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WIND-TUNNEL SIMULATION OF THE FLOW OVER HILLS AND COMPLEX TERRAIN

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Summary

A study has been completed to evaluate the accuracy of a wind tunnel investigation of flow over a complex terrain model. Both terraced and contoured models of the Rakaia River Gorge region of New Zealand were prepared to an undistorted geometric scale of 1:5000. The contoured model was examined for three separate surface roughness conditions. On two spring days, selected for strong adiabatic down valley wind flow, three teams of investigators surveyed up to 27 sites on either side and within the river gorge. Measurements consisted of wind speed and direction at a 10 m height.

The laboratory simulation results were compared with the available field data by means of statistical correlation and scatter diagrams. The model and field results have been used to assess the value of laboratory experiments as part of a strategy to develop and demonstrate efficient and economical techniques for identifying favorable wind energy conversion sites.

Notation

H	Shelterbelt height
L_{u_x}	Longitudinal integral scale
r	Sample correlation coefficient
$\bar{u}$	Mean wind speed
u'	RMS velocity fluctuation
$\bar{u}_\delta$ or $\bar{u}_G$	Mean wind speed at gradient or boundary-layer height
x,y,z	Conventional meteorological coordinate system with z upward
z_0	Roughness length
α	Power-law coefficient
δ	Boundary-layer depth

1. Introduction

Information on the general wind characteristics of a geographical region is a prerequisite to considering the utilization of wind power at a site. Climatological data gathered at area weather stations (usually located at flat open terrain near airports) will often provide information concerning wind speed, duration, return time, direction, etc., over a number of years. However, if the area in which wind power installations are to be made includes hilly country, an obvious desire is to choose sites on or near the top of hills or ridges to take advantage of the faster moving stream of air which results from compression of streamlines near the summit. Thus, it is important to be able to correlate wind behavior approaching a terrain feature and the terrain topography with the character of flow at a prospective site.

A review of the history of wind characteristics research prior to 1970 has been prepared by Meroney [1]. Recognition of site selection importance has led to a separate series of monographs and papers on this subject, details of which have been summarized by Meroney et al. [2]. Early efforts to accomplish site selection systematically were hindered by difficulties in determining the undisturbed winds at levels concerned, inadequate computational capacity, and incorrect laboratory simulation of the effects of the atmospheric surface layer and stratification.

Prediction of upper level flows and surface layer behavior over homogeneous terrain has improved substantially in the last twenty-five years [3]. Successful modeling of atmospheric phenomena in a wind tunnel has only been accomplished in the last fifteen years [4]. Many constraints remain which will be discussed in a following section. Computer capacity and numerical algorithms are now capable of reproducing accurately wind overspeed, streamline patterns, and turbulence changes over idealized topography [5—7]; while general flow field behavior can be reproduced over large mesoscale size areas [7,8]. Nevertheless over geographically complex terrain the simple two-dimensional numerical models are inadequate, the more complex numerical models are insufficiently developed and full-scale resource surveys can be prohibitively expensive.

At this time, therefore, a combination of our understanding of the atmospheric surface layer, laboratory simulation, numerical modeling procedures and field studies is necessary since no single method appears capable of providing a complete solution to the problem. Since laboratory simulation has promise of being a versatile and inexpensive tool, the laboratory approach is considered herein as a principal method.

To evaluate the validity of laboratory simulation methods and provide a confidence measure bound for laboratory data, a simultaneous limited field measurement program was organized. Details of these experiments follow.

2. Characteristics of the Rakaia River Gorge region, New Zealand

New Zealand and the United States have a common Wind Energy Conversion System (WECS) siting problem. They are both geographically complex, contain many potentially attractive wind power sites, and yet in many such areas of complex terrain there are “meteorological data” deserts. One such area is the Rakaia River Gorge region on the eastern slope of the Southern Alps in New Zealand. Climatological records obtained from stations somewhat removed from the area suggest moderate to very high wind energy [9]. Local farmer and fisherman wisdom and folklore speak of incredible winds in the gorge canyon. Extended field measurement programs are invariably expensive and time consuming; hence, 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.

2.1 Terrain characteristics

The Rakaia River rises from the main divide of the Southern Alps where it is fed by waters from the Ramsay and Lyell Glaciers as well as runoff from the Arrowsmith, Ragged, and Rolleston Mountain Ranges. These mountain ranges, which form a portion of the central part of the Southern Alps, act as a major barrier both physically and culturally between the West Coast and Canterbury. Rising to 2644 meters at Mt. Whitcombe northwest of the Rakaia Gorge, these mountains play a major part in the local meteorology and terrain appearance.

The mountains drop steeply to the Rakaia River valley floor (~600–900 meters). The river then flows east and south in a broad flat, steep-walled river valley for approximately 65 kilometers before it enters the region south of Lake Coleridge, which precedes the Rakaia Gorge proper. This section of the river lies on a broad flat plateau lying between 300 and 600 m above sea level running in a northwest-southeast direction. The Mt. Hutt Range rises abruptly to 2188 m on the south valley wall. The north side of the river valley is bounded somewhat irregularly by the Big Ben Range and Round Hill, which rise to a maximum of 1657 m and 900 m respectively.

In the 20-km long fetch of the Rakaia River investigated during this study, the river flows southeast from a broad flat plain of 350 m average height. The valley abruptly narrows as it enters the river gorge itself. The gorge walls rise to 460 m and the width varies irregularly from 500 m to 2600 m. The gorge persists for about 8 km in a northwest-southeast orientation.

2.2 Meteorological characteristics

The Rakaia River Gorge lies within a cool wet hill climate with rainfall from 750 mm to 1500 mm. Northwest winds prevail with occasional very strong gales, especially along river courses. The Rakaia Gorge lies within a region noted for 50 to 100 annual days per year of wind gusts reaching 34 knots (17.50 m/sec) or more. Strong winds over 15 knots from the northwest predominate over the Southern Alps while winds at all speeds also show a marked predominance from the same sector [10].

These are no local data available concerning the depth, profile shape, or turbulence character of the atmospheric surface layer in the Rakaia River Gorge region. No results from meteorological towers, balloon soundings, or airplane soundings were found for similar New Zealand topography in available records. Hence the approach flow characteristics selected to model the approach wind profile are based on available experience from other parts of the world [11].

The surface texture in the Rakaia Gorge region consists of an intermesh of sheep paddock (grass ~5—10 cm), shelterbelts (coniferous trees ~10—20 m), gravel covered river bed (stones ~5—10 cm), intermixed with scrub, gulleys, and river escarpments. The riverbed surface and grass paddocks combined with local terrain undulations has a moderately rough texture typical of a roughness length circa $z_0 \simeq 5$ cm. Shelterbelts similar to those observed have been extensively studied on the Canterbury plain by Sturrock [12]. He examined horizontal velocity profiles behind 10 typical Canterbury shelterbelts mainly of medium density varying in height from 8.5 to 19.8 m. When the visual cross section of these shelterbelts were considered it was concluded that the typical Rakaia Gorge shelterbelt has probable permeabilities between 0 and 20%.

In conclusion, the local micrometeorology of the Rakaia Gorge upwind atmospheric surface layer is controlled for high wind speeds by an effective surface roughness of $z_0 \simeq 5$ cm and an array of 20 m tall shelterbelts. These surface features result in values estimated to be: $1/\alpha \simeq 0.11$—0.14, $\sqrt{\overline{u'^2}}/\bar{u} \simeq 0.11$—$0.14$, and $\overline{u'w'}/u_0^2 \simeq 0.0015$—$0.0018$. Boundary layer depth should be $\delta \simeq 600$—1000 m, and longitudinal velocity integral length scale may be $L_{u_x} \simeq 300$—1000 m at $z = 50$ m.

3. Criteria for physical simulation

The basic tool of laboratory simulation is similitude or similarity, defined as a relation between two mechanical (or flow) systems (often referred to as model and prototype)* such that by proportional alterations of the units of length, mass, and time, measured quantities in the one system go identically (or with a constant multiple of each other) into those in the other. In order that the flow in any laboratory model should be of value in interpreting or predicting the observed flow in the atmosphere, it is essential that the two flow systems should be dynamically, thermally and kinematically similar. This means that it must be possible to describe the flow in the two systems by the same equations after appropriate adjustments of the units of length, time and other variables.

A number of authors have derived the governing parameters for atmospheric heat, mass, or momentum transport by dimensional analysis, similarity theory, and inspectional analysis [4,13,14]. Another group justify similitude by considerations of turbulence theory and recent reviews of full scale wind data which present the characteristics of the prototype atmospheric wind on a parametric basis [15—17]. Although all investigators do not agree

*Prototype: actual airflow involving full scale; Model: airflow involving smaller scale than prototype but usually with geometrically similar boundaries.

concerning details, most would concur that the dominant mechanisms can now be identified and are understandable.

The laboratory method thus 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 scales of the equivalent prototype situations. 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 viability of a given simulation scenario is not only a function of the governing flow physics but the availability of a suitable simulation facility and the measurement instrumentation to be employed. It would seem appropriate, therefore, to suggest bounds for the range of field situations which can reasonably be treated by physical modeling. When one combines operational constraints into a performance envelope, a picture appears of the performance region for typical wind tunnel facilities. Figure 1 is such a performance envelope prepared for a large cross-section boundary-layer wind tunnel. Limiting criteria include model size, instrument resolution, scales of simulated turbulence, and minimum acceptable Reynolds number. Assuming an upper value of length scale of 6,000 and a useable tunnel length of 5 m, a distance of 10 km is well within the capacity of existing facilities to contain in the windward direction [2].

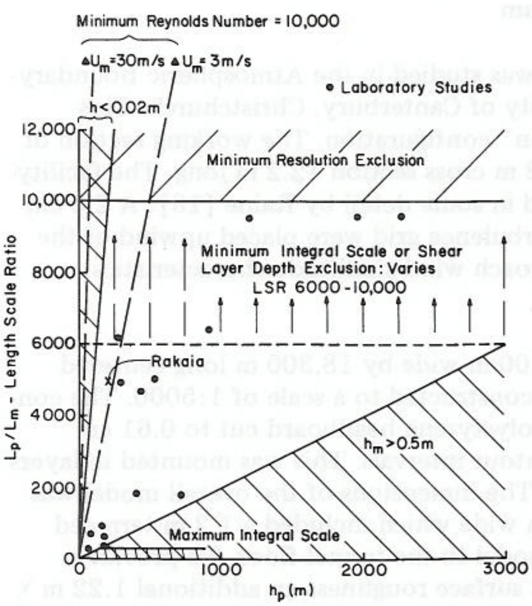

Fig. 1. Performance envelope for physical modeling of shear flows over complex terrain in typical boundary-layer wind tunnel.

The Department of Mechanical Engineering, University of Canterbury, Boundary-Layer Wind Tunnel has a test section 1.22 m × 1.22 m × 12.2 m. Boundary-layer depth and integral scales are controlled by a combination of square rod grids, fences, and surface roughness. An examination of the surface topography and vegetation in the Rakaia River Gorge area and the physical and operational constraints previously discussed suggest the following model simulation criteria:

1. For a modeled region 6 km wide by 18 km long a 1:5000 geometrically undistorted model is required.

2. For a field roughness of $z_0 \simeq 5$ cm a model roughness of $z_0 \simeq 0.01$ mm is necessary.

3. For a region of field shelterbelts $H \simeq 20$ m a model shelterbelt complex $H \simeq 4$ mm is desired. Porosity should range from 0 to 20%.

4. Approach flow velocity profiles should have a power-law coefficient $1/\alpha$ between 0.11—0.14, local surface turbulence intensities $u'/\bar{u}$ between 0.11—0.14, and surface friction coefficients u_*/u_δ between 0.039—0.042.

5. A neutral shear layer whose field depth is 500—1000 meters is probable downwind of a mountain range; thus the model shear-layer depth $\delta = 0.10$—0.20 m. Integral scales in complex flow are expected to range between $L_{u_x} =$ 300 to 1000 m at a height of 100 m over a surface roughness $z_0 \simeq 0.05$ m. Hence a modeled flow should provide $L_{u_x} = 0.06$ to 0.20 m.

Section 4 will discuss the means used to obtain this similitude equivalence and the success therein.

4. Laboratory measurement program

The Rakaia River Gorge model was studied in the Atmospheric Boundary-Layer Wind Tunnel at the University of Canterbury, Christchurch. This facility has an open circuit "suction" configuration. The working section of the wind tunnel is a 1.22 m × 1.22 m cross section 12.2 m long. The facility and its characteristics are described in some detail by Raine [18]. A 2.5 cm high trip fence and a square bar turbulence grid were placed upwind of the model to produce the desired approach wind similitude characteristics.

4.1 Topographic models

A set of models for a section 6100 m wide by 18,300 m long centered over the Rakaia River Gorge were constructed to a scale of 1:5000. The construction material was expanded polystyrene beadboard cut to 0.61 cm thickness to match 100 ft map contour intervals. This was mounted in layers on a particle board support sheet. The dimensions of the overall model was approximately 5 m long by 1.22 m wide which included a 1.2 m terraced section upwind to transition the model to the tunnel floor. To provide a greater upwind fetch of equivalent surface roughness an additional 1.22 m × 2.44 m section of polystyrene beadboard was mounted immediately upwind of the transition subsection. The total model length was thus 7.3 meters (see Fig. 2).

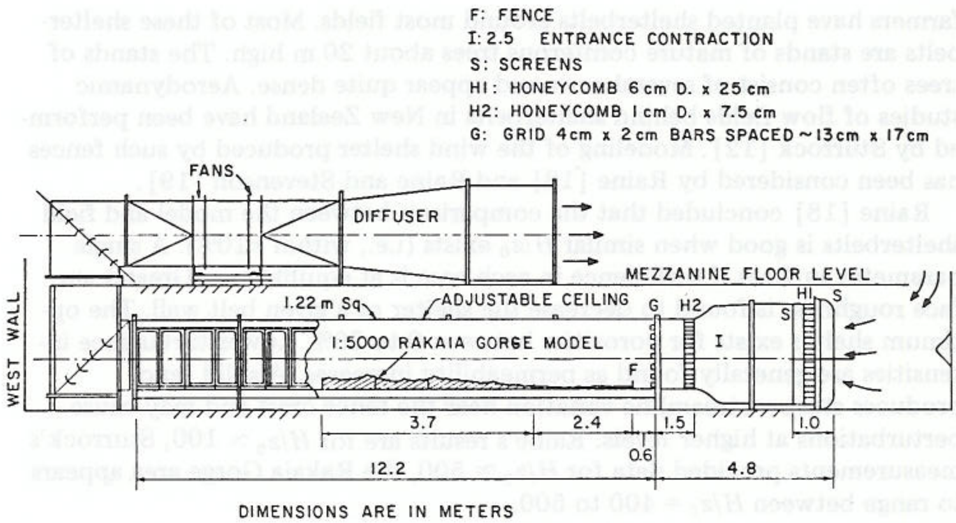

Fig. 2. Boundary-layer wind tunnel — Department of Mechanical Engineering, University of Canterbury.

Terraces resulting from the layers sandwiched together during model construction are often smoothed over with a filler compound, and then roughness is added to the surface to represent the field situation. Since this process appears to remove a roughness and then add it back, many investigators have followed a convenient alternative path which is to leave the model surface terraced. One then assumes separation over the terrace corners provides the drag normally contributed by distributed surface roughness. Whether the alternative terraced model is quantitatively adequate will depend upon the problem examined. A terraced version of the Rakaia River Gorge model was constructed. Contour intervals were at 30 m (100 ft).

A contoured model was prepared from the terraced model after its measurement schedule was completed. Plaster was smoothed between terrace escarpments and was textured to provide an equivalent surface roughness. This surface roughness was such as to provide a $z_0 \simeq 0.01$ mm equivalent to $z_0 = 0.05$ m at full scale. The model was repainted as before.

A series of measurements were made over the smooth contoured model. A second set was made over the contoured model but with shelterbelts modeled with 4 mm diameter wool yarn. Finally a third set of measurements was made over the contoured model but with shelterbelts modeled with 4 mm diameter pipe cleaners. The flow characteristics of the model shelterbelts are discussed in the next section.

4.2 Model shelterbelts

The hillsides to either side of the Rakaia River are primarily devoted to sheep paddock. To protect flocks and paddock surface during high winds, farmers have planted shelterbelts around most fields. Most of these shelterbelts are stands of mature coniferous trees about 20 m high. The stands of trees often consist of several rows and appear quite dense. Aerodynamic studies of flow fields behind shelterbelts in New Zealand have been performed by Sturrock [12]. Modeling of the wind shelter produced by such fences has been considered by Raine [18] and Raine and Stevenson [19].

Raine [18] concluded that the comparison between the model and field shelterbelts is good when similar H/z_0 exists (i.e., within ±10%). A single parameter suffices if turbulence in each case is at equilibrium. Greater surface roughness is found to decrease the shelter of a given belt wall. The optimum shelter exists for porosities between 0 to 20%. Lower turbulence intensities are generally found as permeability increases. A solid fence produces steeper streamline variation near the fence crest and may cause perturbations at higher levels. Raine's results are for $H/z_0 \simeq 100$, Sturrock's measurements provided data for $H/z_0 \simeq 500$, the Rakaia Gorge area appears to range between H/z_0 = 400 to 500.

SYMBOL	z / H	H/z_0	H/L_{u_x}	H/δ	SHELTERBELT
□	2.50	450	0.05	0.04	PIPE CLEANERS
○	1.25	450	0.05	0.04	H ≃ 4mm
△	0.50	450	0.05	0.04	
(horizontal hatching)	0.50	75 → 500	0.17	——	RAINE (1977) (WIND TUNNEL -0%)
(vertical hatching)	0.07 → 0.125	500	0.10 → 0.13	----	STURROCK (1971) (FIELD)

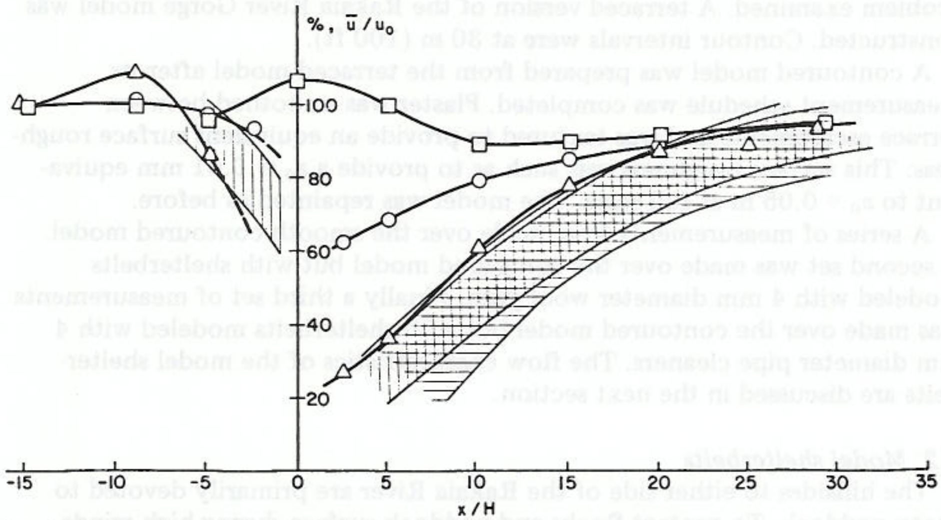

Fig. 3. Comparison of horizontal u/u_0 profiles for pipe cleaner shelterbelts with data in the literature.

A series of velocity and turbulence measurements were made over test shelterbelts 4 mm tall in the simulated boundary layer. These measurements were made at heights $z/H = 0.5, 1.25$, and 2.5 behind a large-aspect-ratio fence perpendicular to the flow. The ratio of winds found with and without the fence present versus location with respect to the fence are plotted in Fig. 3. The yarn appears to behave as a 20% permeable fence, the solid pipe cleaners provide somewhat less shelter. Together the two materials bound

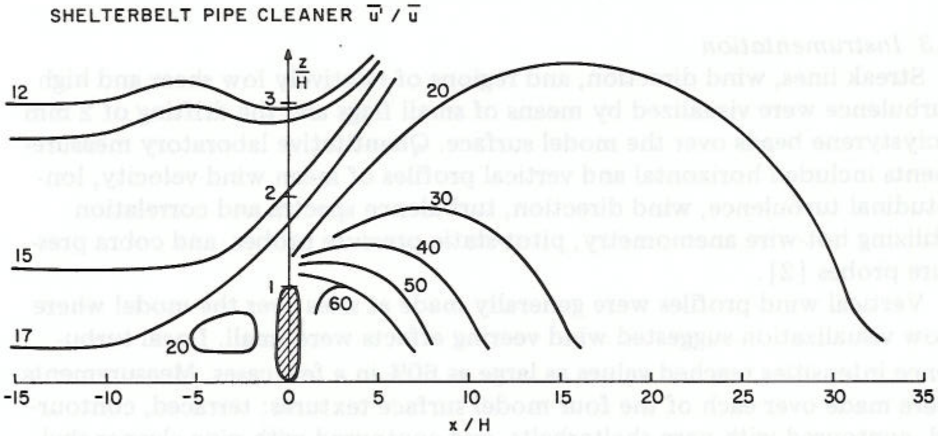

Fig. 4. Isoturbs for pipe cleaner shelterbelts.

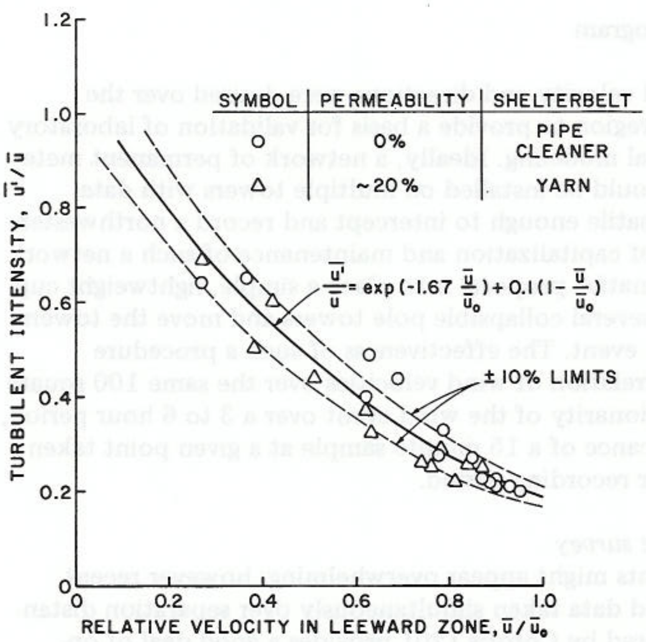

Fig. 5. Correlation of turbulent intensity and relative velocity behind model shelterbelts.

the data provided by Sturrock [12] and Raine [18]. Raine expected shelter to increase as H/z_0 increases; hence it is reasonable that the yarn results lie at the bottom of Raine's measurement on Fig. 3. Isocontours of local turbulence intensity plotted in Fig. 4 agree very well with Raine's measurements. Raine found only a minor effect on $u'/\bar{u}$ distributions versus $\bar{u}/\bar{u}_0$ as the structure of the permeable fence changed. The turbulence intensity results for both the yarn and the pipe cleaner correlate to the same expression suggested by Raine [18] as shown in Fig. 5.

4.3 Instrumentation

Streak lines, wind direction, and regions of relatively low shear and high turbulence were visualized by means of small flags and the drifting of 2 mm polystyrene beads over the model surface. Quantitative laboratory measurements included horizontal and vertical profiles of mean wind velocity, longitudinal turbulence, wind direction, turbulence spectra and correlation utilizing hot-wire anemometry, pitot-static pressure probes, and cobra pressure probes [2].

Vertical wind profiles were generally made at sites over the model where flow visualization suggested wind veering effects were small. Local turbulence intensities reached values as large as 60% in a few cases. Measurements were made over each of the four model surface textures: terraced, contoured, contoured with yarn shelterbelts, and contoured with pipe cleaner shelterbelts.

5. Field measurement program

Measurements of wind velocity and directions were desired over the Rakaia River Gorge test region to provide a basis for validation of laboratory methodology and physical modeling. Ideally, a network of permanent meteorological instruments would be installed on multiple towers with data recording equipment versatile enough to intercept and record a northwesterly wind event. The cost of capitalization and maintenance of such a network was prohibitive. An alternative proposal is to place a simple, lightweight cup anemometer on each of several collapsible pole towers and move the towers frequently during a wind event. The effectiveness of such a procedure depends upon spatial correlation of wind velocities over the same 100 square km region, the quasi-stationarity of the wind event over a 3 to 6 hour period, and the statistical significance of a 15 minute sample at a given point taken once during a 3 to 6 hour recording period.

5.1 Rationale for mobile survey

At first, such constraints might appear overwhelming; however recent statistical analysis of wind data taken simultaneously over separation distances up to 1947 km prepared by Corotis [20] provides a good deal of optimism. The report utilized statistical methods and probability models to determine optimal procedures for survey data. Important conclusions for the purposes of this field study were:

1. At a given site there are only 2 to 4 statistically independent periods during a day. This suggests an autocorrelation time constant from 3.5 to 7 hours. Thus, data taken from the same tower, or a set of towers, erected at a series of nearby stations within a given wind event period may be highly "dependent" or "correlatable" to a character of the wind event.

2. Spatial correlations of wind velocities taken from towers separated by various distances in rolling type terrain revealed that correlation remains as high as 0.7 over a distance of 100 km. This suggests that once anemometers are immersed in wind systems of this scale, or larger, wind patterns and velocities at nested sites must be strongly related. Since field sites within the Rakaia Gorge region were never separated by more than 12 km the behavior of the winds at different sites will be highly correlated at a given time or time lag.

3. Maximum spatial correlation occurred in almost all cases for zero time lag. This suggests that if wind data are available continuously at one site, data taken irregularly at other sites may be normalized by the reference site to a common measurement time.

5.2 Portable and stationary towers and cup anemometers

The criteria for a field station were light weight, rapid erection, and low cost. Three masts were constructed of 5 cm diameter thin-walled aluminum tube. The tubes were made in two 5 m sections which could be connected via a simple sleeve joint. Three nylon rope ties were attached at 7.5 m to the upper section and, when erected, the ties attached to three steel stakes driven at convenient distances from the mast base. The three-cup RIMCO anemometers were attached to the top of the mast by a threaded fitting. A 3-lead supply and signal cable led from the anemometer to a power supply and counter module placed at the base of the mast. The entire system was conveniently light and easy to handle. It could be carried on the luggage rack of a passenger car or in the back of a jet boat. Two or three men could erect the tower in 5 minutes and remove it in somewhat less time (see Fig. 6).

All anemometer cup combinations used were calibrated before and after the field experiments in the University of Canterbury 1.22 × 0.91 meter aerodynamic wind tunnel. Each anemometer calibrated as linear within 1.4% over a wind speed range from 5 to 25 m/sec. The calibration constant variation between anemometers was less than 2%. Calibration change before and after the field experiments was not significant.

Wind directions, air temperature, and air pressure were also monitored at each station as necessary by noting wind compass heading, reading a glass thermometer, or reading a barograph respectively.

The New Zealand Wind Energy Task Force (NZWETF) had erected two 10 m mast measurement sites within the test region. These masts were equipped with pulse counting cup anemometer systems. The count total was

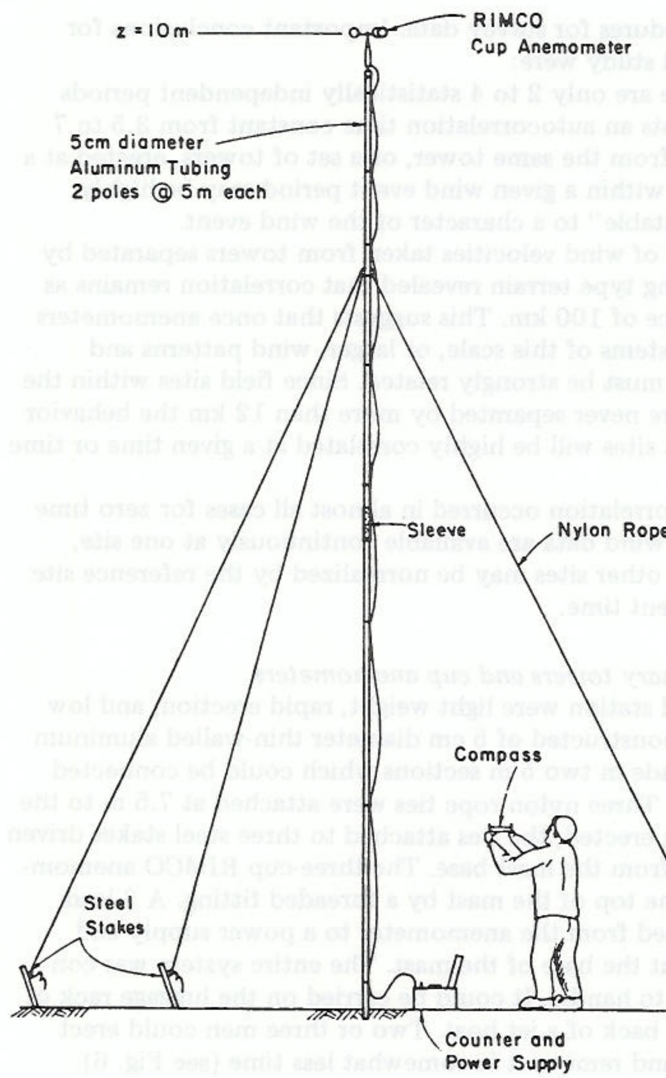

Fig. 6. Portable tower and anemometer, Rakaia River Gorge field experiment.

normally read once each day by local volunteers. During a test period two team members monitored the accumulated counts every 15 min. One team member also monitored air temperature and air pressure at 15 min intervals. Each installation was calibrated against the mobile masts by taking simultaneous measurements while the two masts were separated by distances less than 10 m.

5.3 *Synoptic meteorology on field test dates*

Two days were finally selected to make field measurements: November 25 and December 28, 1977. In each case an extended period of high winds from the northwest were predicted by the New Zealand Meteorological Service based on weather data gathered from Australia, over the Tasman Sea, and satellite weather photographs.

November 25, 1977

On November 24, an anticyclone present to the west of New Zealand was moving east and north. Northerlies and northwesterlies predominated over the west coast areas of the southern island. On November 25 a disturbed southwesterly was expected to move in to cover most of New Zealand; however an early morning forecast suggested that northwesterlies would persist until late afternoon. In the Rakaia Gorge area, moderate northwesterlies existed from early morning until past noon with small variation. After noon a slow drop off in wind speed occurred. At 13:45 wind died. A half hour later southwesterlies appeared over the region. The sky was overcast most of the day.

December 28, 1977

On December 28 an anticyclone existed over the Chatham Islands moving east. It drew after it a strong northerly flow over the Tasman Sea which also moved east. Northerlies predominated over the west coast areas turning to northwesterlies as they passed over the mountains. A ridge of high pressure extended onto the North Island from the southeast. A trough over the Tasman Sea was moving rather slowly eastward. In the Rakaia River Gorge area, strong northwesterlies existed from early morning until late afternoon with little variation. The sky was generally overcast with some rain on the mountain ridges. A large amount of dust was generated by winds blowing over the upwind, graveled, braided riverbed.

6. Wind tunnel test results

6.1 Approach flow field characteristics

The character of the approach shear layer was monitored at a distance 3.3 m downwind of the fence 10.36 m upwind of the first topography. The scales noted are compared against those specified for this locality in Table 1. Spectra measured downwind over the model match the Harris generalized shape quite well [2].

TABLE 1

Approach flow characteristics

Parameter	Specified	Measured approach flow
α	0.14	0.13—0.14
z_0	5 cm	4.5 cm
$\overline{u'}/\bar{u}$	0.14	0.14—0.15
$\overline{u'w'}/\bar{u}_\delta$	0.00197	0.0019
δ	600—1000 m	~500 m
L_{u_x} at 50 m	300—1000 m	~600 m

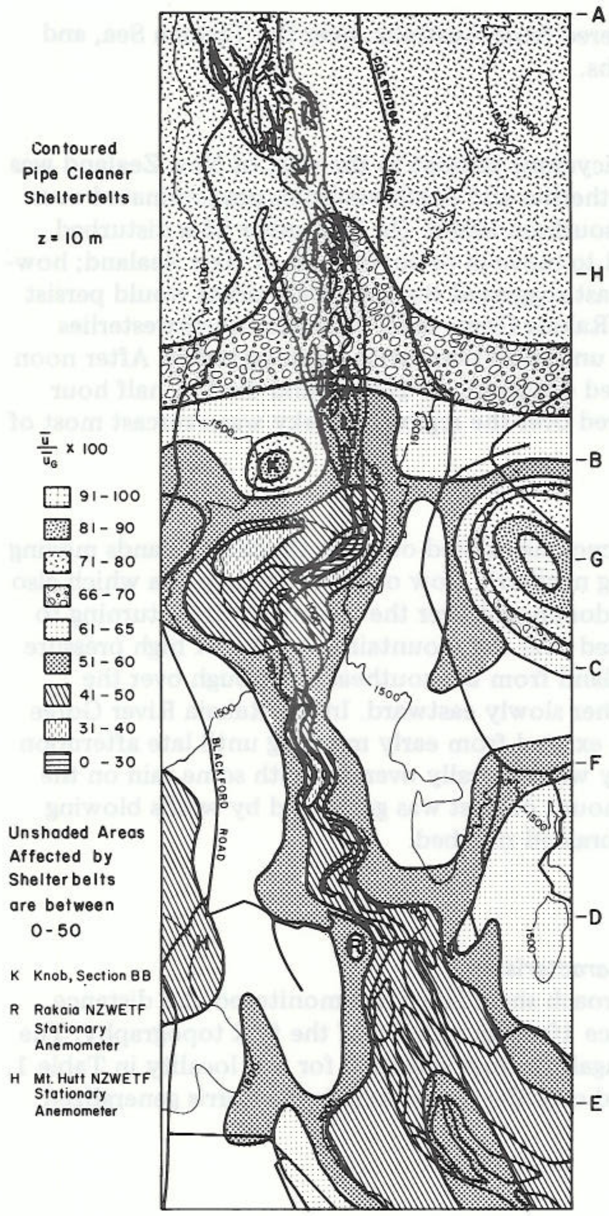

Fig. 7. Horizontal isotachs, contoured model, z_p = 10 m.

6.2 Flow visualization and trajectory results

In general the flags aligned with the contour lines of the topography as shown in Fig. 7. As the river valley narrowed into the river gorge at Section B-B, streamlines were deflected to the south as the ground level flow followed the river bed. There was extensive evidence in flag flapping just upwind of

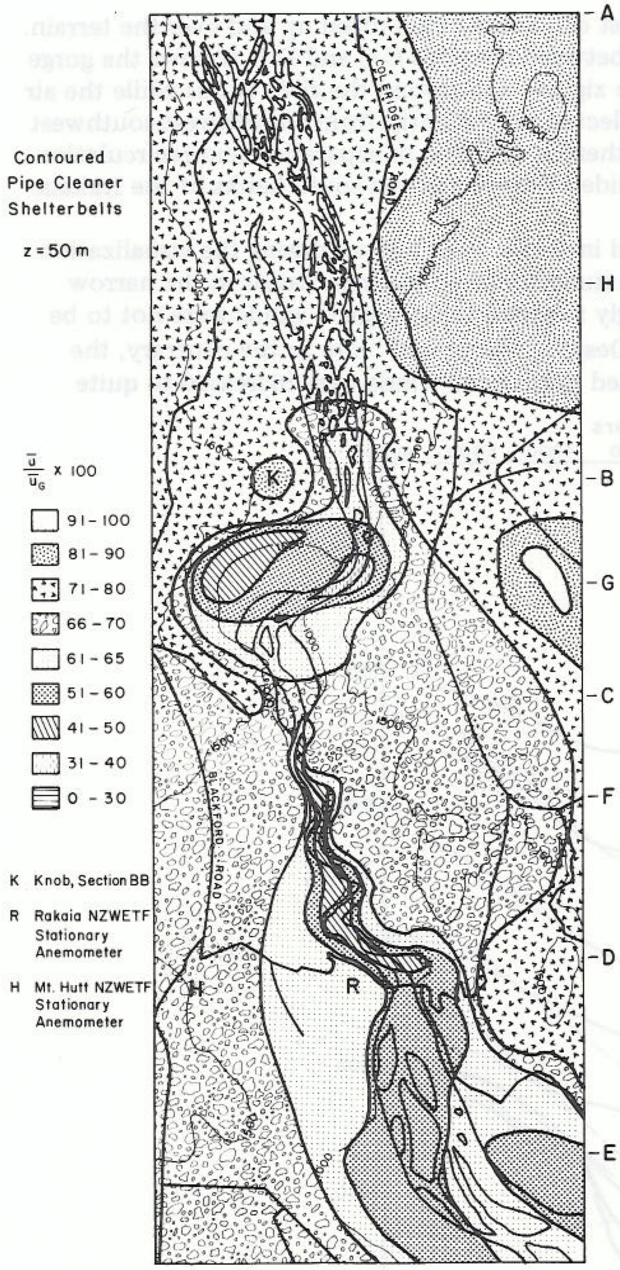

Fig. 8. Horizontal isotachs, contoured model, z_p = 50 m.

the cliffs at the right side of Section G-G or downwind of the ridge on the left of Section G-G of flow separation, recirculation and turbulence. As the gorge narrowed further at Section C-C only a small volume of the fluid entered the gorge while most of the airstream lifted up and over the terrain. Wind along the river gorge between Sections C-C and D-D follows the gorge centerline causing the air to zig and zag around the river bends while the air above the gorge cliffs is deflected only slightly from a northwest-southwest trajectory. At Section E-E there is evidence of separation and recirculation behind the cliffs on either side of the north and south banks of the Rakaia River gorge.

Polystyrene beads drifted into low wind regions during the visualization experiment. The rapid accumulation of polystyrene beads in the narrow sections of the gorge strongly suggested that highest winds were not to be expected in these regions. Despite "fisherman" lore to the contrary, the river gorge retained deposited beads until winds were increased to quite

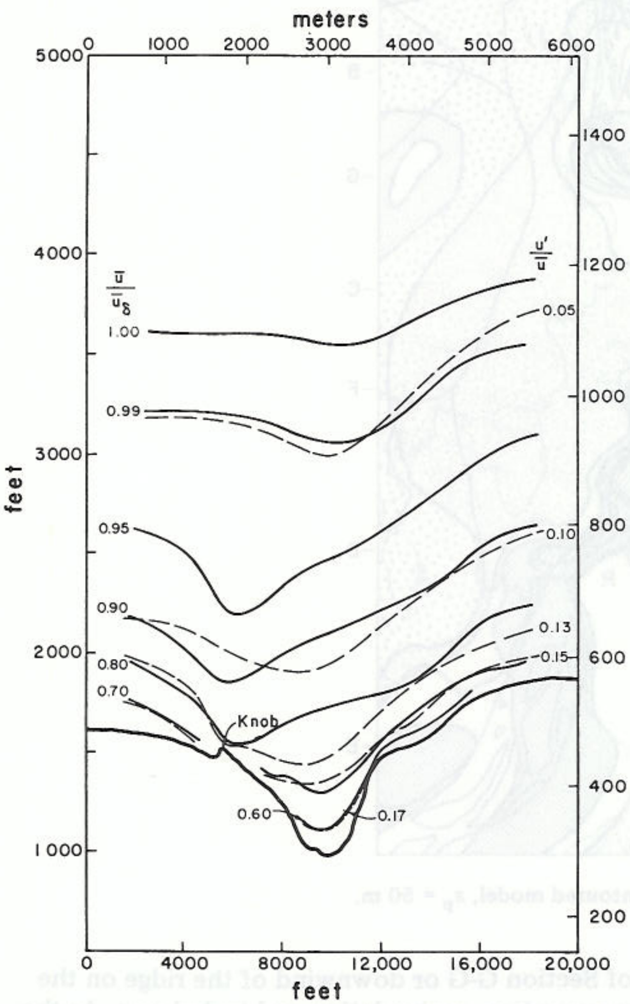

Fig. 9. Vertical section B-B isotachs, contoured model.

large values. Indeed given a large supply of beads the model gorge filled to its upper lip at lowest drift velocities. Beads also collected in separation regions downwind of ridges, hills, and in lateral stream gullies. Individual particles tended to stream along the gorge centerline at all wind speeds. For the terraced model the sharp change in elevation at the ends of each terrace produced a local quiescent area where beads would often catch or accumulate on the rough textured surface.

6.3 *Flow field results*

Vertical traverses of mean velocity and longitudinal turbulent intensity have been measured at seven cross wind sections or 40 stations. Iso-contour lines of the vertical variation of constant velocity or turbulence intensity

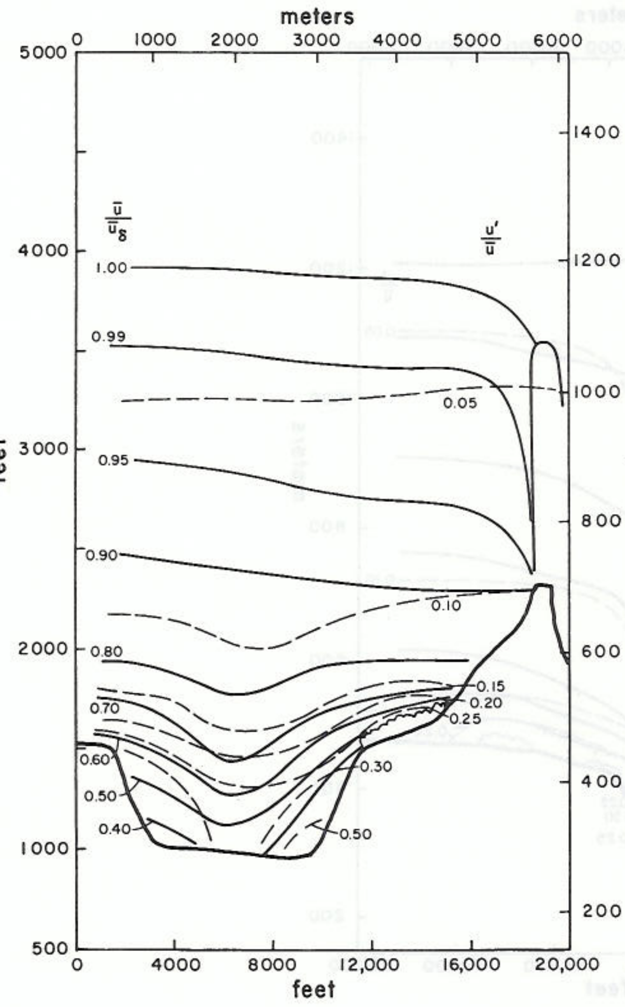

Fig. 10. Vertical section G-G isotachs, contoured model.

have been prepared for each section as typically displayed in Fig. 9 through Fig. 12. Iso-contour lines of the horizontal variation of velocity at 10 m and 50 m above the ground surface are displayed in Figs 7 and 8.

Upwind Section B-B displays the first region where significant perturbations of the uniform approach flow occurs. Velocities at riverbed level decrease while flow over the ridge 1500 m north of the south model boundary increases to a magnitude of 0.80. Local turbulent intensities over the ridge decrease in the same area as velocity increases. Turbulence intensities at gorge level are less than normal; consequently, turbulence increases as the wind moves down the gorge.

In Section G-G the riverbed develops a wide bend downwind of the ridge

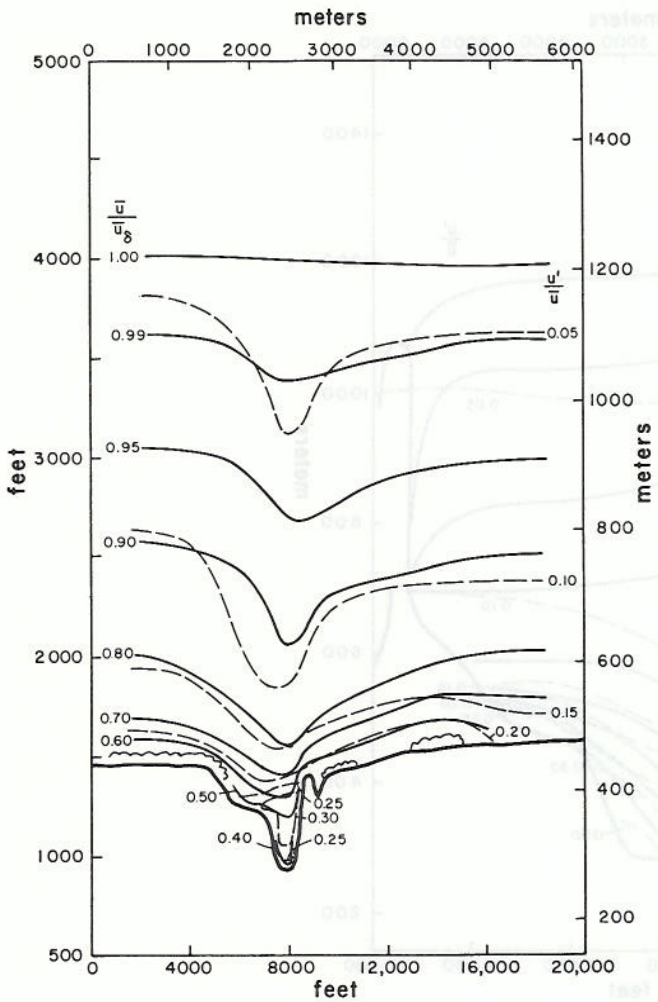

Fig. 11. Vertical section F-F isotachs, contoured model.

observed at Section B-B. In the separated region, winds drop to 20% of the gradient velocity; whereas, turbulent intensity increases to 55% near the ground. On the top of Fighting Hill, wind speedup produced model maximum wind speeds of 99% gradient wind. Locally turbulent intensity falls to a minimum of 10%. This section developed the maximum range of wind conditions observed over the entire model; the values provide a demonstration of the importance and magnitude of terrain resistance as well as enhancement. In a distance of little more than two miles (3 km) the ratio of power available from the wind varies by a ratio of 100 to 1. Thus in complex terrain climatological data from a single station may be clearly inadequate or misrepresentative.

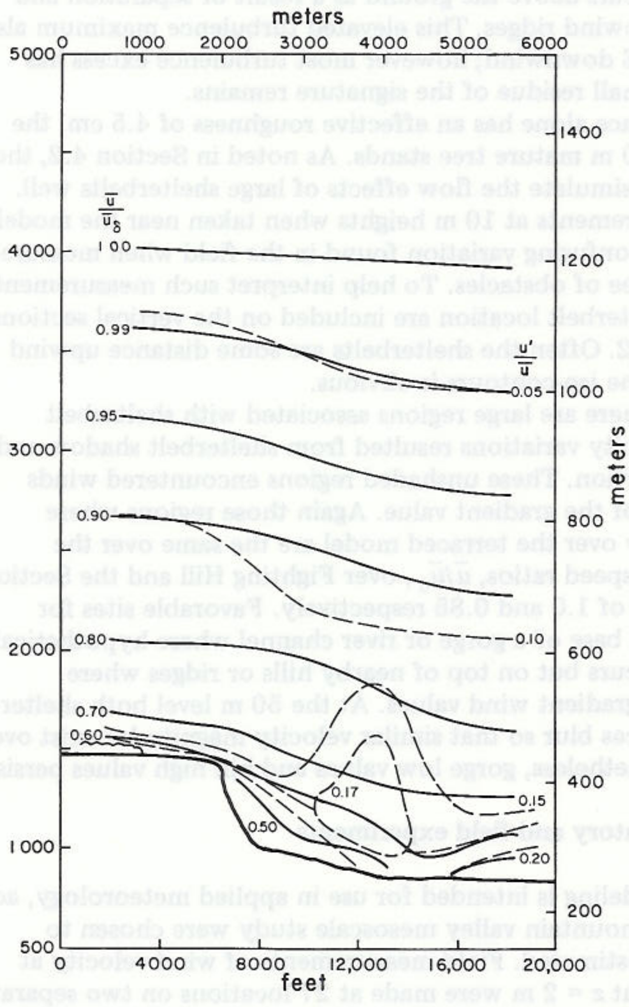

Fig. 12. Vertical section E-E isotachs, contoured model.

Wind accelerates over the flat wide riverbed between Sections G-G and C-C while the turbulence associated with separation over the ridge dissipates. Between Section C-C and Section F-F the river enters the narrowest part of the Rakaia Gorge. Most of the air rises above the gorge; air velocities in the gorge drop to less than 30% while local turbulence intensity rises to 30%. The surface on either side of the gorge becomes relatively flat, sheep pasture only interrupted by occasional shelterbelt. Wind profiles approach shapes typical of homogeneous terrain.

At Section D-D velocity contours are plotted with reference to both the actual terrain shape as well as the model terraced configuration. Although slight variations appear in the iso-contours, there is no significant departure. Downwind of this Section the river broadens into a flat plain. Maximum turbulence intensity occurs above the ground as a result of separation and shear associated with upwind ridges. This elevated turbulence maximum also is evident at Section E-E downwind; however most turbulence excess has dissipated and only a small residue of the signature remains.

While the model surface alone has an effective roughness of 4.5 cm, the shelterbelts represent 20 m mature tree stands. As noted in Section 4.2, the pipe cleaners appear to simulate the flow effects of large shelterbelts well. Indeed, hot-wire measurements at 10 m heights when taken near the model shelterbelts depict the confusing variation found in the field when measurements are made in the lee of obstacles. To help interpret such measurements, sketches of upwind shelterbelt location are included on the vertical sections shown in Figures 9 to 12. Often the shelterbelts are some distance upwind but their influence on the iso-contours is obvious.

At the 10 m height there are large regions associated with shelterbelt effects where local velocity variations resulted from shelterbelt shadow and not topographical distortion. These unshaded regions encountered winds varying from 0 to 50% of the gradient value. Again those regions where velocity was high or low over the terraced model are the same over the contoured model. Windspeed ratios, $\bar{u}/\bar{u}_\delta$, over Fighting Hill and the Section B-B knob exceed values of 1.0 and 0.85 respectively. Favorable sites for windmills are not at the base of a gorge or river channel where hypothetical venturi-like speedup occurs but on top of nearby hills or ridges where velocities approximate gradient wind values. At the 50 m level both shelterbelt and terrain influences blur so that similar velocity magnitudes exist over most of the region. Nonetheless, gorge low values and hill high values persist.

7. Comparison of laboratory and field experiments

Because physical modeling is intended for use in applied meteorology, actual data sets from a a mountain valley mesoscale study were chosen to validate the wind field estimated. Field measurements of wind velocity at z = 10 m and direction at z = 2 m were made at 27 locations on two separate days involving strong northwesterlies over the Southern Alps. These days were one month apart and represented flows caused by completely separate weather systems; hence, results are statistically independent. Laboratory measurements were made at the equivalent points over a 1/5000 scale model, or they were extrapolated horizontally from nearby measurement locations.

A gradient wind speed was estimated by assuming the $\bar{u}/\bar{u}_\delta$ value measured over the model was correct for one of the NZWETF tower sites. Field wind speeds were then converted to velocity ratio by division of the time-corrected portable anemometer reading by the proposed gradient wind speed. Each field data set has been compared separately against measurements made over the terraced model, the contoured model including pipe cleaner shelterbelts, and each other. Correlations and scatter diagrams have been prepared for each case.

Figures 13 and 14 present typical scatter diagrams of field versus model measurements. The sample correlation coefficient, r, between the two field days — November 25 and December 28, 1977 — is 0.68. Since these two days appeared to the authors to have similar boundary conditions, the same

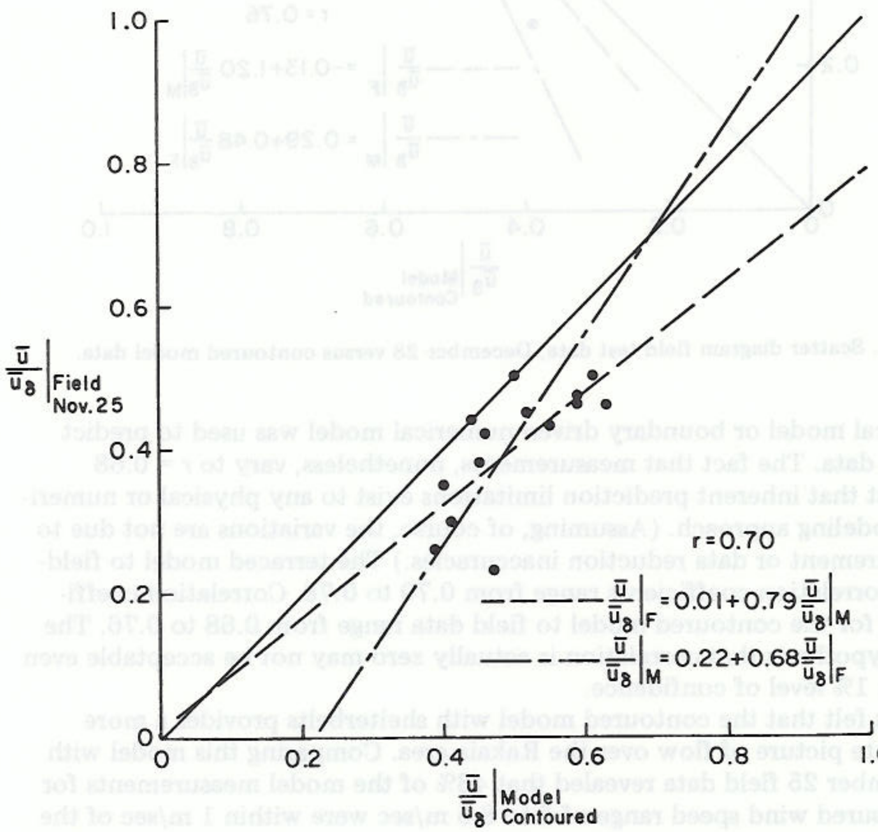

Fig. 13. Scatter diagram field test data, November 25 versus contoured model data.

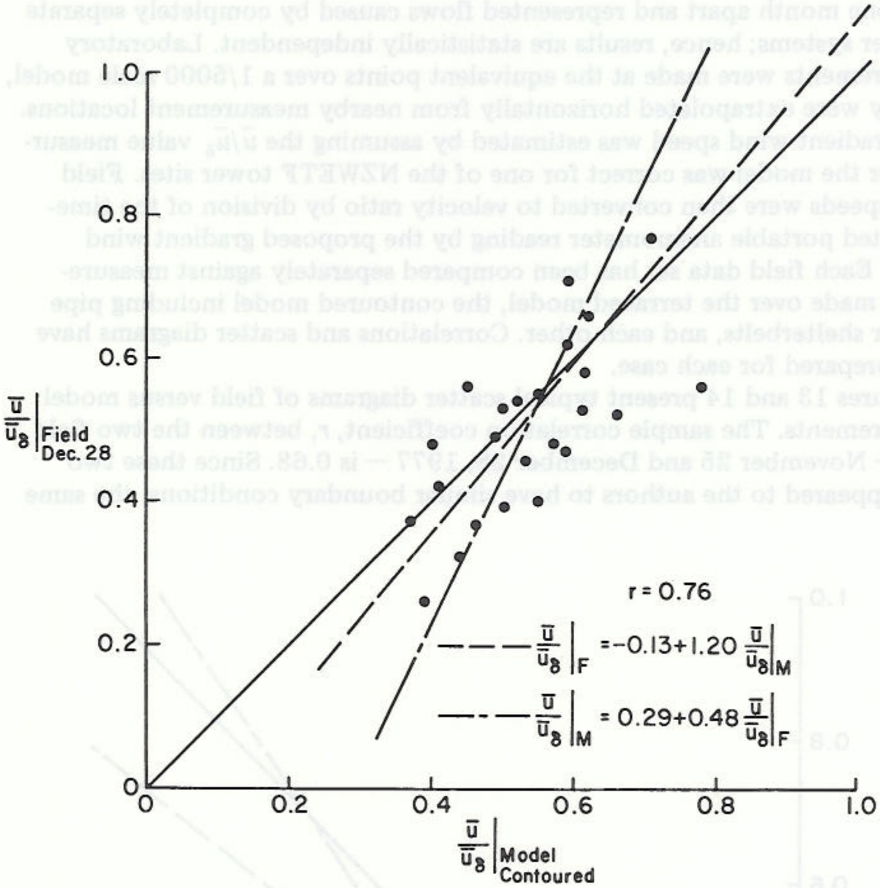

Fig. 14. Scatter diagram field test data, December 28 versus contoured model data.

physical model or boundary driven numerical model was used to predict either data. The fact that measurements, nonetheless, vary to $r = 0.68$ suggest that inherent prediction limitations exist to any physical or numerical modeling approach. (Assuming, of course, the variations are not due to measurement or data reduction inaccuracies.) The terraced model to field-data correlation coefficients range from 0.70 to 0.78. Correlation coefficients for the contoured model to field data range from 0.68 to 0.76. The null hypothesis that correlation is actually zero may not be acceptable even with a 1% level of confidence.

It is felt that the contoured model with shelterbelts provides a more accurate picture of flow over the Rakaia area. Comparing this model with November 25 field data revealed that 43% of the model measurements for a measured wind speed range of 5 to 8.5 m/sec were within 1 m/sec of the field data, and 86% were within 2 m/sec of the field data.

Individual meteorological measurements are frequently characterized by extremes in magnitude about the actual mean as large eddies sweep across the terrain. Such large eddies are not modeled in a boundary-layer wind tunnel. Hence, an alternative way to consider field data to physical model correlations would be to correlate station rank when both sets of data are ordered according to relative wind speed magnitude. Correlation by rank may be calculated by

$$r = 1 - \frac{6 \sum_{i=1}^{n} D_i^2}{n(n^2 - 1)} \tag{1}$$

where $D_i = \text{Rank}_{\text{field station}} - \text{Rank}_{\text{model station}}$.

November 25 data correlated with the contoured model as $r = 0.95$; whereas the December 28 data correlates with the contoured model as $r = 0.78$. This improved correlation is gratifying and suggests that the addition of roughness elements such as shelterbelts may be critical to accurate local simulation.

One prospective role for physical modeling in the array of techniques used for WECS siting would be to rank sites considered as good or not so good. The high correlation found during the rank test discussed above should provide credibility when physical modeling is used to sort WECS sites.

Wind direction at each field site was estimated at eye level by a member of each team using a hand-held compass and the fluctuations of a small flag or the wind pressure variation on the team member's face. This crude wind vane indication has been compared with sketches of miniature wind vane deflection over each model. Correlations are somewhat low, 0.65 to 0.67; however, one may still reject the null hypothesis that $r_{\text{field/model}} \equiv 0.0$.

Again the correlation of wind-speed angles between the two field days is strikingly low, $r = 0.47$. Can the physical model be expected to perform too much better than field data taken at the same sites under apparently identical situations?

8. Conclusions

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 Wind Energy Conversion Systems siting, great care must be taken that horizontal inhomogenuities in roughness and terrain are faithfully reproduced. Specific conclusions suggest that:

1. A wide range of scales and meteorological conditions may reasonably be simulated in existing boundary-layer wind-tunnel facilities.

2. To produce equivalent wind speeds near ground level requires accurate reproduction of surface roughness, shape, and vegetation. Hence terraced

models, adequate for certain dispersion simulations, are not appropriate for Wind Energy Conversion Systems site analysis.

3. Current meteorological data in complex terrain is not yet adequate to stipulate inflow conditions to either numerical or physical models with confidence. Hence an adequate approach flow model length must be provided to allow the surface layer to come to an equilibrium with underlying terrain undulations.

4. Physical modeling can reproduce wind patterns produced by the atmospheric shear layer flowing over complex terrain to within the inherent variability of the atmosphere to produce stationary results.

5. Physical modeling reproduced the relative wind speeds found over complex terrain by rank to sample correlation coefficient levels equal to 0.78 to 0.95*.

6. Physical modeling reproduced the individual day to day quantitative wind speeds found over complex terrain to sample correlation coefficient levels equal to 0.70 to 0.76.

7. 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.

8. Physical modeling reproduced the individual day to day site wind directions found on complex terrain to sample correlation coefficient levels equal to 0.65 to 0.67.

9. Adequate physical modeling of adiabatic shear flow over complex terrain requires attention to surface roughness, terrain shape, and vegetation as well as upstream velocity profile, turbulence intensity, and turbulence eddy structures.

10. Over complex terrain local wind speeds may vary by over 100% in a distance of a few hundred meters as a result of terrain shadowing, flow separation, or flow enhancement.

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*These numbers are somewhat sensitive to the sites chosen to normalize and compare model to field results.

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