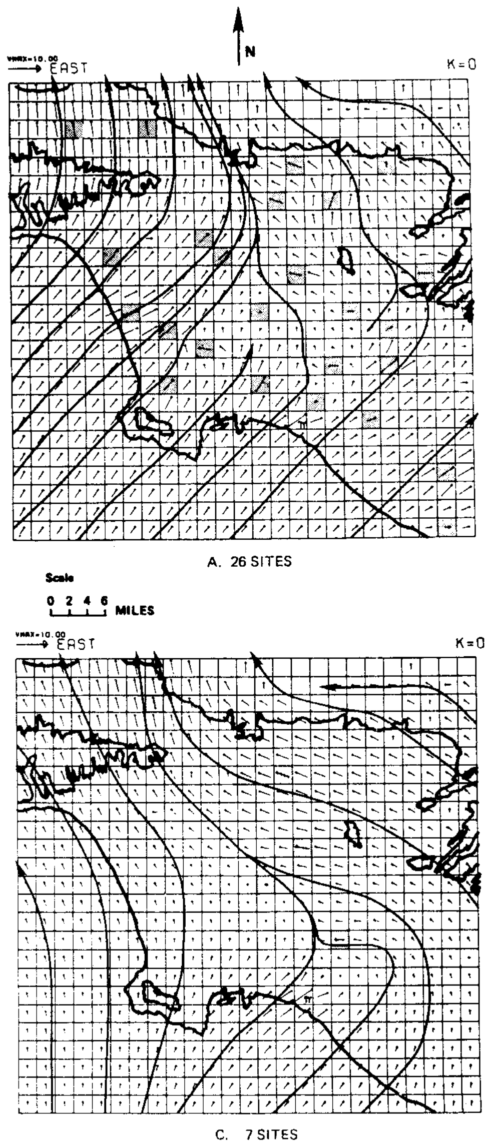


FIG. 5.—Objective Analysis Validation Test Using Los Angeles Data (1500 hours, 30 October 1974) Comparing Streamline Patterns as Function of Number of Meteorological Inputs (15)

Fosberg (4) compared an SF model to seven sets of field data. Six come from studies conducted in the Oregon Cascade mountains. Forty-five percent of the calculated wind speeds fell within 1 m/s of the observed, and 75% fell within 2 m/s. For 51 data points the sample correlation coefficient is $r = 0.60$. Sixty percent of the calculated directions fell within one compass point of the observed direction. For 43 data points the sample correlation coefficient is $r = 0.62$.

Site Screening and Localization Techniques

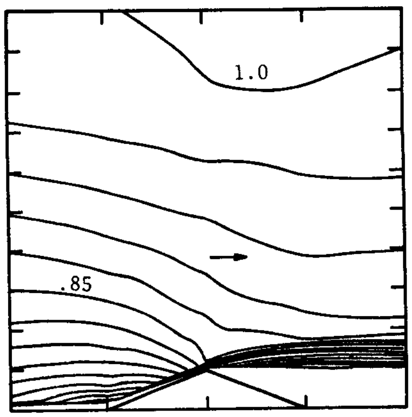
In the mesoscale wind program, large areas on the order of 1,000 km on a side are analyzed. It is also necessary to identify smaller regions within the large area where high winds exist. While the variations from site to site within several kilometers of each other in flat or rolling terrain are not significant, in regions of nonhomogeneous and complex terrain these variations may be large enough to jeopardize the economic feasibility of a given turbine site. A number of complimentary tools are available for solving this problem which might be applied in the following order: (1) Rules of thumb based on generic laboratory data; (2) biological indicators; (3) physical models; and (4) statistical methods with short-term on-site meteorological measurements.

Handbooks, as mentioned previously, are being prepared based on extensive wind-tunnel and numerical simulation of flow over various ridge shapes, slopes, and surface roughness and different atmospheric stabilities (2). This same data has provided a stationary accurate datum against which to check sophisticated PE or OA models (15). Contours of typical flow characteristics over a triangle ridge are shown in Fig. 6. Measurements such as these have resulted in predictive equations for wind-speed amplification factor as a function of upwind profiles and hill shape.

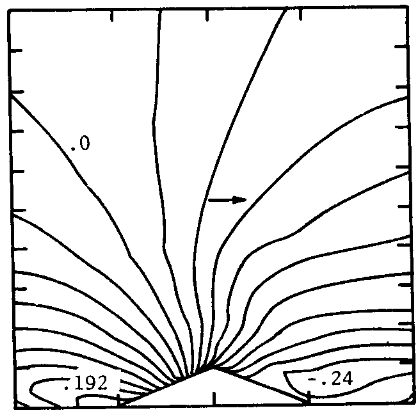
Biological wind prospecting based on the flagging or shape of different species of trees can be used to detect local anomalies in surface winds (17). These methods are dependent on calibration of a given species against known wind fields.

In view of the extreme difficulties in obtaining local wind power estimates over irregular terrain, it is also natural to explore the possibilities of simulating flow over complex terrain by means of physical model experiments on the laboratory scale. Similitude criteria and previous laboratory case studies are reviewed by the writer et al. (11,12). The laboratory method consists of obtaining velocity and turbulence measurements over a scale model of selected terrain placed in a simulated atmospheric flow. The wind characteristics of the simulated atmospheric flow are chosen to reproduce the wind-profile shape and length of the equivalent prototype situation. Since field profiles are rarely available in advance, velocity profiles and turbulence characteristics are chosen to fit an equivalent class of conditions as recorded by earlier investigators over terrain of similar roughness.

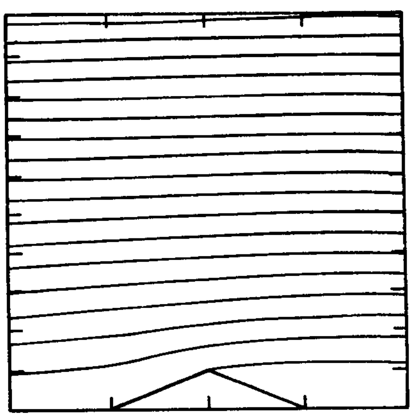
The representative area studied by means of a laboratory model is located along the Rakaia River as it emerges from the Southern Alps, South Island, New Zealand. The primary terrain features consist of the Rakaia River Gorge which runs generally in a northwest-southeast direction. Gorge walls rise 180 m, surrounding hills rise to 460 m. To the south lies the Mount Hutt range which climbs to 2,188 m. The range parallels the course of the Rakaia River in this area. To the north lies the Rugged Range but nearby Fighting Hill and Round Hill are the largest features. A model section 6,100 m wide by 18,300 m long centered over the Rakaia River Gorge was constructed to an undistorted scale of 1:5000.



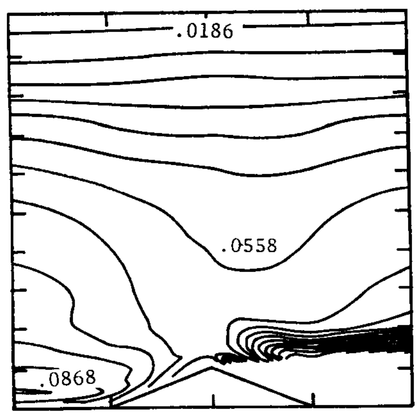
a. Mean longitudinal velocity, $\Delta u/\bar{u}_o$ (δ) = .05



b. Static pressure, ΔC_p = .027



c. Streamlines



d. Longitudinal turbulence intensity, $\Delta u'/\bar{u}_o(\delta)$ = .0062

FIG. 6.—Contours of Flow Characteristics over Triangular Ridge, h/L = 1/2: Test Case 1 (2)

Climatological records obtained from stations somewhat removed from the area suggest moderate to very high wind energy suitable for wind energy conversion system sites. Local farmer and fishermen wisdom and folklore speak of incredible winds in the gorge canyon. Extended field measurement programs

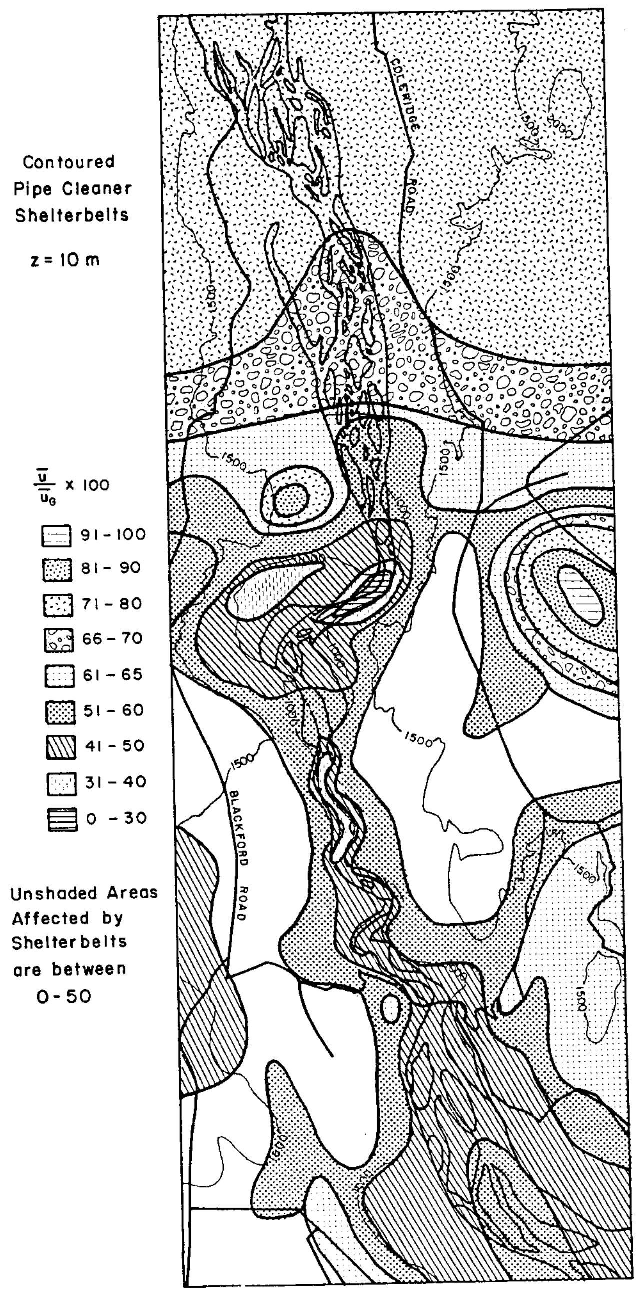


FIG. 7.—Horizontal Isotachs: Contoured Model, Rakaia Gorge, New Zealand (12)

are invariably expensive and time consuming, therefore a survey program was proposed to utilize laboratory simulation of the relevant wind characteristics in a meteorological wind tunnel. To evaluate the validity of laboratory simulation methods and provide a confidence measurement bound for laboratory data, a simultaneous limited field-measurement program was organized.

A series of contour diagrams were prepared from the laboratory velocity and turbulence intensity measurements into isotach and isoturb charts. Horizontal sections prepared for a 10 m equivalent height (Fig. 7) reveals the river valley and gorge consistently has lower wind speed and greater gustiness than the surrounding ridges. The laboratory simulation results were compared with field data by means of statistical correlation and scatter diagrams. The model and field results were used to assess the value of such laboratory experiments for predicting wind over complex terrain.

It would appear that the conventional simulation wisdom developed in the past few years is appropriate for physical modeling of flow over complex terrain. Since the flow region of interest is usually in the lowest surface layer ($z <$ 100 m) for WECS siting, great care must be taken that horizontal inhomogeneities in roughness and terrain are faithfully reproduced. Specific conclusions suggest that:

1. To produce equivalent wind speeds near ground level requires accurate reproduction of surface roughness, shape, and vegetation. Thus terraced models, adequate for certain dispersion simulations, are not appropriate for WECS site analysis.
2. Current meteorological data in complex terrain is not yet adequate to stipulate inflow conditions to either numerical or physical models with confidence. Thus an adequate approach flow length must provide to allow the surface layer to come to an equilibrium with underlying terrain undulations.
3. Physical modeling reproduced the relative wind speeds found over complex terrain by rank to sample correlation coefficient levels equal to 0.78–0.95 (these numbers are somewhat sensitive to the sites chosen to normalize and compare model to field results).
4. Physical modeling reproduced the individual day-to-day quantitative wind speeds found over complex terrain to sample correlation coefficient levels equal to 0.70–0.76.
5. Physical modeling reproduced the two-field day average quantitative wind speeds found over complex terrain to a sample correlation coefficient level equal to 0.81.
6. Physical modeling reproduced the individual day-to-day site wind directions found on complex terrain to sample correlation coefficient levels equal to 0.65–0.67.

Summary

Climatology statistics and simulation techniques are the "pick and shovel" of the modern mountain meteorologist. It is expected that rapid and inexpensive site evaluation procedures will eventually coalesce into methods to aid in the evaluation of such characteristics as air-pollution potential or suitable locations for wind-powered electrical generator systems.

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Appendix II.—Notation

The following symbols are used in this paper:

h = base to peak height of hill or mountain;
L = half width of hill height, i.e., distance from hill peak to location where height is $1/2\ h$;
R = ratio of wind speed at height of 40 m to wind speed at height of 10 m;
u = wind speed;
α = wind speed velocity profile power law exponent; and
SLOPE = vertical hill rise expected in specified horizontal distance.

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KEY WORDS: **Aerodynamic characteristics; Climatology;** Electric power generation; Numerical calculations; Simulation; **Site evaluation;** Site investigation; **Site selection;** Wind forces; **Wind (meteorology); Windmills; Wind power generation;** Wind tunnel models

ABSTRACT: Past experience with power generation by windmills indicates that the most important factor controlling success or failure is site wind characteristics. Incorrect placement on a site sheltered by buildings, terrain or agricultural growth may drop performance to one-third of the original expectations. Conversely, the appropriate hill or ridge shape may amplify power available. Site selection procedures, which are the "pick and shovel" of the modern wind prospector, include statistical climatology, numerical simulation, and physical simulation in meteorological wind tunnels. Laboratory measurements of wind overspeed, streamline patterns, and turbulence changes over idealized topography are compared with "frozen vorticity" numerical models. Field measurement of wind velocity and direction over the Rakaia Gorge region, Southern Alps, New Zealand, compare favorably with wind tunnel measurement over a 1/5000 scale model.

REFERENCE: Meroney, Robert N. (Prof., Fluid Mechanics and Wind Engrg. Program, Colorado State Univ., Fort Collins, Colo. 80523), "Prospecting for Wind: Windmills and Wind Characteristics," *Transportation Engineering Journal,* ASCE, Vol. 107, No. TE4, **Proc. Paper 16386**, July, 1981, pp. 413-426

9. Hills with slopes greater than 1:3 should probably be avoided.
10. Vertical wind speed above a summit does not increase as much with height above ground as over level terrain.

A great deal has been learned about atmospheric flows since the early siting exercises. Research sponsored by the Federal Wind Energy Program has resulted in the preparation of several handbook volumes which attempt to deal systematically with the separate or combined influence of terrain features, surface roughness, buildings, etc. (6,14,17).

National and Regional Wind-Energy Potential

A study comparing, evaluating, and synthesizing three previous independent national assessments of wind-energy potential was reported by Elliot (3). This

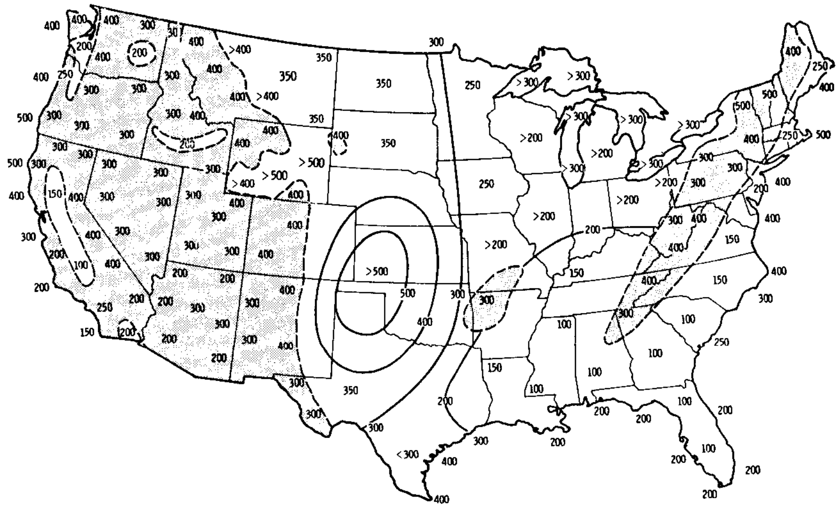

FIG. 1.—Mean Annual Wind Power (*W* per square meter) Estimated at 50 m above Exposed Areas [over Mountainous Regions (Shaded Areas) Estimates are Lower Limits Expected for Exposed Mountain Tops and Ridges (3)

report examined some of the inherent problems with respect to representativeness and reliability of the surface and rawinsondes wind data, techniques employed in the vertical extrapolation of wind power, in the estimation of wind power over mountainous and offshore areas and areas of sparse data, and in the analysis and interpolation of the values. The refined result for mean annual wind power at a typical 50-m hub height above exposed ground over the contiguous United States is shown in Fig. 1. The estimates are considered to be lower limits for exposed sites; however, a few areas may have 50%–100% greater wind power. Since in mountainous areas the estimates are based on the climatology of the winds aloft, some isolated ridges or gaps may provide power a factor of two or three greater. An area where annual mean wind power (w/m^2) exceeds 400 is considered very good.

To meet the need for more detailed analyses over regions below areas of 100 km × 100 km, a series of data-screening techniques have been proposed. Analytical techniques, which involve the use of aerial photography and satellite imagery of eolian geomorphological features, suggest that stabilized eolian features in arid climate areas are reliable indicators of wind patterns (10). About 52% of the 17 western states are susceptible to eolian action.

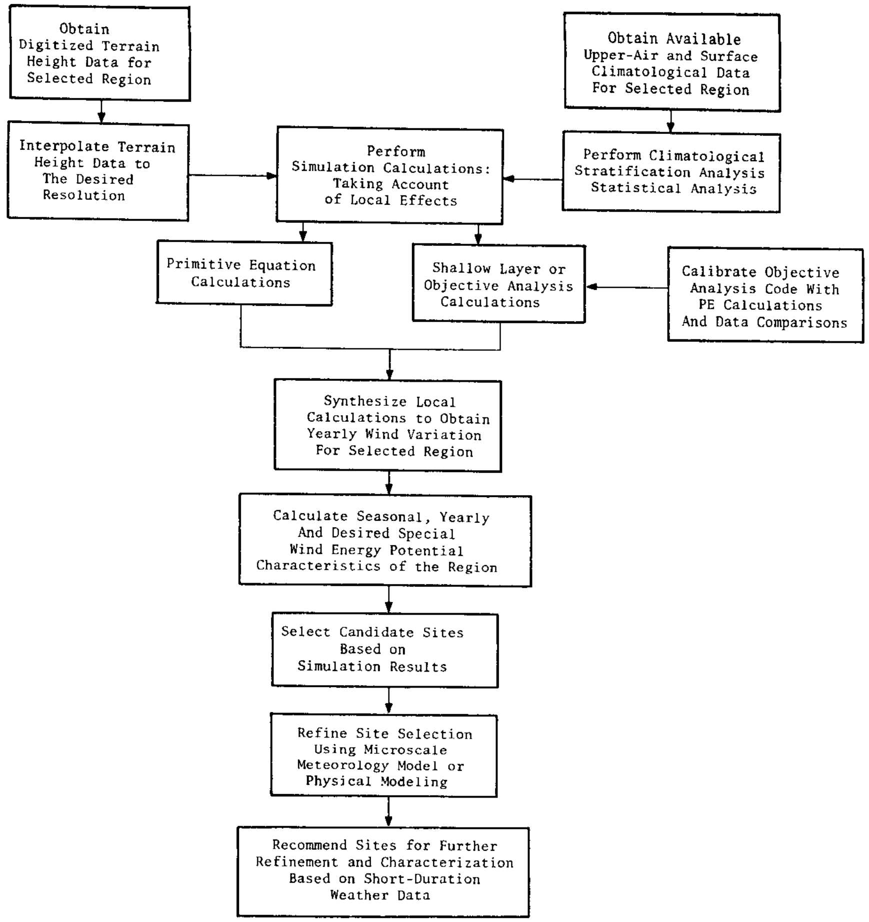

FIG. 2.—WECS Siting Methodology

Joint climatological-numerical screening methods appear suitable for mesoscale area evaluation. These methods employ mathematical models of meso and micrometeorology over coastal or complex terrain to extend clomatological data from meteorological stations where records are available and predict the climatology of sites, within the region of interest, where data are unavailable. A schematic of such a siting methodology is shown in Figure 2.

Three classes of numerical models have been considered for such a methodol-