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THE SITING OF WIND TURBINES.

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Town in partial fulfilment for the
degree of Master of Science in
Engineering.

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ABSTRACT

In September 1984, Guy Roberts completed a report on the cost of wind energy in South Africa. His results showed that wind energy in South Africa was uneconomical, but they suggest that at locations with higher wind speeds, the cost of wind power would approach the South African grid electricity cost.

Knowing that locations with high annual average wind speeds would make the most suitable wind turbine sites, it was decided to investigate the wind enhancement, due to localized topography in such areas. Existing available wind data, together with previous studies on the South African wind energy potential suggested that the site worthy of investigation was in the vicinity of Cape Agulhas.

A number of methods of ascertaining the wind potential over a given region were considered for investigating the area of interest. The two readily available techniques, physical and numerical modeling, were chosen to investigate the topographical wind enhancement. Previous work done on the siting of wind turbines using physical modeling was investigated prior to proceeding with the construction of and experimentation with a scale model. The utilization of two modeling techniques enabled the direct comparison of results.

By running the two modeling techniques, for the same site, in parallel with one another, initial results were compared to ascertain the direction further experimentation should take. These results compared favourably, both suggesting a maximum wind enhancement of approximately ten percent with respect to the Weather Bureau's records at the Cape Agulhas lighthouse. Further experimentation showed that the point of maximum wind enhancement was on the top of a hill as opposed to in a valley where wind enhancement was initially anticipated. This result was due to the

valley not being constricted enough to enhance the airflow which is then enhanced by the surrounding hills. Results showed that wind speeds close to ground level are affected by minor changes in topography but that as the height above ground level increases this dependency decreases.

The environmental impact that wind turbines pose on the surrounding environment was investigated for internationally operational wind energy conversion sites. These are discussed in detail, and reference is made to the possible impact turbines may pose on the area investigated.

The area at Cape Agulhas can be classified as an area of high wind energy potential. From the nature of the wind speed curve and from an environmental aspect this area could be labeled as one of the most suitable locations for wind energy conversion systems in South Africa.

GLOSSARY / NOMENCLATURE

A	Area	[m ²]
a.g.l.	Above ground level	
anemometer	An instrument that measures the speed of the wind	
a.s.l.	Above sea level	
α	Dimensionless exponent used in the vertical extrapolation of wind speeds.	
b	Turbine blade chord length	[m]
d	Diameter of area swept by a wind turbine	
dB(A)	Decibels, (average). Unit of noise level measurement	
ENE	A wind which blows from the compass direction east of north-east.	
ESE	A wind which blows from the compass direction east of south-east.	
F	Force	[N]
Hz	Hertz. Unit of frequency measurement	[cycles/second]
Isopleths	A line on a map connecting points at which a given variable has a specified constant value.	
K.E.	Kinetic energy	
ln	The natural log	
m	Mass	[kg]
Manometer	Instrument to measure pressure difference. This instrument can be calibrated to produce values for velocity	
n	Number of turbine blades	
P	Power	[kW]
ρ	Density	[kg/m ³]
S	Rotor speed	[revolutions per minute]
U	Relative velocity between turbine blade and wind speed at 70% span	
V	Velocity	[ms ⁻¹]
WECS	Wind Energy Conversion Systems	
Wind rose	A method of representing wind-speed graphically also showing its direction.	

WNW A wind which blows from the compass direction west of north-west.

w.r.t With respect to.

WSW A wind which blows from the compass direction west of south-west.

CHAPTER ONE

1. BACKGROUND TO WIND ENERGY

1.1 CLASSIFICATION OF WIND ENERGY

Wind energy is one of the oldest forms of energy used by mankind. The earliest known wind machines date back to the ancient Persian wind mills in 200 B.C. which were used for grinding grain^(1,4,5,6). The main focus of today's "windmills" is on machines where the millstone has been replaced by an electrical generator and the sails by a complex aerofoil. These modern day "windmills", designed for power generation are often referred to as wind energy conversion systems or simply WECS. Today, energy from the wind is being investigated as one of the many renewable energy forms which can be classified as shown in Figure 1.1.

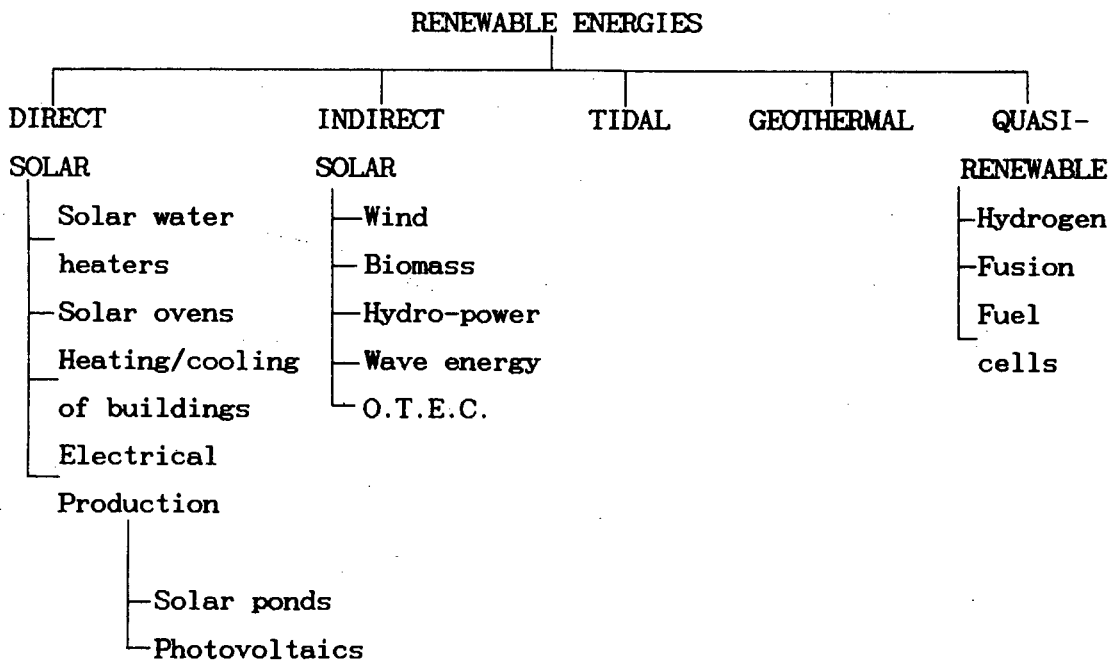


FIGURE 1.1. RENEWABLE ENERGY BREAK-DOWN

1.2. ORIGIN OF THE WIND

Winds, defined by their direction and speed, are the motion of air particles about the earth's surface due to the uneven heating of the earth by the sun and the movement of the earth. During the day part of the sun's energy is absorbed by the land but a larger proportion is reflected, heating the atmosphere. The air over the oceans and lakes remains relatively cool since a large percentage of the sun's energy is consumed in evaporating water or absorbed by the water itself. The warmer air over the land expands, becoming lighter and rises allowing the heavier cooler air over bodies of water to move in and displace it. At night these breezes are reversed since the land cools at a faster rate than the water. The cool land air then blows towards the sea replacing the warm air which rises from the water surfaces. Similar local breezes are generated in the valleys and on mountainsides as the warmer air rises from the heated slopes (see Figure 1.2.).

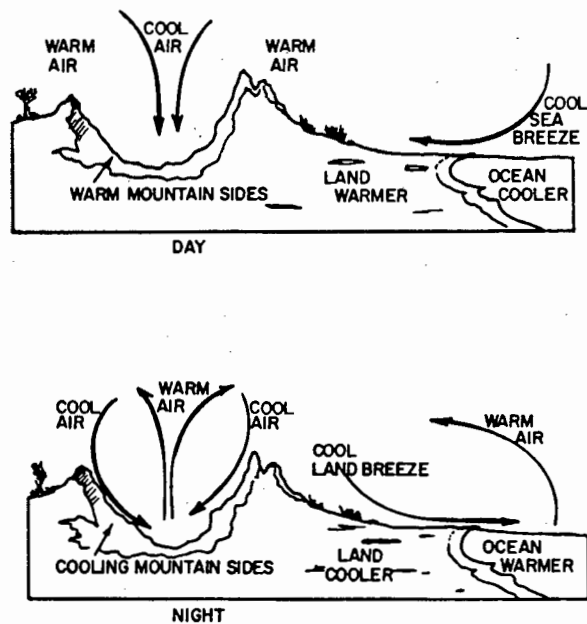


FIGURE 1.2. LAND - SEA BREEZES

On a much larger scale, large circulating planetary winds are generated by the greater heating of the earth's surface near the equator than at the poles. The hot air from the tropical regions rises and moves in the upper atmosphere towards the poles, while cool surface winds, from the poles, blow towards the equator as shown in Figure 1.3.

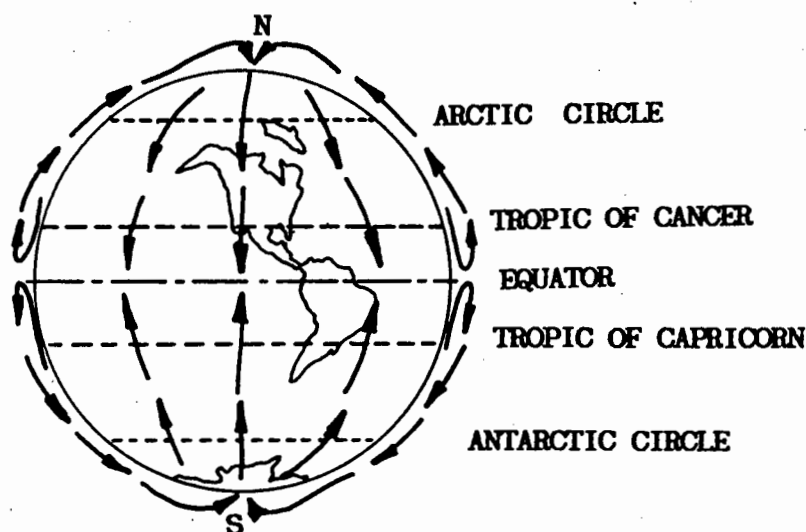


FIGURE 1.3. DIRECTION OF IDEAL PLANETARY WINDS

The earth's rotation and its movement around the sun also influence these planetary winds. The inertia of the cold air moving near the surface, towards the equator, tends to twist it to the west, while the warm air in the upper atmosphere, moving towards the poles, tends to move eastward. This results in a large counter-clockwise circulation of the air around low pressure areas in the northern hemisphere and a clockwise circulation in the southern hemisphere. Since the earth's axis of rotation is inclined at $23,5^\circ$ to the plane in which it moves around the sun, seasonal variations in the heat received from the sun result in seasonal changes in the strength and direction of the winds at any given location on the earth's surface (see Figure 1.4). It has been estimated that the total power capacity of the winds surrounding the earth is of the order of 10^{11} GW (2, 4, 6).

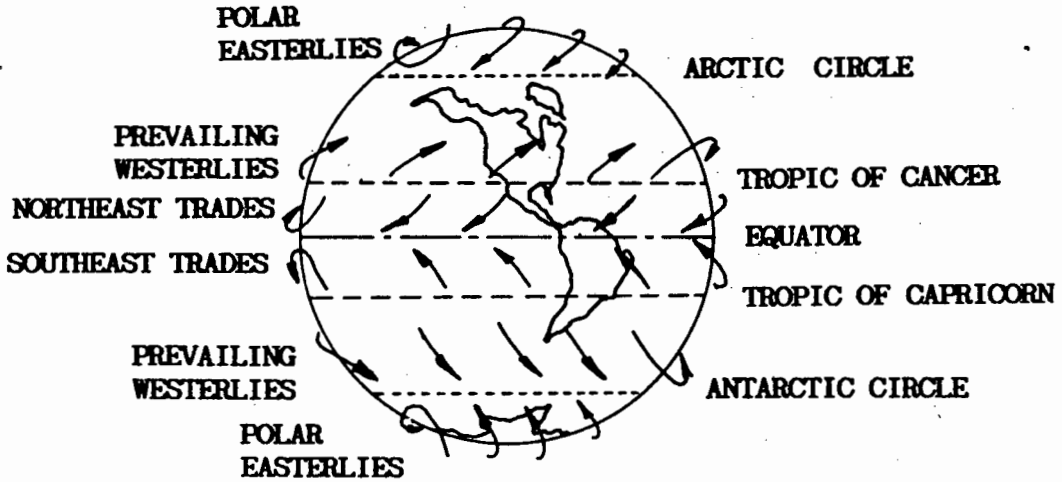


FIGURE 1.4. DIRECTION OF THE PLANETARY WINDS

1.3. ENERGY IN THE WIND

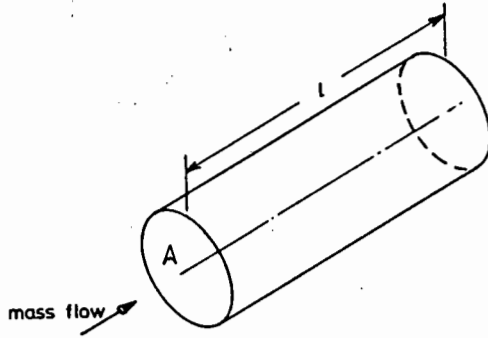
Energy exists in the wind as the kinetic energy of the moving air particles. The kinetic energy of a moving particle is defined as:

$$\text{K.E.} = \frac{1}{2} m v^2 \quad \dots\dots\dots(\text{equ.1})$$

where: m = mass (kg)

v = velocity (ms^{-1})

By considering an area, A , (see Figure 1.5.) perpendicular to the wind direction it is clear that a mass $\rho v A$ will pass through this area each second.



$$m = \rho v A \dots\dots\dots(\text{equ.2})$$

FIGURE 1.5. MOVEMENT OF AIR MASS

The kinetic energy of the moving air mass can thus be defined as:

$$\begin{aligned} \text{K.E. / unit time} &= \frac{1}{2} m v^2 \\ &= \frac{1}{2} \rho v A v^2 \\ &= \frac{1}{2} \rho A v^3 \dots\dots\dots(\text{equ.3}) \end{aligned}$$

But K.E. /unit time = Power

$$\therefore \text{Power} = \frac{1}{2} \rho A v^3$$

$$\begin{aligned} \&\text{ Power density} &= P \div A \\ &= \frac{1}{2} \rho v^3 \dots\dots\dots(\text{equ.4}) \end{aligned}$$

From the equations above it can be seen clearly that wind energy is proportional to the square of the wind velocity and the power is proportional to the cube of the prevailing wind speed. This relationship between the power density of the wind and the wind speed is of vital importance when siting wind turbines, for a marginal increase in the wind speed will give a significant increase in the available power. It follows from the power density equation above that the two possible methods of maximizing the available power from the wind are:

1. To site a wind turbine at a site having the highest annual mean wind speed.
2. To increase the cross-sectional area swept by a wind turbine's rotor.

This relationship is shown graphically in Figure 1.6. It also follows from equation 4 that for a mean wind speed of 7 ms^{-1} the energy density of the wind is 206 W/m^2 which is comparable with the energy value of solar flux falling on a horizontal surface, (see Figure 1.7.).

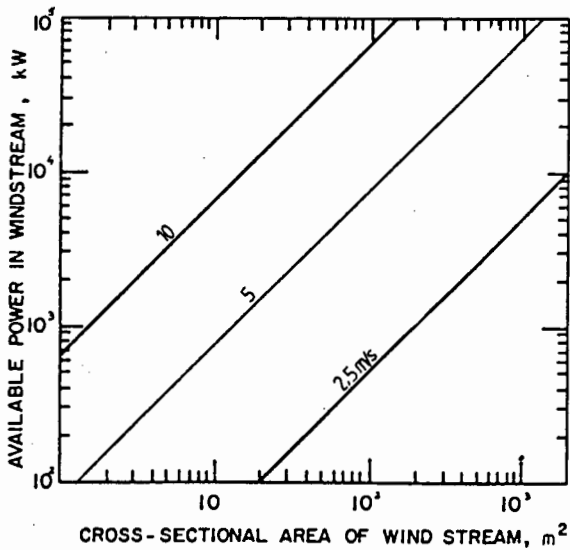


FIGURE 1.6. AVAILABLE WIND POWER

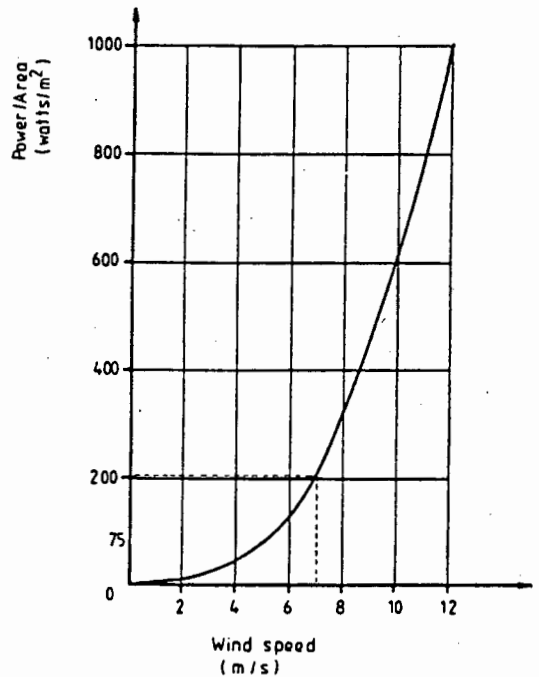


FIGURE 1.7. WIND POWER DENSITY

It is however not possible to extract all the kinetic energy available in the wind for if this was the case the wind behind the turbine would stop moving, having no kinetic energy, and would pile up behind the wind turbine. The relationship concerning the maximum theoretical power extractable from the wind was established by A. Betz of the Institute of Gottingen⁽⁸⁾. Betz assumes that the wind

rotor is ideal i.e. it has no hub and has an infinite number of blades which offer no resistance drag to the flow of air through it. This implies that the turbine's rotor is a pure energy converter. Betz also assumed that the whole area swept by the rotor is uniform and the direction of the air through and beyond the rotor, flows perpendicular to the swept area of the turbine blades. It can be shown (see Appendix 1.1) that the maximum extractable power is only 59,3 percent of the theoretical power in the wind and it is this value that is known as the Betz limit.

It should however be noted that the theory for the derivation of this value depends on simplifying assumptions, and thus could in principle even be exceeded. Other studies on the theoretical maximum extractable wind power have shown that due to the depression effect behind the rotor, a mass of air is drawn into a vortex from the surrounding air flow with a consequent increase of momentum and power. These theories suggest a theoretical maximum power of 68,7 percent rather than 59,3 percent. These theoretical limitations on extractable power do not take into account aerodynamic losses and mechanical and electrical conversion efficiencies associated with wind power extraction. Horizontal axis wind turbines have a maximum overall power coefficient in the range of 0,42 to 0,48 while for vertical axis machines this value lies between 0,15 and 0,35⁽¹⁰⁾.

1.4. EFFECT OF TOPOGRAPHICAL FEATURES ON WINDSPEED

The siting of a wind turbine in flat terrain with uniform surface roughness represents the simplest type of terrain for a WECS site. In a large flat area of uniform terrain with no obstacles (buildings, hills, trees) the wind speed at a given height is more or less constant over the whole area. The only way to increase the available power in such areas is to raise the turbine higher above the ground. Barriers or obstacles should be avoided as they produce disturbed areas of airflow downwind, called wakes, in which the

windspeed is reduced and the turbulence increased. These wakes should be avoided in order to maximize available power and to minimize turbulence which has adverse effects on a wind turbine's blades.

The flow of air over ridges with gentle gradients (15 - 30%) and low smooth hills (<200m) is often enhanced to give a maximum value at the peak of the hill.^(2,4,5,24) Some of the approaching air will flow over the ridge or hill while the balance will flow around it at either end. The distribution of the approaching airstream will depend on how much work is required to deflect a quantity of air vertically over the hill or ridge as opposed to the work required to deflect it horizontally around the hill or ridge. It is for this reason that winds would be enhanced to a maximum if the ridge were oriented perpendicular to the prevailing wind direction as shown in Figure 1.8. It is also for this reason that winds may not be enhanced by totally isolated hills.

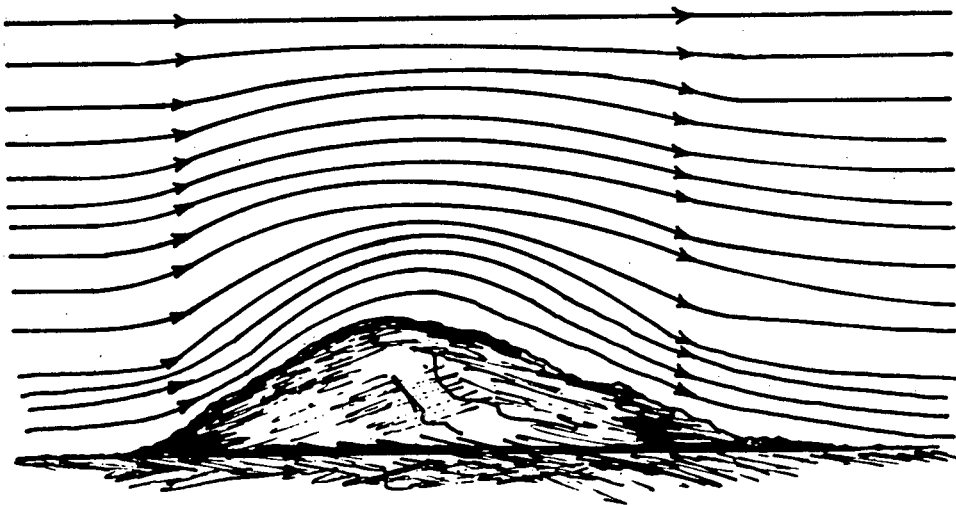


FIGURE 1.8. WIND FLOW OVER A RIDGE/HILL.

It has also been found that winds are rarely enhanced at the summits of mountains (>800m) but frequently have velocities, lower than the prevailing wind speed, here.^(2,5,24) The wind power available at the summit of a mountain does however depend on the shape and

alignment of the mountain and the height of the surrounding terrain as much as it depends on the height of the mountain itself. Saddles and passes, which are low spots in mountain barriers, are often known to have wind speeds greater than the prevailing wind speed. This occurs because they are flanked by much higher terrain which causes the air to be funneled as it is forced through the pass.

The enhancement of winds by valleys or canyons is predominantly dependent on the orientation of the valley with respect to the prevailing wind direction. To obtain a funneling effect of the winds through a valley it is necessary for the valley to lie in the same direction as the approaching wind. It has also been found that unless the valley is constricted at some point, the surrounding ridges would probably provide greater enhancement than the floor of the valley.⁽⁶⁾

Information on the effect that such terrain types have on the prevailing winds has been obtained predominantly from the American experience in wind turbine siting. However, since the siting of wind turbines in hilly terrain requires careful consideration if the performance of the installation is to be optimized, much work has subsequently been done in trying to establish analytical solutions to the flow over various hill shapes.

The task of trying to establish speed-up factors due to typical hill shapes is not an easy one. Putnam⁽²⁴⁾, in 1948, wrote that after five years work on the problem of site selection, no analogy could be found between the profiles of mountains and the profiles of aerofoils by which mean wind velocities at hub height could be predicted. This view has been shared by others and Davidson even suggests that it is almost impossible to estimate a numerical value for a speed-up factor if such a value even exists for any particular site.⁽²³⁾ Meroney et al state that it would be unfortunate if work on speed-up due to topography were abandoned for the energy advantages are significant even if the prediction was within 25 percent. Several laboratories are however using meteorological wind

tunnels to evaluate the wind characteristics of different sites. Laboratory work is done on both site specific models of proposed WECS sites^(30,33,34) to establish the point of greatest enhancement and on idealised hill shapes^(25,35-38) to establish general solutions to the speed-up over various hill shapes.

Wind tunnel investigations performed to investigate the topographical enhancement of wind speeds have been completed for various terrain types. There are generally four different terrain classifications which are categorised by Meroney et al⁽³⁷⁾ as:

- a) Variation of wind speed over uniform terrain,
- b) Local wind circulations,
- c) Flow over slight or moderate relief, and
- d) Flow over high mountains.

The first category is well documented and generally well understood. Much has been learned about local wind circulations, caused by changes in roughness, temperature or pressure, which can enhance winds significantly but are not usually reported in national wind surveys. Experience with work done on wind flow over low to medium hills or ridges has shown the following:⁽²³⁾

1. Ridges should be athwart the principal wind direction, but high velocities are not likely on upwind foothills.
2. Hilltops 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 a 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), where h =height of ridge and L = half width of ridge.
7. Topographical features in the vicinity of the hill produce the structure of the flow over it.

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

The results from wind tunnel experimentation are also used to validate numerical and analytical models which in turn can then also be used for predicting wind enhancement due to topographical features.

1.5. VERTICAL EXTRAPOLATION OF WIND SPEEDS

The increase in wind speed with height above ground level is a well known occurrence. There are many factors which influence the variation in wind speed above the ground, such as terrain roughness, atmospheric stability and prevailing wind speed. Close to ground level, reductions in wind speed are primarily a result of surface friction generated by vegetation, buildings and other obstacles. Since frictional forces decrease with elevation, the wind velocity will increase as one ascends through the atmosphere.

As shown above, the estimation of available wind power is critically dependant on the wind velocity thus it would be meaningless to predict the output of a large wind turbine using wind velocities measured at, say 10m . Also, there is a lack of wind speed data taken at heights above 10m and therefore extrapolation procedures must be relied upon to predict wind velocities at various heights. The models and procedures developed for the vertical extrapolation of wind speeds need to take into account terrain roughness and thermal stratification. Both of these factors are, however, subject to a great deal of spatial and temporal variation. For this reason these influencing factors can only be approximated in extrapolation procedures. Because of these approximations it is not feasible to use these extrapolation techniques to extrapolate instantaneous wind speeds vertically, though they do yield good results for the average wind speeds.

The simplest and most frequently used extrapolation procedure is Hellmann's exponential law for determining the vertical profile of the mean wind speed^(3,4,5). This law is also better known as the power law relationship. The relationship between velocity and height is expressed as:

$$V_2 / V_1 = [h_2 / h_1]^\alpha \quad \dots\dots\dots(\text{equ.5})$$

where: V_1 = mean velocity at height of measurement
 V_2 = mean velocity at desired height
 h_1 = height of measurement
 h_2 = height of interest
 α = dimensionless exponent dependent on surface roughness and atmospheric stability

Generally for coastal regions the value of α is taken as 0,143 or 1/7. It has however been argued that an average value for α should be taken as 0,23. Although the exact value of this exponent is uncertain and varies from site to site, it is common practice in the field of wind power estimation to take α as 1/7. Since the vertical velocity profile of wind flow over the earth's surface is primarily dependent on the frictional forces generated by the earth's surface, the value of the exponent α is sometimes taken as a value dependent on the surface roughness. Values sometimes used are⁽¹⁾:

TERRAIN TYPE	α
Smooth (sea, snow, sand)	0,10 - 0,13
Moderately rough (short grass, grass crops, rural areas)	0,13 - 0,20
Rough (woods, suburbs)	0,20 - 0,27
Very rough	0,27 - 0,40

By obtaining a value for the surface roughness of an area and a relationship between the surface roughness and the exponent α , the

power law relation can be expressed in a way in which it would be dependent on the surface roughness.

Another extrapolation procedure which is sometimes used is the logarithmic velocity profile. This relationship is normally expressed as:

$$\frac{V_2}{V_1} = \frac{\ln (h_2 / Z_0)}{\ln (h_1 / Z_0)} \dots\dots\dots(\text{equ.6})$$

where: V_1, V_2, h_1, h_2 , have the same meaning as above
and Z_0 = the surface roughness length

Le Gourieres⁽¹⁾ suggests that this log-law yields the best fit for the 30m - 50m height range but throughout the boundary layer height the power law is more accurate. De Renzo⁽²⁾ suggests that the logarithmic profile is suitable for neutral stability conditions and high wind speeds. De Renzo does however also use the power law relation for wind assessment, but the value of the exponent α is either taken as 0,2 or 1/7. Jarass et el⁽³⁾ represent only the power law extrapolation procedure, saying it is the best known and simplest method to use. They go on to say that an exponent of 1/7 is generally applied to coastal regions and that for forested or hilly regions inland an exponent of 0,2 to 0,3 is often used. Cheremisinoff⁽⁴⁾ gives only the power law relationship for vertical extrapolation but suggests an exponent of 0,23. Hunt⁽⁵⁾ and Dunn⁽⁶⁾ also only present the power law relation but don't specify any distinct values for the exponent α .

Roberts⁽⁷⁾, Diab⁽⁸⁾ and Dutkiewicz⁽¹¹⁾ all suggest that while the 1/7th power law may not yield precise results, it does predict a conservative estimate of the vertical velocity profile of a wind regime. Roberts⁽⁷⁾ and Dutkiewicz⁽¹¹⁾ both use an exponent of 1/7 to extrapolate wind speeds in order to estimate wind power production costs. Diab⁽¹²⁾ also used the power law relation with an exponent of 0,14 (1/7) in normalizing wind speeds, recorded throughout South Africa, to 10m in order to assess the wind energy potential over

South Africa^(9,12). Diab used this extrapolation technique in the absence of wind profile or stability measurements since it was shown to be the most suitable for a relatively smooth site and it yielded conservative yet realistic estimates⁽¹²⁾. Van Wijk et al⁽⁹⁾ suggest an improved scaling method to predict wind speeds at heights greater than 10m. Their method is based on the logarithmic wind profile extrapolation method and utilizes stability correction factors. According to tests performed in the Netherlands they claim that by using this improved method and by keeping the capacity factor of the wind turbine constant, the turbine would produce as much as 20% and 48% more energy at 40m and 80m respectively. This extrapolation method is however complicated and while it may hold true for the tested site it may not be valid for others. If it does hold true for other sites it will not necessarily predict energy increases as high as those predicted above.

From the foregoing discussion it is clear that no extrapolation technique will yield the correct profile under all circumstances but it is evident that the 1/7th power law is generally the most suitable and most universally used procedure. It is for these reasons that this extrapolation procedure will be used in this study.

CHAPTER TWO

2. WIND ENERGY POTENTIAL IN SOUTH AFRICA

A number of reports addressing the subject of wind energy potential in South Africa have already been completed^(7, 8, 12, 13, 14). These reports cover various aspects of the wind energy potential but together form a useful base for further studies on the utilisation of wind for power generation.

The work by Roberts⁽⁷⁾ entitled "The Cost of Wind Energy in South Africa", focused on the cost of wind generated electricity at nine sites in South Africa (see Appendix 2.1). The criterion for the choice of sites in his work was that each site was to have first order weather station data available for the wind speed characteristics. The wind data available from first order weather stations is taken every hour, by an anemometer, as opposed to every six hours at second order stations which sometimes use the Beaufort scale for wind speed measurements. The Beaufort scale, (see Appendix 2.2.), is used for predicting wind speeds by examining conditions of certain features on land and at sea under the influence of the prevailing wind. While the readings taken by a lighthouse keeper, for example, may not give the absolute value of the wind speed there is normally a good correlation between all the readings. The wind speed values taken using the Beaufort scale are also normally checked against a set of anemometer readings, taken over the same period, and the necessary corrections made if required. The criterion used by Roberts in his study did not therefore necessarily include the windiest sites in South Africa but included those sites having the most reliable wind data.

The utilisation of wind data collected by the Weather Bureau for the purpose of analysing potential sites for wind turbine installations is sometimes questioned. The Weather Bureau's weather stations are sited at places where their weather data is required for some goal

other than that of siting wind turbines. In most instances in South Africa the first order weather stations are sited at airports, collecting weather data to facilitate safe aviation. Airports are, however, often located in areas having low prevailing wind speeds. If the wind data collected from these weather stations is used for siting wind turbines it can give misleading results. The D.F. Malan Airport in Cape Town, for instance, is sited in an area which is situated in a regional high pressure cell^(7,22). Consequently in this region the winds are not fully affected by the local sea breezes, resulting in lower prevailing winds than those experienced within close proximity to the airport. On the other hand, however, in order to get a reasonably accurate wind speed curve over time it is important to use the data having a short log period, the log period being the time between two consecutive wind speed recordings.

It is advisable to have values with a short log period because of the cubic relation between the wind speed and the available power in the wind. Wind does not blow steadily at an average value between any two recorded values, but fluctuates continuously. The cube root of the mean of a series of cubed terms is greater than the mean of the series. For example, the cube root of the mean of the cubes of the series 2, 3, 4 is 3,21 while the mean of the series is 3. The ratio of $3,21/3$ is called the cube factor and is always greater than one. If the wind blew, for equal periods, at say 2ms^{-1} , 3ms^{-1} and 4ms^{-1} and the total period was averaged by one reading, the energy of the wind would be based on a mean wind speed of 3ms^{-1} . However, if three readings were taken, the energy density would effectively be based on a wind speed of $3,21\text{ms}^{-1}$. It is therefore likely that wind data collected with long log periods will tend to underestimate the available power in the wind, assuming there is an equal chance for the wind to either increase or to decrease during logged values.

Roberts calculated the cost of wind generated electricity based on the mean wind speeds shown in Appendix 2.1. These wind speeds were extrapolated to the wind turbine's hub height using the 1/7th power

law and the power output of each site calculated by fitting the turbine's power curve to the wind speed curve. By matching the wind speed curve to the turbine's power curve, wind velocities lower than that of the turbine's cut-in velocity are ignored. Similarly, if the turbine has a cut-out velocity, wind speeds greater than this cut-out velocity are also ignored. By performing this task a value for the turbine's extractable power is obtained as opposed to a value for the theoretical maximum extractable power. The results of Roberts' costing exercise are shown in Appendix 2.3. These results are based on an exchange rate of R1,20 = U.S. \$1, an installation cost of 10% of the purchase price, an annual maintenance cost of 3% of the purchase price, a capital charge rate of 12% and an economic life of 25 years. It is clear from these results that the higher the mean wind speed, the lower the resulting unit cost of wind generated electricity.

TABLE 2.1. THE COST OF WIND GENERATED ELECTRICITY AT NINE SITES

WIND TURBINE STATION	WIND SPEED (ms ⁻¹)	ENERGY COST (cents/kW-hr)
Port Elizabeth	4.4	15.6
Alexander Bay	4.3	16.0
Cape Town	4.3	16.3
East London	4.3	18.9
Durban	3.2	23.6
Kimberley	3.0	37.6
Johannesburg	3.0	47.2
Pietersburg	2.4	56.8
Pretoria	1.5	423.9

Roberts also investigated the effect on the cost of wind power under theoretical wind enhancements. The theoretically enhanced wind speeds and their corresponding generation costs, for Cape Town, are

shown in Table 2.2. These results clearly show that for wind generated electricity to become a more viable alternative method of power generation in South Africa, sites having higher wind speeds are required.

There is a definite relation between the winds over South Africa and the physical configuration of the subcontinent^(11,12,15-20). South Africa consists primarily of a high plateau rising in all directions from about 1 000m in the centre (the Kalahari region) to a general level of about 1 200m and culminating in the Great Escarpment, which in the Drakensberg region rises to over 3 000 meters. The Great Escarpment falls abruptly to its base which lies between 100 to 200 kilometers from the coast. The prevailing winds at the coast blow approximately along the direction of the coast, eg. N and S at Cape Town, WSW and E at Port Elizabeth, SW and NE at East London and SSW and NNE at Durban. The costal winds are generally much stronger than the winds occurring inland.

TABLE 2.2. THE EFFECT OF WIND ENHANCEMENT ON THE COST OF WIND GENERATED POWER FOR CAPE TOWN

INCREASE IN WIND SPEED	MEAN WIND SPEED (ms^{-1})	ENERGY COST (CENTS/kW.hr)			
		DVI15-3	WTS-75	WINDANE 29	WINDANE 9
0%	4,3	22,3	20,9	25,0	16,3
10%	4,7	17,9	17,5	20,4	13,7
20%	5,2	15,1	15,3	17,3	11,9
30%	5,6	13,5	14,0	15,2	10,6
40%	6,0	12,6	13,3	13,7	9,6
50%	6,5	11,8	12,7	12,6	8,8
60%	6,9	11,5	12,5	11,9	8,3
70%	7,3	11,3	12,4	11,3	7,8

From Diab's work⁽¹²⁾, (see Appendix 2.4 and 2.5), it is clear that the sites used by Roberts in his study are not the windiest in South

Africa. The areas in South Africa quoted as having the highest wind speeds are Cape Point, Cape Agulhas and Cape St. Francis. Diab suggests that prime stations in terms of potential wind turbine development are Cape Agulhas and Cape Point. This was based on both the monthly and yearly average wind speeds at various sites. While Cape Point has the highest annual mean wind speed of $9,7 \text{ ms}^{-1}$ it is not an ideal location for the siting of wind turbines since it is a nature reserve and a place of natural scenic beauty and severe opposition would be encountered if plans were made to establish a WECS site in this area (this is discussed in more more detail in chapter 7).

On examining the daily wind speed duration curves for various sites compiled by the Weather Bureau, it was noted that the winds at Cape Agulhas were not only higher in comparison with other sites, but they were very constant over time (see Figure 2.1.).

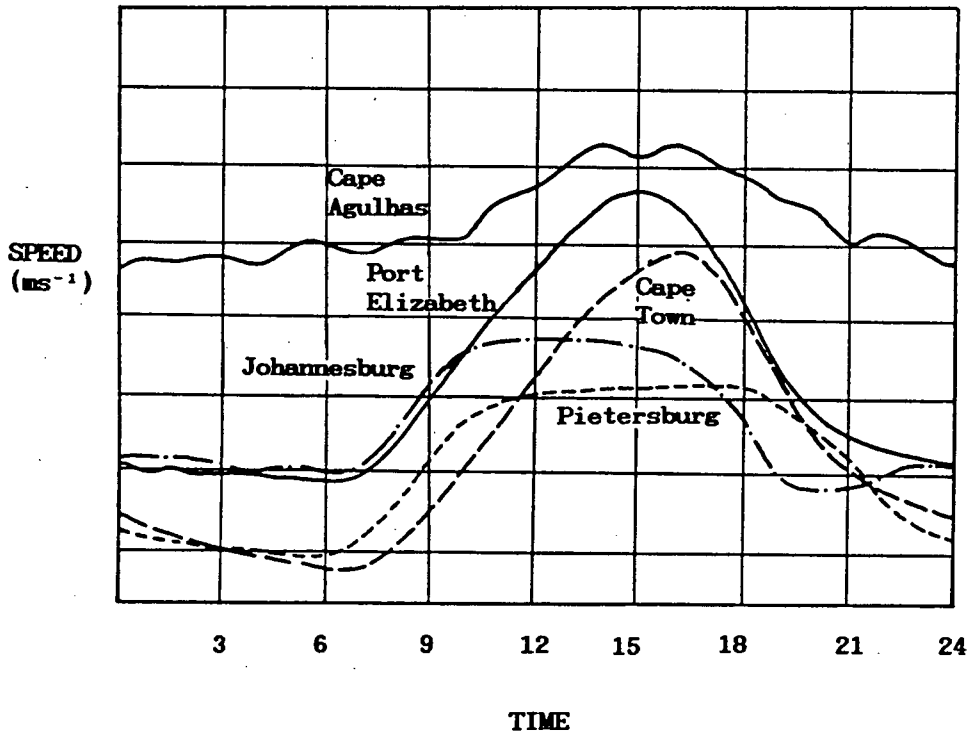


FIGURE 2.1. WIND SPEED DURATION CURVES FOR VARIOUS LOCATIONS

(Source: Ref 17)

The nature of the wind speed curve at Cape Agulhas makes it very suitable for wind generation as it would be possible to match a turbine's operating curve to the wind speed duration curve in such a way as to utilize a much higher percentage of the winds than would be possible at other sites. The combination of this high utilisation percentage and the high prevailing average wind speed means that the generating capacity of the winds at Cape Agulhas are significantly higher than at all the sites used in Roberts' study.

From Diab and the Weather Bureau's wind speed values, Cape Agulhas has a mean prevailing wind speed approximately 50 percent higher than that at Cape Town (based on the wind speed measurements recorded at the weather station). If, however, it was possible to find a location in the vicinity of Cape Agulhas which had a mean wind speed greater than that recorded by the Weather Bureau it would be possible to establish a realistic figure for wind enhancement due to the topography in this area. Furthermore it would also be possible to calculate the cost of wind power in a windy environment under a true figure for wind enhancement. This cost would then give a more realistic value for the cost of wind power in South Africa.

CHAPTER THREE

3. SITE ASSESSMENT TECHNIQUES

Experience with wind turbines has indicated that the single most important factor controlling the success or failure of these systems is site selection. The incorrect siting of a wind generator by only a few kilometers may drop the performance to one-fifth of the original expectations.⁽²⁴⁾ In one of the rows of wind turbines operating at Altamont Pass, Central California, the energy production drops by almost 40 percent between turbines, 300m apart and with an altitude difference of 53m.⁽⁴⁰⁾

The difference between the available power in an average annual wind speed of 14.4km/h (4ms^{-1}) and 18km/h (5ms^{-1}) is one hundred percent. Once a wind generation system is designed to operate optimally at a lower wind speed, mechanical, aerodynamic and generating efficiencies may only allow a linear increase in power at higher average annual velocities.⁽²⁴⁾ This linear increase will not allow full exploitation of the available wind resource. Since this siting aspect is of such vital importance, it becomes necessary to assess the wind energy potential of large areas before making estimates on the cost and the feasibility of wind power generation at a particular site.

Anemometers and wind vanes can only record the wind speed and direction at a fixed point. These recorded values are useful in predicting a wind turbine's power output, if a wind turbine were to be sited in close proximity to the anemometer. The wind speed values recorded by an anemometer would enable the calculation of the wind energy potential in the areas surrounding the anemometer but not at some distance from it. In order to assess the wind potential of the surrounding areas, one of a number of available techniques can be used. These techniques can be classified as follows:

1. Ecological Surveys

2. Wind Measurement
3. Mathematical Modelling
4. Physical Modelling

3.1 ECOLOGICAL SURVEYS

The technique of using ecological surveys to predict wind speeds is based on either the examination of eolian landforms or on the deformation of vegetation. Relationships between eolian landforms have been investigated in order to assess the wind potential over a given area, by examining satellite images and wind speed data. Types of eolian landforms examined include sand dunes and playa lakes (blowouts). The characteristics of these landforms can be studied from satellite imagery e.g. LANDSAT and aerial photographs taken over a number of years. Particular features of these eolian landforms are used to describe the characteristics of local winds. (25)

The other technique used in ecological surveys is to examine the deformation and direction of growth of various plant and tree types. (14, 24, 26, 30) It has been shown that surveys done on the quantification of tree deformation are extremely sensitive. Each species and each habitat has some minimum critical value of mean wind speed, below which deformation will not occur. It also appears that certain types of trees are the best indicators of wind speed in certain areas and that occasional, very severe storms do not deform these trees. A project in New England showed that in the 16km/h (4.4ms^{-1}) wind speed range between 27km/h (7.6ms^{-1}) and 43km/h (12ms^{-1}) it was possible to easily recognise five types of tree deformation. (24) Although the absolute value of wind speed for each category is uncertain, it was believed that these deformation classes could be used to:

1. relate sites in order of merit.
2. indicate which sites are of submarginal economic interest.

3. provide direct estimates of the long term mean annual velocity. (The degree of uncertainty associated with this velocity was unknown but it was suggested that it could be in the order of ± 20 percent.⁽²⁴⁾)

Hewson et al ⁽²⁰⁾ have developed five different indices of wind effects on trees and these are calibrated in terms of various wind characteristics. Each index provides an easily obtainable, non-dimensional number which will yield an approximation of the average wind speed. Although some of the index values are easily obtainable, others require special equipment and laboratory analysis on core samples to ascertain the index value. Environmental factors, other than wind speed, which may affect these index values were initially ignored but further research is being done to include these.

3.2 WIND MEASUREMENT

Although wind measurement may seem like the obvious manner in which to assess the wind potential of an area, it becomes a very lengthy and costly exercise to evaluate a large area using this technique. Some investigators do however utilise a large number of measuring instruments which monitor the wind characteristics at a number of different locations.^(28, 30, 31, 44)

Hand held and mobile anemometers have also been used to record wind data over large areas.⁽³¹⁾ Due to the fluctuating nature of the wind, it is impossible to obtain an accurate value for average annual wind speed by using these types of systems alone. To obtain an accurate value for the annual mean wind speed at a site it is important to monitor the winds for at least a year. The values recorded using hand held and mobile anemometers are sometimes related to existing long-term wind data using statistical models in order to get a better representation of wind characteristics at the measured points.

Meteorological balloons, kites and doppler acoustic sounders are also used for measuring wind speeds, but these measuring techniques are normally used to obtain vertical velocity profiles or wind speeds at heights above an anemometer mast. (19, 22, 27-29, 31) Kite anemometry is also often used to predict the turbulence levels of the winds over the range of heights that a wind turbine's blades would be subjected to. From a comparison done on wind turbulence levels, measured by rigidly mounted anemometers (on a mast) and by kites, it was found that the measurements taken by kites predicted the turbulence to which wind turbine blades are subjected more accurately. (28)

Wind site measurements, using an anemometer to obtain an annual wind speed and either balloons or kites to obtain vertical velocity profiles, should however be carried out at a proposed WECS site. These results should be used to confirm that the energy potential of the site is what was predicted and that the proposed wind turbine is correctly matched to the prevailing wind speed in order to utilize the available wind energy resource optimally.

3.3 NUMERICAL MODELLING

Numerical modelling techniques are becoming increasingly popular for screening areas for possible wind turbine sites. This modelling procedure allows the effects of terrain on the prevailing airflow to be examined. All numerical models do, however, still require historical wind data records for any one point within the particular area being investigated. The historical records are then used to predict wind velocities at any other point due to the particular terrain characteristics.

A number of different mathematical models have been developed over time. (29, 41-43) These models have been used to determine the wind

characteristics over particular areas⁽⁴³⁾ and to serve as a direct comparison between the various methods of assessing the wind potential of a site. Numerical models have been shown to have good correlations with both wind tunnel studies and full-scale site measurements.⁽³³⁾

Numerical modelling is a very convenient tool to use to assess proposed WECS sites if the model has been developed into a computer programme to allow the user to assess a chosen site. Full scale site measurements must also be available to facilitate the immediate execution of the model to yield quick results.

3.4 PHYSICAL MODELLING

As mentioned in section 1.3, the use of wind tunnels to assess the wind energy potential of an area is a well-used and recognised technique of analysis. Wind tunnel studies performed in the field of wind turbine siting have concentrated on two different approaches. The first technique, which is site specific, utilizes a physical scale model of a proposed WECS site and investigates the enhancement over the modelled area. (See references 24,30,33,34,40,46) In the second case, generalised hill shapes are examined under various flow conditions in order to establish generalised solutions for airflow over hills. (See references 35 to 38.) The second type of analysis allows the results to be used for analytical and numerical solutions for predicting wind enhancement due to various landforms. The first method ensures that a proposed wind turbine is sited in a position as to fully utilize the available wind energy.

The use of wind tunnels to site wind turbines in an optimum position has been a more frequently used technique than numerical modelling. This stems from the fact that, firstly, some other method (e.g. physical modelling) is required to validate any numerical model

developed and, secondly, that the use of wind tunnels is a well-known and used technique of establishing variations in airflow. Since wind tunnels are used for much other work on environmental winds^(27, 32, 47-50), the understanding of their requirements and limitations to achieve valid results is well documented.

The physical modelling of proposed WECS sites does however have some limitations. The physical size of the wind tunnel's test section may limit the size of the model and hence the scaling factor used. In monitoring geometric similitude the limitation of the scaling factor will restrict the variation in height across the length of the model. If the height difference across the model is too small, the true effect of the topography on the winds could be lost. The modelling of relatively flat terrain would then require a large scale factor which restricts the outer limits of the physical model. It becomes a difficult task to use physical modelling for assessing the wind energy potential of very large areas and national wind energy surveys, using this technique, would be impossible.

3.5 METHOD ADOPTED FOR SITE ASSESSMENT

The installation and monitoring a number of anemometers at a site is a prohibitively expensive technique of evaluating a site. Since the assessment of the site is primarily a task of looking for possible wind enhancement, the use of ecological surveys is considered inadequate. Although ecological surveys can help to relate various sites in order of merit, they are not suitable when trying to establish the true enhancement in a small area, for example, on top of a hill.

Both wind tunnel facilities and a numerical model were available for site assessment and it was decided to use both of these techniques to evaluate potential sites in the Agulhas area. By utilizing both modelling techniques for the same site it would also be possible to

establish the most suitable technique for further investigations. To complete the site assessment it was thought that an anemometer may be placed at what was found to be the best site, if it looked a feasible WECS site.

CHAPTER FOUR

4. THE PHYSICAL MODEL

4.1 SITE SELECTION PROCEDURE

To ascertain which section of the area at Cape Agulhus was to be modelled, two 1:50 000 topographical maps covering an area 46 km wide (in the east-west direction) and 37 km long (in the north-south direction) were examined. Cape Agulhus lay in the center of the southern-most boundary. The area extended to Arniston in the east, Bredasdorp in the north and the western foot of the Soetanytsberg mountain in the west, (see Appendix 4.1.). As can be seen from these topographical maps, the area is largely flat with the exception of the mountain range in the north, which has a maximum altitude of 654m, the Soetanytsberg along the coast, which rises to 248m, and the Sandberg which is immediately north of the lighthouse and has a height of 156m. On examining these topographical features it was decided that the Sandberg and the Soetanytsberg had characteristics which would possibly enhance the prevailing wind speeds. The Sandberg consists of two hills running in the east-west direction which form a valley, lying on the same axis as the prevailing winds. This feature could produce enhanced winds due to the channelling effect of the two hills. The Soetanytsberg is a hill with gentle sloping sides, which could enhance the winds to a maximum at the top of the range, (see Appendix 4.2.)

Aerial photographs, (see Appendix 4.3.) of these two areas were then obtained and examined under a stereoscope. Both these areas were viewed in three dimensions, under the stereoscope. It was noted that the valley in the Sandberg area diverged gradually from both the east and the west directions. Due to the constriction formed, the valley looked ideal to optimally enhance the winds at its center. Figure 4.1. shows the shape of the valley together with the

wind roses for the annual average wind speed and direction, for Cape Agulhas, measured by the Weather Bureau. From figure 4.1. it can be seen that the valley lies on the axis of the most predominant wind directions (WNW, W, WSW, ESE, E, ENE) and it is these winds that have the highest velocities.

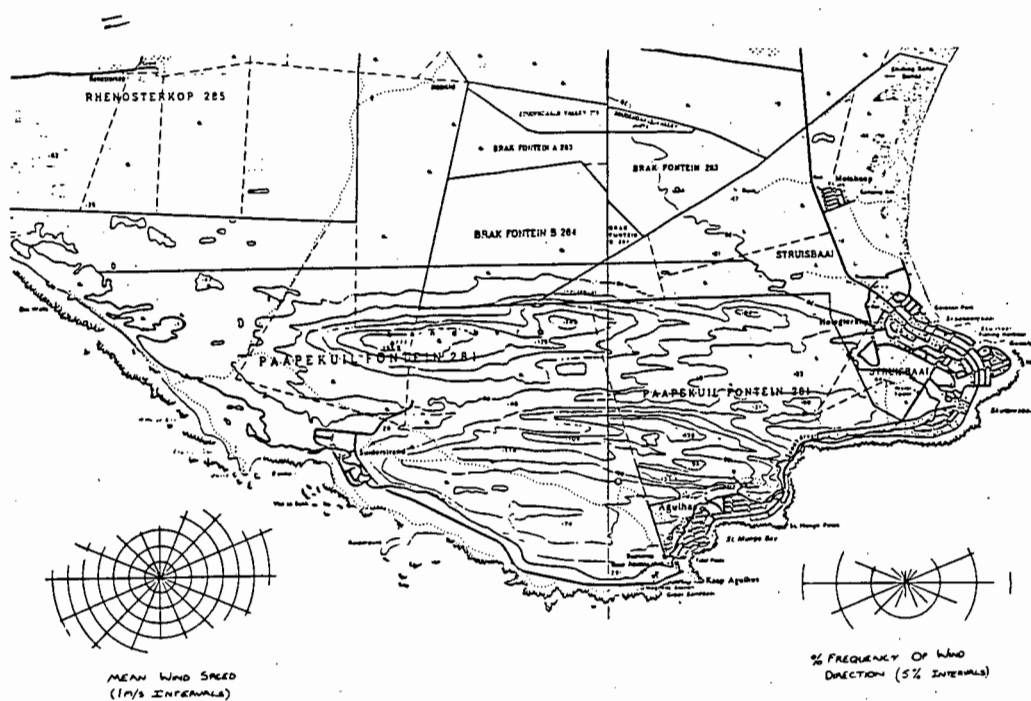


FIGURE 4.1. THE SHAPE OF THE SANDBERG VALLEY

Through the stereoscope it could be seen that the Soetanyberg was a hill with gentle sloping sides, but it was long and narrow and also ran on the axis of the prevailing winds. Although this area did possess characteristics which could enhance the winds, it was decided that the features formed by the valley in the Sandberg were more likely to enhance the airflow and therefore it was this area that was chosen to be modelled and tested in the wind tunnel.

4.2. CONSTRUCTION OF THE MODEL

Once this topographical feature had been chosen to be examined for wind enhancement, the exact size of the area to be modelled and the scale of the model had to be decided upon. The area which contained the valley was 12km long (8km west and 4km east of the lighthouse) and 4km wide (4km north of the lighthouse), as shown in Appendix 4.2. The area further north is very flat while the area further west is made up of sand dunes. Since the highest point in the area to be modelled was only 156m high it was necessary to build the model to as large a scale as possible in order to achieve a maximum height variation on the model. The scale of the model could not be too great as it was also necessary to model the complete valley (4km wide), which meant that the scale of the model was limited by the dimensions of the wind tunnel. A scale of 1:2 000 was chosen to satisfy the above conditions.

A 1:10 000 orthophoto was enlarged to 1:2 000 and every 20m contour line was traced off the enlargement. The shapes bounded by each of these 20m contour intervals were cut out of 10mm polystyrene sheets and glued one on top of another forming a stepped model. The 'steps' of the model were then filled in, using a commercial filler material, and the whole model smoothed off.

The model, which measured 6m by 2m, was constructed in six separate sections as shown in Figure 4.2. Only four pieces of the model could fit into the wind tunnel at any one time, but by using various sets of four pieces it is possible to examine the model under all of the six predominant wind directions (viz. WNW, W, WSW, ESE, E, ENE). (See Appendix 4.4.)

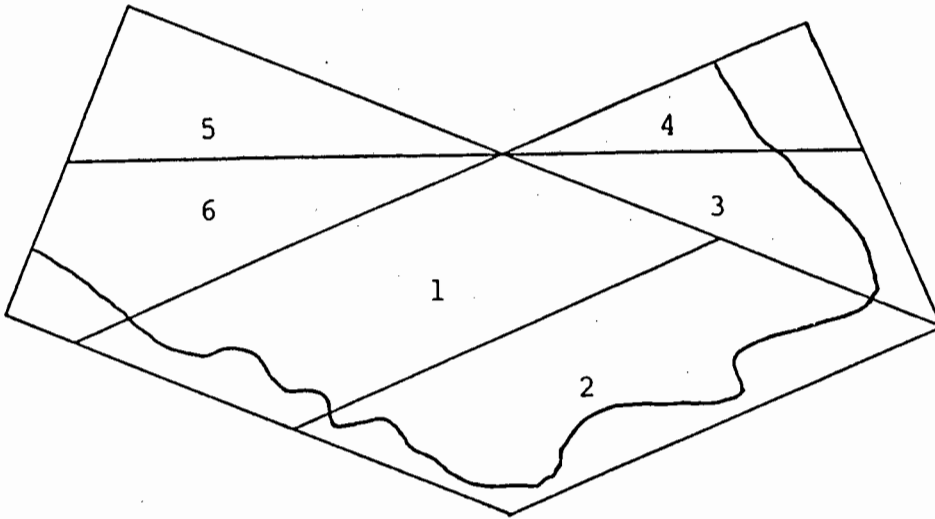


FIGURE 4.2. THE DIVISIONS OF THE MODEL

4.3. THE VELOCITY MEASURING EQUIPMENT

A hot film anemometer, of the probe type, was used to measure the velocity of the airflow above the model. The probe was coupled to a flow analyser which displayed the probe output voltage. A calibration curve for the the flow analyser was obtained by calibrating the probe in a high wind speed wind tunnel, having a contraction ratio of 1:10. By using the contraction ratio and a manometer it was possible to calibrate the probe over a wind speed range of 0 ms^{-1} to 10 ms^{-1} . By fitting a 4th order polynomial to the measured values, an equation for the calibration curve was calculated. (See Appendix 4.5.)

Due to the size of the model being examined an overhead gantry to support the probe was constructed in the wind tunnel. The gantry was supported close to the roof of the wind tunnel and could position the probe anywhere within its X, Y, Z, co-ordinate system. The gantry was powered by three stepper motors, each driving a separate axis. The motors were linked through an interface to a computer. By entering the co-ordinates to which the probe was

required to move, into the computer, the gantry would automatically transverse to the desired position at the required speed.

4.4. THE APPROACH VELOCITY PROFILE

Initial measurements in the wind tunnel, in the absence of the model, revealed that the boundary layer of the airflow, extended to 500mm from each of the four walls. This meant that there was an area only 0,5m x 1,0m, in the center of the wind tunnel, which had fully developed flow. By constructing a bell mouth on the entrance to the wind tunnel the boundary layer in the tunnel was reduced to 80mm from each of the walls as shown in Figure 4.3.

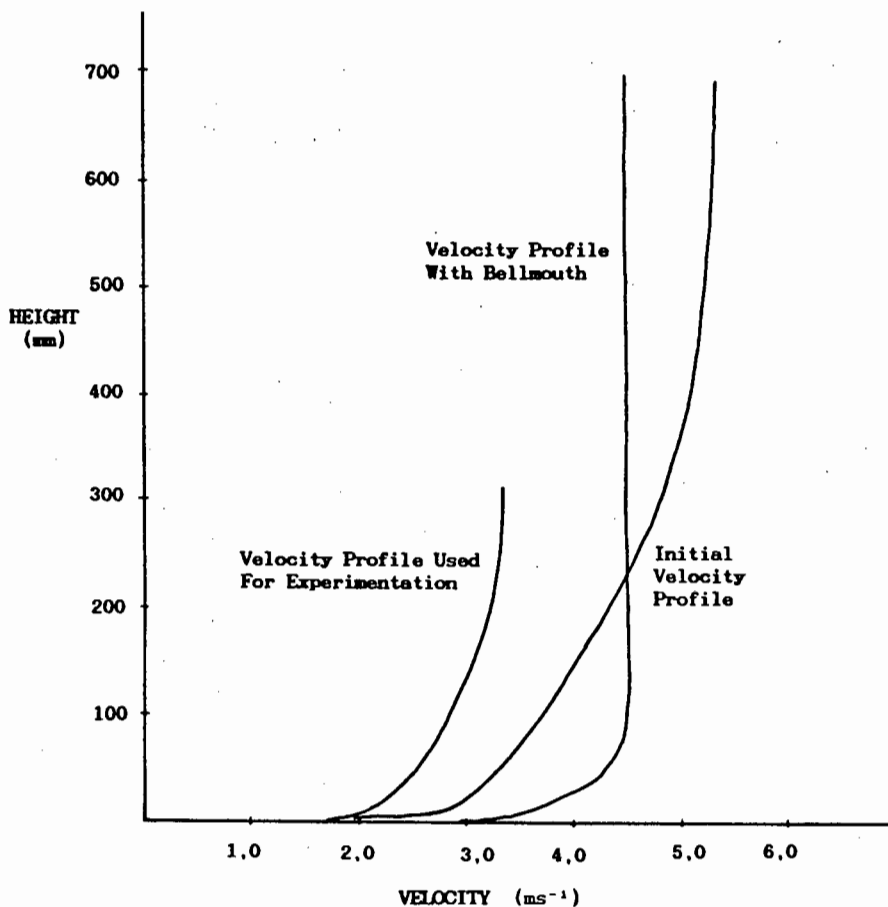


FIGURE 4.3. THE VELOCITY PROFILE CHANGE IN THE WIND TUNNEL

Once the boundary layer had been reduced the model was placed in the wind tunnel. Since the model had to be mounted on a base to facilitate its ability to be moved in and out of the wind tunnel, sea level, on the model, was actually 20mm above the the floor of the wind tunnel. To ensure that the approach airflow developed gradually, a ramp was built which lead from the floor of of the tunnel up to the edge of the model. This technique is frequently used in wind tunnel modelling, to overcome the thickness of the base on which the model is mounted^(23, 30, 32).

The turbulence level of the airflow in the wind tunnel was raised to the required level, of between 0.1 and 0.2, by introducing a turbulence promoter. With the turbulence at the correct level the vertical profile of the approach velocity was measured at different points across the width of the wind tunnel, but at a point beyond the top of the ramp and before the start of the land itself. The velocity profile of the airflow measured is shown in Figure 4.3. In order to compare the velocity profile in the wind tunnel to that estimated by the 1/7th power law, the curves were replotted in Figure 4.4. with percentage of free stream velocity versus percentage height at which free stream velocity is achieved.

It can be seen from the curves in Figure 4.4. that the original vertical velocity profile measured in the tunnel did not represent that predicted by the 1/7th power law. By using only the top six of the nine fans in the wind tunnel, it was found that the approach velocity profile, measured at the same points as previously, corresponded very closely to that predicted by the 1/7th power law as indicated in Figure 4.4. The velocity profile in the wind tunnel does deviate slightly from the ideal curve above 45% of full height. The velocity profiles above the topography were only to be measured to 100m above ground level, (the height for large wind turbines), and since the highest point on the model corresponds to 156m, it means that the maximum height for measurement is 256m above sea

level. On the scale model of 1:2 000 this corresponds to a height of 128mm and in terms of percentage of full height, as depicted in Figure 4.4., it corresponds to 43% of full height. This means that although the approach velocity profile in the wind tunnel does deviate slightly from the ideal curve at heights greater than 45% of free stream height, velocities in this region were not measured. The final approach velocity profile is shown in absolute terms in Figure 4.3.

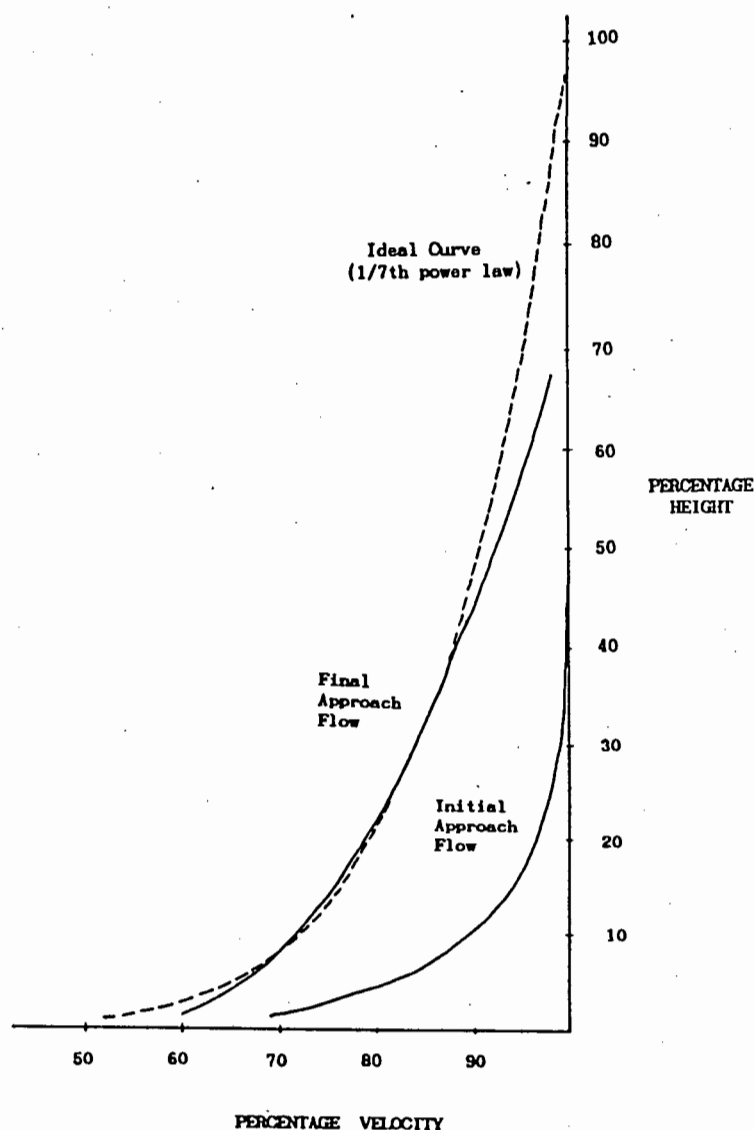


FIGURE 4.4 . COMPARISON BETWEEN IDEAL VELOCITY PROFILE AND THAT OCCURRING IN THE WIND TUNNEL.

CHAPTER FIVE

5. THE NUMERICAL MODEL

5.1. DESCRIPTION OF THE MODEL

An internationally developed computer programme which models airflow over topography was available. The programme, which was developed especially for the purpose of investigating proposed WECS sites, is currently being used in some European countries in their wind energy siting programmes. The computer programme was run for the same area as that covered by the physical, model to allow a direct comparison between the results.

The programme requires a number of data files for the site being investigated to be inputted. These data files are:

1. A digitized map of the investigated area.
2. Historical wind data for a point within the digitized area.
3. Roughness description of the area.
4. Descriptions of any major obstacles in the area (eg. houses, dense forest etc.).
5. An operating curve for a wind turbine if the absolute energy (in kW) is to be calculated.

The digitized map and wind data files are read in by the programme and the site co-ordinates of the wind reference point is fixed. The wind speed and energy density at any point is found by changing the site co-ordinates and by entering the roughness and obstacle description at this new site. By changing the height of calculation a vertical velocity profile can be obtained for any point within the area.

5.2. THE DIGITIZED MAP

The computer programme requires a map to be defined by a number of digitized contour lines. These contour lines are fed into the programme as a long string with the first value giving the number of co-ordinate pairs in the string (contour line) and the second value setting the height of that particular contour line. The string is completed by the specified number of co-ordinate pairs (X and Y values) defining that particular contour line. Each separate contour line is fed in as a separate string.

To obtain the digitized values of the contour lines, the digitizing tablet in the Department of Land Survey was used. The contour lines to be digitized were traced off a 1:10 000 orthophoto of the area. Because the computer programme had an upper limit of 10 000 co-ordinate pairs defining any one digitized map, only every 20m contour line was digitized. In critical areas, however, intermediate contour intervals were included to increase the definition of the terrain shape.

To obtain values from the digitizing tablet a short computer programme had to be written. This programme also had to make allowance for the fact that 1:10 000 map could not be digitized in one, but had to be split into two sections (see Appendix 5.5). The area that was digitized was defined by about 6 000 co-ordinate pairs defining 50 contour lines. These data points were transferred onto floppy disc and arranged in the correct format for the numerical model. Images of the digitized points are shown in Appendix 5.2 and 5.3. The contour map shown in Appendix 5.2. is not the one that was used for digitizing purposes but is one that was drawn by the Saclant Graphics Package (on the UCT Sperry Computer) using the digitized points. It compares well with the map shown in Appendix 4.2.

5.3 THE HISTORICAL WIND DATA

The historical wind data records, recorded by the Weather Bureau at the Cape Agulhas lighthouse, were obtained on floppy disc from the Weather Bureau in Pretoria. It was decided to use those values that were recorded in meters per second and hence the wind speed and direction values for the years 1980 to 1985 inclusive, were used as an input for the numerical model. The wind data for these six years was reorganised into files that were recognisable by the computer programme.

The raw data being used by the numerical model requires an anemometer height to be fed in, in order to establish a reference height for the historical data. The height at which the wind speeds are measured by the Weather Bureau at Cape Agulhas is questionable. Weather Bureau publications state that a Beckly cup at 15m above ground level is used to record wind speeds at Cape Agulhas which has an annual mean speed of $6,5 \text{ ms}^{-1}$.^(15, 16, 18) Diab however, uses an anemometer height of 5m above ground level and normalises an annual average wind speed of $6,5 \text{ ms}^{-1}$ to $7,2 \text{ ms}^{-1}$, at 10m above ground level.⁽¹²⁾ On visiting the Weather Bureau office at Cape Agulhas it was found that a new anemometer and recorder have recently been installed but wind speeds are still being estimated by the lighthouse keeper using the Beaufort Scale (see Appendix 2.2.). The Weather Bureau office at D.F.Malan in Cape Town, which is responsible for this anemometer, confirmed that the new anemometer was not fully operational but that the values recorded by the lighthouse keeper are periodically cross-checked against true anemometer readings.

In running the computer programme it was decided to use approximately the same value as Diab calculated as the reference wind speed (ie. $7,2 \text{ ms}^{-1}$ at 10 m above ground level). When the wind speed data, obtained from Pretoria, was fed into the numerical model, an anemometer height was inputted to give a wind speed of 7,4

ms^{-1} at 10m above ground level. It should be noted that while there might be uncertainty attached to the true value of the wind speed at Cape Agulhas, the frequency at which the wind blows at various sectors is known. Also the percentage difference between the wind speeds over the 16 compass sectors remains constant irrespective of the mean wind speed. Thus, by arranging for the inputted raw data to have a mean wind speed of $7,4 \text{ ms}^{-1}$ at 10m above ground level only the absolute values of the average values obtained and not the percentage change in the wind speed due to the topography are altered.

The raw data is read into the computer programme, which then produces a table summarising the percentage frequency the wind blows from each sector and the percentage of time the wind blows within various wind speed ranges. A table for each year of data used is shown in Appendix 5.4 while Appendix 5.5 gives a summary of all six years of data used by the computer model.

5.4. SITE ROUGHNESS DESCRIPTION

To calculate the percentage change in the wind speed between various points on the model, the programme uses the digitized map, the terrain roughness and any specified obstacles. The site roughness has to be described according to a set of rules supplied with the programme. The roughness of the area has to be described for each point examined. The point being investigated forms the centre of a circle of at least 10 km diameter. The roughness characteristics of each of the twelve sections within the circle are then described according to the terrain type. Changes of roughness lengths can occur a number of times within a given sector where required. No obstacles were used in the site analysis since the terrain being investigated was open land with no major obstacles.

CHAPTER SIX

6. DISCUSSION OF RESULTS

6.1 EXPERIMENTAL PROCEDURE USED FOR PHYSICAL MODELLING

In order to get a true representation of the velocity profile over the terrain it was necessary to take velocity measurements at numerous points above the physical model. A rectangular grid was drawn on a map of the area representing the physical model. By taking velocity measurements at the grid intersection points it ensured that the whole of the area was examined. This procedure also eliminated the possibility of taking measurements only at points where enhancement was expected.

The grid points on the map represented points that were 450m apart in reality. It was possible to take eight readings across the width of the wind tunnel and it was only necessary to take ten readings down the length of the model. Only ten grid points were required in this direction for this covered all possible WECS sites in the area, ie. the grid covered the topography between Struisbaai, upstream and the coast downstream. A total of eighty grid points were thus used to investigate the velocity profile in the X-Y plane. To map the vertical velocity profile three readings were taken in the Z direction at each of the eighty grid points. These velocity measurements were taken at scale heights which corresponded to true heights of 20m, 50m and 100m above ground level. The reason for taking readings at fixed heights above ground level as opposed to heights above sea level, is that a given wind turbine will always have the same hub height irrespective of its location. To compare two proposed turbine sites it is necessary to compare the wind energy potential, at the turbine's hub height, of the two respective sites. A total of two hundred and forty velocity measurements were taken in the wind tunnel to represent the airflow from an ENE direction.

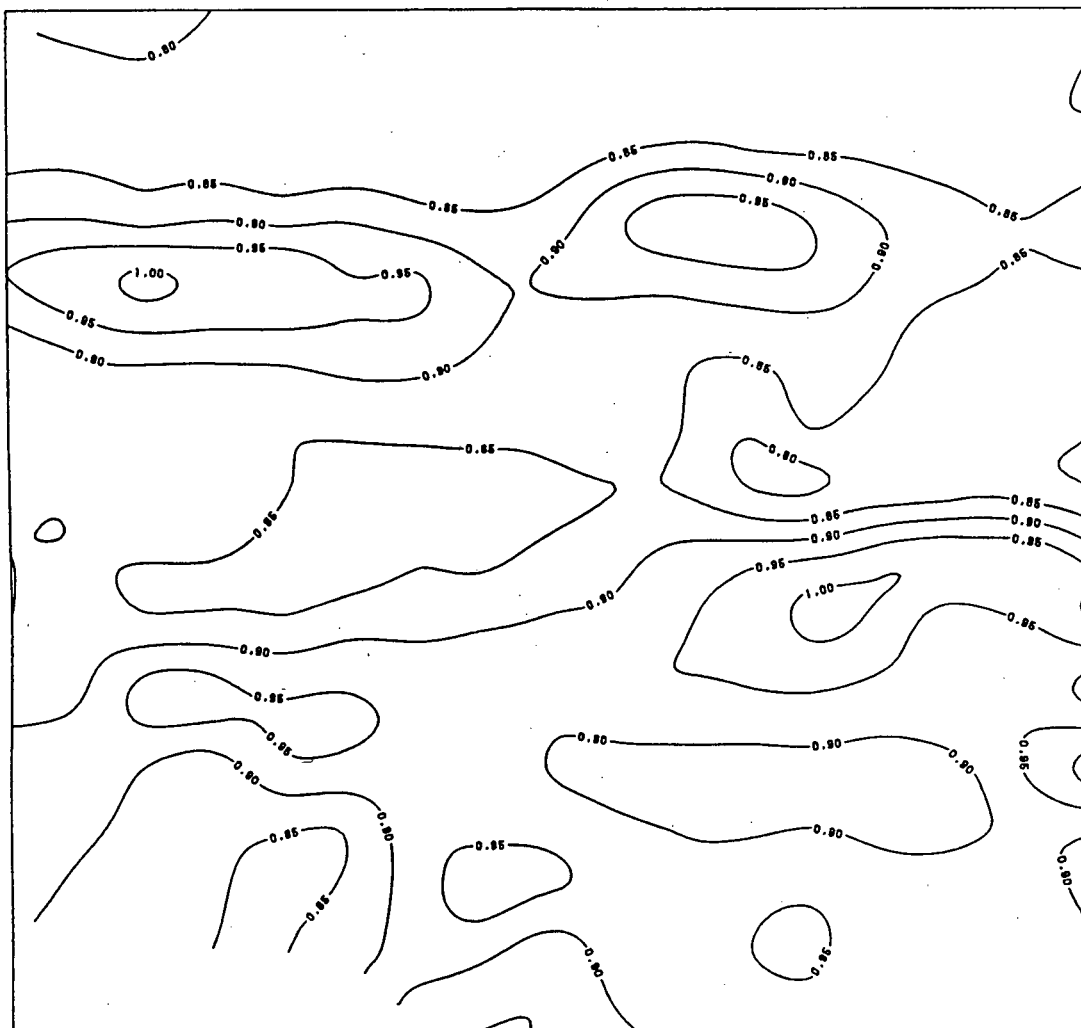
The X, Y and Z co-ordinates of the grid points were established for the 1:2 000 scale model. The Z co-ordinates were expressed as heights above sea level to allow the overhead gantry to position the probe within its own co-ordinate system. The probe, however, still always represented incremental heights above ground level. These data points were entered and stored in the the computer which positioned the probe in the wind tunnel.

Before each test, the gantry supporting the probe was positioned at its origin. The interface linking the computer to the probe was then switched on and the reference point zeroed. The probe then moved, on command, between grid points and the value for the probe voltage was recorded. Values for the upstream airflow and the velocity at the lighthouse were recorded periodically during experimentation.

After the probe voltage at all the grid points had been recorded they were entered into a computer programme and transformed into velocity readings using the 4th order probe calibration curve for the probe (See Appendix 4.5.). The co-ordinates for each of the grid points were transformed into values which corresponded to co-ordinates on the same axis system used for the numerical model. This was done because the X-axis in the wind tunnel was the ENE-WSW axis, which was inclined at $22,5^\circ$ to the east-west axis. It is the east-west axis that represents the X-axis on all maps and was also the direction used for the X-axis during numerical modeling.

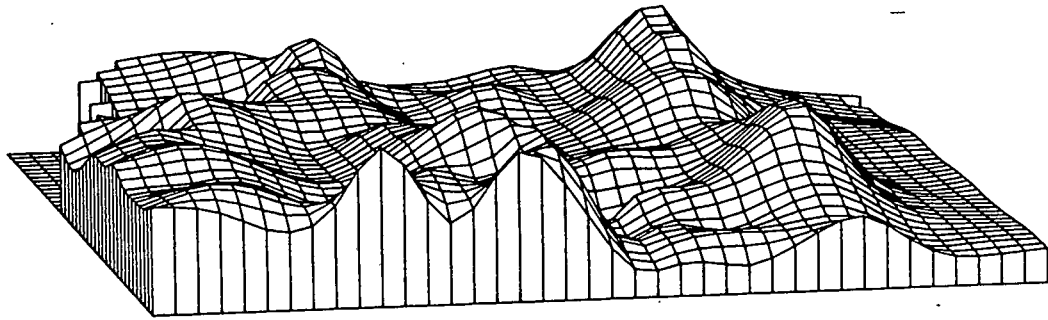
In order to represent the results in a form which could easily be interpreted and analysed it was decided to plot isopleths representing wind speed enhancement. The velocity at each point was divided by the velocity measured at the lighthouse, yielding values for velocities relative to the lighthouse. Using the X and Y co-ordinates of each point as its grid value and the value for relative velocity as its corresponding Z co-ordinate, it was possible to plot isopleths as both contours and 3D images using the Saclant graphics

package. On the maps showing these isopleths, a line having a value of 1,00 represents zero wind enhancement, with respect to the lighthouse, while one with a value of 1,05 depicts an increase of five percent in the wind speed. Maps showing these isopleths were plotted for each of the heights 20m, 50m and 100m above ground level. Typical representations of the results are shown in Figures 6.1. and 6.2. In order to ascertain the absolute location of a point of say maximum wind enhancement it would be necessary to superimpose the relative velocity isopleths upon a contour map of the same area. (See Appendix 6.1.)



VELOCITY. H=20M A.G.L.

FIGURE 6.1 TYPICAL MAP REPRESENTING ISOPLETHS OF RELATIVE VELOCITY
(The horizontal border lines are in a east-west direction)



VELOCITY. H=20M A.G.L.

FIGURE 6.2 TYPICAL 3D REPRESENTATION OF RELATIVE VELOCITY

On initial examination of the results it was noticed that the maximum wind enhancement was only of the order of ten percent. To obtain a ten percent total annual enhancement would require a point to have this same enhancement for all wind directions or to have at least a sixty percent enhancement in one of the predominant wind directions. Since this seemed unlikely from the results for a ENE wind direction, it was decided to run the numerical model for the area before proceeding with the other five wind directions in the wind tunnel.

6.2 EXPERIMENTAL PROCEDURE USED FOR NUMERICAL MODELING

After storing all the required data for the numerical model on disk, (see chapter 5), the site could easily be analysed. Again a square

grid was superimposed upon a map of the area and the co-ordinates of the grid intersection points established. Grid points were taken at intervals representing a true distance of 300m apart. A total of 240 grid points covered all locations for possible wind turbine sites. The grid points were taken on the same co-ordinate system used when digitizing the topographical map, which had an X-axis in an east-west direction.

The recorded data files were read in by the wind analysis programme. The roughness description file for a given point was then entered together with the site co-ordinates of that point. The numerical model displayed all the raw data input, on the computer monitor (see Appendix 6.2.) and by invoking the calculation procedure the model calculated the wind speed and energy density at the specified site and height (see Appendix 6.3). The model was run for all 240 grid points and the average wind speed and energy density were calculated for six heights viz. 2m, 10m, 50m, 75m, 100m, above ground level at each site.

Again the relative velocities were mapped with isopleths representing the wind enhancement at a point with respect to the lighthouse. Initial results showed that the maximum enhancement, in total average wind speed was only eight percent. If the numerical model was directly compatible with the physical model the results would imply that the velocities measured in the wind tunnel were typical of a particular wind direction and other directions would yield similar results. To investigate the compatibility of the two models, the numerical model was re-run for the same heights and wind direction used in the physical modeling procedure. Since the numerical model was only capable of dividing the compass into a maximum of twelve wind directions, the enhancement in wind speed in the sector with compass bearing of between 45° and 75° was used to represent a ENE wind direction. A ENE wind direction would have a true bearing of between $56,25^\circ$ and $78,75^\circ$ when used in the numerical model. The results obtained from the numerical model for this wind direction were used when comparing the results between the two modeling procedures.

6.3 METHOD ADOPTED FOR DISCUSSION OF RESULTS

In discussing the results obtained through both the physical and numerical modeling exercises, reference will be made to the diagrammatic representation of the results given in Appendices 6.4. to 6.9. All the results are represented in the form of both 'contour' plots and 3D images of these plots. The 'contours' represent lines of constant relative velocities, relative energy densities, absolute velocities and absolute energy densities. The 3D images represent exactly what is shown in the 'contour' plots with the Z-axis representing the values corresponding to the 'contour' lines. In Appendix 6.8., for example, where the contours represent the total average annual wind speed at 20m a.g.l., the 3D representation gives the velocity profile at 20m a.g.l.

The extent of the area covered by these graphical representations is the total area covered by the grid used during the numerical modeling procedure. It covers all the areas where wind turbines could possibly be sited, within the digitized map, i.e. it excludes areas containing houses, sanddunes and sea. This area extends 4 800m in the east-west direction and 4 500m in the north-south direction. In order to show the exact position of point, say having the maximum velocity, these wind 'contours' would either have to be superimposed on a topographical contour map or the co-ordinates of the point obtained and reproduced on a topographical map. The reason for not representing the results superimposed on topographical contours was that the combined map contained so many lines that it was difficult to assess where the winds were being enhanced. The contour images are shown on maps with a north-south axis in the direction of the vertical lines on the edges of the maps, north being at the uppermost end. The 3D images are all represented from the same viewpoint. With reference to Figure 6.3., the viewpoint has a value of 10° for θ and 10° for ϕ . When viewing

these 3D images, one is looking down on the given profile, roughly in a westerly direction, ie. the horizontal line in the foreground lies more or less on a north-south axis.

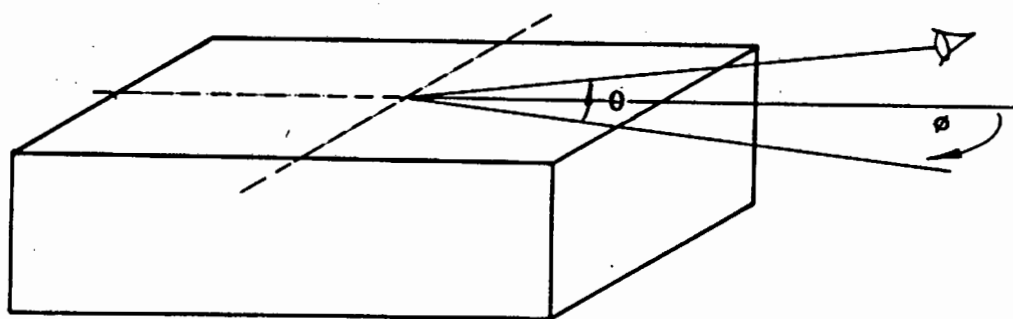


FIGURE 6.3. THE LOCATION OF THE VIEWPOINT FOR THE 3D REPRESENTATIONS.

The location of points of maximum wind enhancement are discussed with reference to their location with respect to either the southern or northern ridge in the Sandberg range (see Appendix 4.2). The valley in this area lies between these two particular ridges. Areas in the results which are represented as blank areas, ie. the SW corner in the numerical results and the northern border in the results from the physical model, are areas where the results were either unobtainable or not required.

6.4 DISCUSSION AND CORRELATION OF THE RESULTS

From Appendix 6.4 it can be seen that the maximum wind speed obtained in the tunnel, for a ENE wind and all the examined heights, is only 5% greater than that recorded at the lighthouse. The point of maximum enhancement occurs on the slope of the southern ridge and extends in a south westerly direction at greater heights. At 20m

By re-running the numerical model, results were obtained for the relative change in wind speed, the relative change in wind energy density, the absolute wind speeds and absolute energy density. These results are shown in Appendices 6.6 to 6.9 respectively. The results represented in these appendices show values which correspond to the total annual averages of wind speed and energy density as opposed to values for a single wind direction.

From the results for the relative change in velocity (see Appendix 6.6) it can be seen that the maximum total wind enhancement is five percent, occurring at a point close to the summit of the western end of the northern ridge (also shown in Figure 6.5). The area in the region of the valley has the lowest values for wind speed enhancement. The wind speed in areas having low average winds at 20m increases by a factor greater than that for areas with high winds as the height above ground level increases. For example, an area having a relative wind speed of 0,85 at 20m increases to 0,95 at 100m, while an area having a relative velocity of 1,00 at 20m increases to 1,05 at 100m. This emphasises the fact that the positioning of a wind generator with a hub height of approximately 20m is more critical than a turbine with a height of approximately 75m. This characteristic is even more clearly visible from the plots of relative change in energy density (see Appendix 6.7). The 3D images of relative change in energy density show the point of maximum energy as more or less constant with changes in height, but that the areas of low energy density at 20m increase significantly with height. This phenomena creates a flattening effect of the energy density profiles as height increases. By examining the representations of both relative velocities and relative energies it becomes clear how significantly minor changes in wind speed effect the energy density of the wind. At the site of most enhanced wind speeds, ie. five percent enhanced with respect to the lighthouse, the energy density of the wind is enhanced by thirty percent. The availability of thirty percent more energy would increase the overall operational efficiency of a turbine located at this site which would, in turn, reduce the cost of wind power.

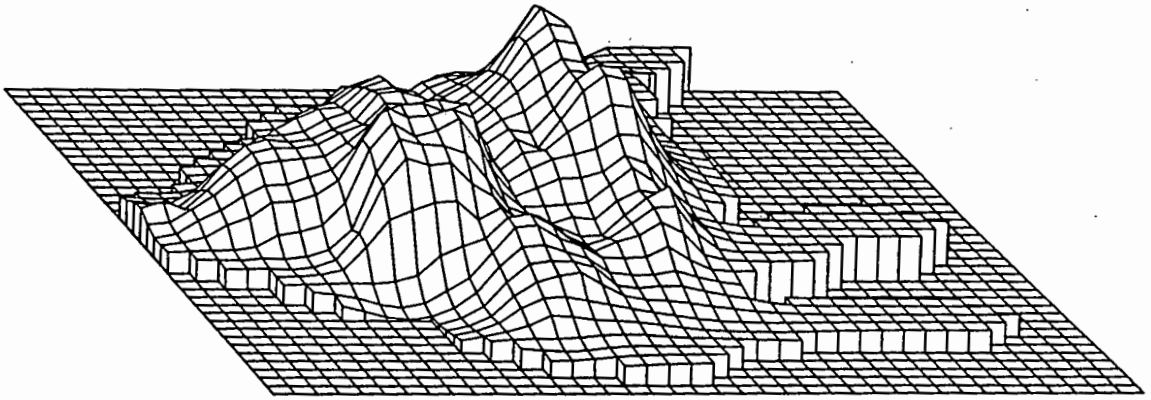
Appendix 6.8 represents the total average annual velocity over the investigated site at the heights 20m, 50m, and 100m a.g.l. These results are shown to compare the 'windiness' in this area to that experienced at existing WECS sites. It can be seen that the velocity varies between a minimum of $6,4 \text{ ms}^{-1}$ at 20m a.g.l to a maximum of $10,0 \text{ ms}^{-1}$ at 100m a.g.l. It is suggested⁽¹²⁾ that sites with average wind speeds greater than 4 ms^{-1} should be investigated for their suitability to support WECS. A value of 5 ms^{-1} is sometimes considered as the minimum required velocity, but it is generally accepted that the velocity should fall between the values of 5 ms^{-1} and 10 ms^{-1} .⁽¹²⁾

The results shown in Appendix 6.9 are those representing the true annual average energy density of the wind. The values range from 400 W/m^2 at 20m a.g.l to a maximum of 1200 W/m^2 at 100m a.g.l. These are the theoretical values for wind energy density, but if they are multiplied by the Betz limit of 59 percent, (see Appendix 1.1.) the theoretical maximum extractable power falls in the range of between 240 W/m^2 and 700 W/m^2 . Sites are sometimes classified according to this theoretical extractable wind power at 50m a.g.l and can be classified as:

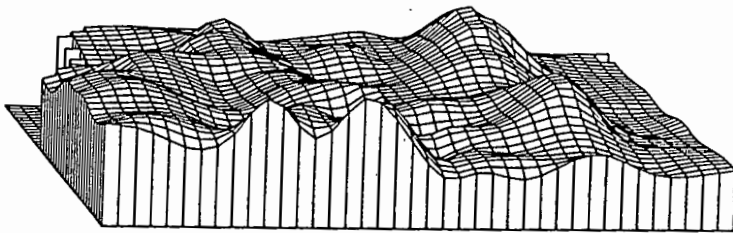
1. $>400 \text{ W/m}^2$ - Site of high wind power.
2. $>300 \text{ W/m}^2$ - Site of moderate wind power.
3. $>200 \text{ W/m}^2$ - Site of marginal wind power.
4. $<200 \text{ W/m}^2$ - Site of high low power.

From Appendix 6.9 it can be seen that the value obtained for the theoretical wind energy at Cape Agulhas, at 50m a.g.l, lies between 500 W/m^2 and 900 W/m^2 . These values apply to the available wind power based on the cube of the wind velocity. By multiplying these values by the Betz limit (see Appendix 1.1), they are converted into figures for the maximum extractable wind power which are used in the above classification. After conversion, the maximum extractable wind power at 50m a.g.l at Cape Agulhas, falls within the range of 300 W/m^2 and 530 W/m^2 . From these figures and the above

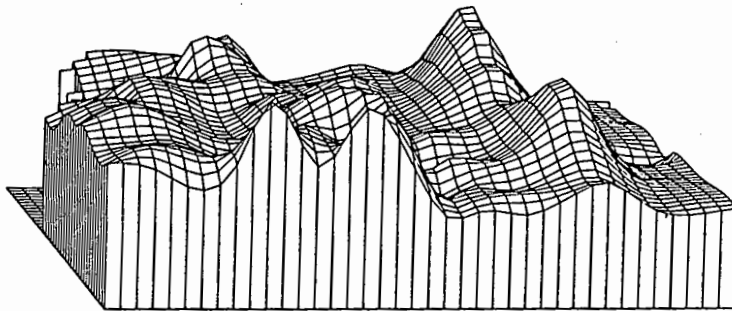
classification it is evident that the area is clearly an area of high wind power potential.



CAPE AGULHAS



VELOCITY. H=50M A.G.L.



ENERGY DENSITY. H=50M A.G.L.

FIGURE 6.5. THE RELATIVE LOCATION OF THE SITE WITH MAXIMUM VELOCITY AND ENERGY ENHANCEMENT

CHAPTER SEVEN

7. ENVIRONMENTAL IMPACT

All power generation systems have some effect on the environment in which they operate, and wind energy conversion systems are no exception. Wind turbines are seen as non-polluting in the normal sense, but they do however have their own associated environmental impacts. The siting of wind turbines is not just a matter of acquiring a piece of land in a windy environment, but is a matter of examining the related institutional, environmental, economic and technical questions. A well functioning and economically viable wind turbine also has to be located at a suitable site. The suitability of a site has to include the assessment of factors such as noise production, security, landscape electromagnetic interference, etc.

Wind power is considered by many as being a clean, domestic and 'free' source of energy. It is a clean form of power generation having no waste problems, making it more compatible with the environment than existing methods of power generation. In order to assess the extent to which wind turbines affect the environment, the following environmental impacts will be discussed with reference to international wind turbine sites currently in operation.

1. Noise generation
2. Electromagnetic interference
3. Visual acceptability
4. Light hindrance
5. Ecological impacts
6. Land use restrictions
7. Safety

The majority of these environmental impacts will be discussed with reference to horizontal axis machines. This is a result of a greater number of such machines in current operation world wide.

which has led to the research and documentation of their associated environmental impact. It should also be borne in mind that while these impacts are discussed with reference to foreign turbine sites, the majority of these are characteristics of wind generators themselves, making these environmental impacts directly applicable to South Africa. The other impacts, which are more site specific, are also important to South Africa for these factors indicate the negative effects wind turbines may have on a proposed WECS site.

7.1 NOISE GENERATION

Noise is one of the most serious consequences of operating wind turbines, especially in populated areas, or in instances where residences or farms are located within close proximity of a WECS site. The noise generated by wind turbines can be divided into three sources: (51, 57, 59, 67, 68)

1. Mechanical noise
2. Tower shadowing or variations in inflow
3. Aerodynamic noise

Mechanical noise, also known as drive train noise, is the noise emitted from the gearbox, generator, bearings, etc. This noise can often be absorbed by sound proofing techniques which are state-of-the-art techniques. (58, 59, 67) The noise emitted due to tower shadowing only occurs with horizontal axis, downwind turbines. The rotor blades of the turbine undergo strong loading variations as they pass through the wake of the turbine's tower. The acoustics emitted from the tower shadow are of very low frequencies consisting of many harmonics of the blade passing frequency. (59, 67) This low frequency noise is known to be disturbing in certain weather conditions and is the predominant source of noise in downwind, horizontal axis wind turbines. (58, 59, 67) Aerodynamic noise is generated by the trailing edges and blade tips of a turbine's blades. The aerodynamic noise of the rotor blades is permanent

because the shedding of vortices occurs whenever the turbine blades move. (57-59,67) Measurements taken on various wind turbines during operation, have shown that aerodynamic noise is largely dependent on the tip speed of the blades. (59,67) For upwind horizontal axis machines it has been found that the trailing edge noise is the major cause of noise emission compared with the other sources. (67) Aerodynamic noise seems to obey the equation established for jet noise where (61):

$$\text{Total sound power} = 10 \log_{10}(nU^6bd) + \text{Constant}$$

n = Number of blades

U = Relative velocity between blade and wind speed at 70% span

b = Blade chord

d = Diameter of wind turbine.

Although it is now possible to quantify the noise generated by wind turbines, the degree to which this noise is likely to be noticeable depends on a number of factors. The two primary variables influencing the extent of a turbine's noise pollution are the vector distance from the turbine, and the background noise level at the turbine site. (61,69,83,84) The background noise level rises with wind speed which means that the noise generated by the turbine will not necessarily be most pronounced at high power levels. (69) The Netherland's government has enforced a rule where the maximum allowable noise generation from a wind turbine is a function of the ambient noise levels. This limit of noise generation from a wind farm as a whole, was set at 5dB(A) above the background noise at a distance of 250m from the nearest turbine. (84)

Although upwind turbines emit more noise than downwind machines, there are no definite rules establishing the distance at which noise levels become acceptable. Since atmospheric conditions play such a vital role in the process of noise propagation it is difficult to fix a legal value. A limit to audibility for noise generation from large wind turbines appears to be in the order of 2 000m downwind of

the machine, but is considerably less in other directions. It is clear that noise may be acceptable at much lower distances, but this is dependent on the locality. (63-66, 67, 68, 69)

Two large mega-watt horizontal axis wind turbines in Sweden, have yielded interesting results on noise levels. The first machine is a 3 MW downstream wind turbine sited at Maglarp. Experimental work done at the turbine site showed that the disturbing, low frequency thumping noise generated by the turbine arose due to the uneven loading on the blade, caused by the tower wake. Families living within 750m of the turbine complained about the impulsive thumping noise. On a few rare occasions this thumping noise was heard at two villages 2 000m away from the turbine, which is sited in flat open countryside. It was suggested that the tower-wake noise generation should be a serious consideration during the design of downward machines, and noise levels could be minimized by improved tower design. (63, 64)

The second Swedish example is a 2 MW upstream horizontal axis machine sited at Nasudden on the island of Gotland. The major noise source is the aerodynamic noise of the blades. The mechanical components add to the noise level at the frequency level of about 800Hz. This contribution to the total noise level of 65 dB(A) (at 114,5m from the turbine) was approximately 3 dB(A). The background noise level, with the turbine at standstill, was measured to be 48 dB(A) in a 12-15m/s wind. Since this machine is of the upwind design there is almost no contribution to the low frequency noise from the tower passage. The closest resident to the turbine is again 750m, but there have been no complaints in this case. (69)

The Growian WECS (3MW, 2 bladed downwind turbine with 100m diameter rotor) sited near the mouth of the river Elbe in Germany has been found to emit aerodynamical noise in the frequency range of 200 to 4 000 Hz caused by rotor blades. The gearbox emits a narrow band noise of 200 Hz at half to full load. The noise level at 340m (ie. twice the overall turbine height, = $2R_0$, according to the IEA

recommendations for noise measurement) was 54 dB(A) at idle operation and 60 dB(A) at rated power. The background noise level was approximately 45 dB(A). At a distance of less than 250m from the tower, infrasound waves can be felt by sensitive people when the rotor blades pass the downwind area of the tower. (57)

The low frequency noise emitted from wind turbines has to be considered very seriously, for it propagates through the atmosphere more efficiently than higher frequency noises. Low frequency noises, unlike those of high frequencies, are not subject to atmospheric absorption. It is, for this reason, very easily diffracted around obstacles, rendering screening ineffective. It can cause resonance in buildings which leads to the vibration and rattling of objects. (51)

Small WECS in operation in Germany have shown that mechanical and aerodynamical noise is only slightly above the background noise level. It was found that although the difference in sound level between an operating and non-operating turbine was very small, it may be audible due to the differing sound frequencies. (58) A 300 kW upstream wind turbine in the Orkney Islands, Scotland is inaudible at 150m, under normal operating conditions. (55)

It is clear that noise generation from wind turbines should be a major consideration both in the design and siting of a wind turbine. If legislation is to be implemented as to the maximum allowable noise generation from a wind turbine, it should be related to the background levels while the turbine is in operation, and not to those measured under calm conditions. It should also be realised that noise propagation is heavily dependent on atmospheric conditions and the topography, which limits the direct comparison of output noise levels from various turbine sites.

7.2 ELECTROMAGNETIC INTERFERENCE

The potential for a wind turbine to cause electromagnetic interference requires significant attention. Navigational equipment is designed to minimize possible interference from unwanted noise sources and therefore, unless a wind turbine is placed almost adjacent to a transmitter, there is little likelihood of interactions. Microwave communication links are high capacity, line of sight communication between fixed points, utilizing directional dish antennae. Due to the directional nature of antennae, microwave interference is only likely to occur if a wind turbine is on, or close to the line of sight. Due to the difficulty and cost of correcting microwave signals, this type of interference should be avoided when siting a wind turbine. The ability for a wind turbine to interfere with the video portion of a television signal is a more serious problem. (50, 52, 53, 65)

Television interference effects depend on a number of known parameters which include : (50, 52, 65)

1. The size, the design and the material of both the turbine tower and blades.
2. The position of relevant television transmitters
3. The strength, polarization, coding, and frequency of the signals
4. The local topography surrounding the wind turbine site.

It is only the first of the above parameters which is dependent on the wind turbine itself, the others all being dependent on the turbine site. It is for these reasons that electromagnetic interference is largely site specific and thus each site has to be assessed separately.

A wind generator causes television interference by creating two transmission paths, the primary signal and a scattered interfering signal as shown in Figure 7.1.

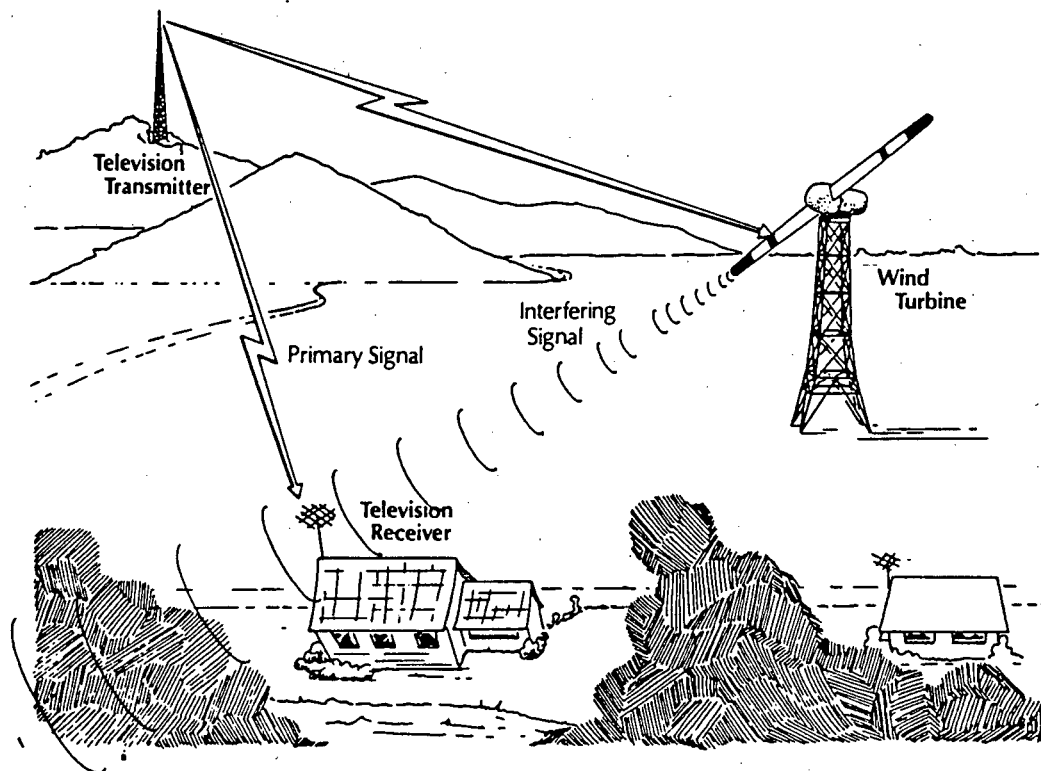


FIGURE 7.1. THE SCATTERING OF A TV SIGNAL

(Source: Ref 52)

Since the blades of a wind turbine move (i.e. the object causing the scattering), the phase of the interfering signal varies with time. The combination of the direct and the scattered signal generates alternate constructive and destructive interference, causing the signal at the receiver to be modified predominantly by amplitude modulation. Wind turbines on or close to the line of sight produce amplitude modulation of the signal, while those off it can produce periodic multipath signals. The degree to which the scattered signal may cause interference is dominated by the scattering area or radar cross-section of the wind turbine. Television interference caused by wind turbines appears only to interfere with the video portion of the signal, the sound signal seems to be immune to interference. (50)

In the U.S.A it has been noticed that television interference by wind turbines results from :⁽⁵⁰⁾

1. A wind turbine lying between a television transmitter and a receiver, which causes a periodic variation in the signal strength resulting in a picture of varying brightness.
2. Reflected signals from the turbine blades give a multipath interference resulting in an irritating, flickering ghost on the screen.

South Africa uses YJ 625 line PAL television transmission system which is the same transmission system as the U.K but different to the NTSC system used in the U.S.A. The only difference between the South African system and that used in the U.K. is that the sound channel in South Africa is broadcast at 6 MHz as apposed to 5,5 MHz in the U.K. The modulation thresholds of the PAL and the NTSC systems differ, which means that the interference zones will probably differ. The PAL system gives a better picture, which means that South African viewers may be more critical of interference than U.S.A viewers. The PAL system does however have an advantage of being less susceptible to distortion.

Public attitude to interference will be strongly influenced by the frequency of disruption seen by the individual viewer. It has been suggested that in the U.K a viewer upstream of a wind turbine may experience interference only 5-10% of the time. This is a result of interference being caused only at specific orientations of the turbine. In the area behind the wind turbine, interference could be experienced 50% or more of the time in those areas where interference does occur. These figures are however dependant on the strength of the TV signal, the local topography, the prevailing wind direction and on television viewing hours.⁽⁵⁰⁾

The two Megawatt wind turbines in Sweden have both caused television interference to different degrees. The turbine at Maglarp causes severe and continuous television interference in the area located

behind the wind turbine (ie. as seen from the transmitter). The affected area is parabolic in shape and includes several farms and part of the village Skare at the coast. The depth of the parabolic area is measured to 2000m at the coast. The interference problem was overcome by installing a slave transmitter, on a meteorological tower, 250m north-west of the turbine. Undisturbed television signals are received here and are retransmitted to a limited area. (64)

The turbine at Nasudden shows television interference to be less than expected. One of the reasons for this is that the signal strength between 10m and 120m above ground level is almost independent of height. This means that the direct and the reflected signal have approximately the same strength which does not cause severe disturbance. Another reason for the low disturbance is that the pulse length of the disturbance is long, due to the steel turbine blades, and these longer pulses are capable of being sorted by the TV receiver. This is contrary to the suggestion that conducting blades will cause more disturbance than insulated composite blades. Observed television disturbances occurred when the rotor blades were vertical, resulting in a flickering 50 times per minute. The disturbance was only experienced on one particular television channel. No complaints have been received about television interference from people in the neighborhood, with the distance to the nearest farmhouse being about 750m. The distance to the television transmitter is approximately 58km. (65)

The British have also reported television interference due to the operation of a 300 kW aerogenerator at Burger Hill on the Orkney Islands. Before the wind turbine was installed, tests were done on the strength of existing TV signals. The results showed that the houses in the shadow of Burger Hill were outside the area of the local TV transmitter. It was concluded that any minor change to the existing television signals would cause a very noticeable effect on TV reception in the area. After the commissioning of the HWP-300 and the W.E.G. 200kW machines, complaints about television

interference were received from many households. Interference took the form of bright and dull pulses coinciding with the rotational speed of the turbine blades. The worst interference occurred when the turbine blades were orientated at 90 degrees to the television signal. An active television deflector was then installed on the meteorological mast to remedy the interference problem. This deflector does not provide top quality reception to the affected viewers, but it restored the signal to a level which was better than that attainable by these viewers prior to the installation of the wind turbines. (55)

The Growian WECS in Germany also causes television interference affecting households in the immediate neighborhood of the turbine. Initial examination of the electromagnetic interference showed two variations in the field strength per revolution of the rotor. It was found that the amplitude and the duration of the interference depends on the TV frequency and the distance from the wind turbine. The maximum interference seemed to be caused by the shading of the television signal by the rotor blades. A reflection interference phenomenon has also been found, but has not yet been intensively investigated. (57)

Electromagnetic interference is very site specific and while it may not be a deterrent to wind energy as a whole, it requires that sites, particularly those near the fringe of television reception areas, be analysed to ascertain whether or not interference will be encountered. The siting of wind turbines must take into account any television relay stations in the area and the links between these stations. These stations are generally features of remote areas which are often the areas with the most suitable wind regimes for siting wind turbines. At some extra cost, television interference can, in certain cases, be overcome by the reorientation of aerials, where an alternative signal is available, cable television systems or by the installation of new repeater stations or deflecting devices.

7.3 VISUAL ACCEPTABILITY

It is thought that the public acceptability of wind turbines will be strongly influenced by the visual impact of these machines. This is however uncertain, since public acceptability and hence visual acceptability depend primarily upon subjective opinion, but also upon the value of the landscape and the aesthetic design of the machine. Acceptability may also include opinions held on energy and other matters.

Public reactions to wind generators in Sweden and the U.S.A, have been positive and encouraging. (50, 54, 60) The 2MW MOD-1 wind turbine sited at Boone in North Carolina was a tourist attraction until it was dismantled in 1983. These views could however be based on the present existence of only a few machines, and the novelty of these initial turbines.

The slender design of large modern machines which stand alone, tends to provoke favourable comment, but the extent to which siting wind turbines in clusters would be favorably received is uncertain, and will vary between locations. It is evident that for an array of wind turbines in a flat landscape, an observer is conscious of about only 3 turbines. Large wind turbines sited individually are visually dominant for a radius of at least 1 000m, and are perhaps extremely dominant at 500m. The motion of the blades increases the visual impact compared with static structures, for the rotor motion tends to exaggerate their size. (60)

The design of wind turbines takes into account public preference. Surveys have suggested that tubular towers are preferred to lattice structures, which is the trend in the design of the modern wind turbine towers. With public approval of the turbine design, it is perhaps a matter of common sense in siting a wind turbine in such a manner as to minimize the visual impact.

7.4 LIGHT HINDRANCE

Operational experience with wind turbines has shown that the shadow formed by rotating turbine blades, could cause serious problems. The possible health hazard associated with light flicker should be considered when investigating possible wind turbines sites. This interference phenomena should be considered in the area immediately surrounding a wind turbine or when siting turbines in built up areas.

It is known that people get disturbed by a periodic shadow caused by an object rotating in the sunlight. The extent to which people may be disturbed is greater for people indoors because almost all the light that would reach an observer would be modulated in intensity by the turbine blades. If a wind turbine is sited between the sun and a building it should cause shadow hindrance for certain periods. This period could range from hours to days depending on the sun's position, the daily sunshine hours and the turbines operational time.

The passage frequency or flicker frequency gets its name from perceptual physiology. It is used in the field of lighting technology where light sources can cause flicker frequencies. The flicker frequency of a turbine rotor would be dependant on the rotor speed(S) and the number of blades n, and is defined as :⁽⁰²⁾

$$f = S.n.1/60 \text{ Hz (s}^{-1}\text{)}$$

The flicker frequency resulting from medium sized wind turbines in the Netherlands ranges between 1 and 6 Hz.

The degree to which light flicker will affect an observer depends primarily on the frequency of the flicker. At frequencies below

1 Hz every change in light intensity can be felt, but at frequencies greater than 50-80 Hz, flickers are no longer perceived separately. This higher frequency range is known as the flicker fusion frequency and is the principal on which motion picture and television appear to give continuous movement. Experimental work done on flicker frequencies in tunnels shows that flicker frequencies between 5 and 10 Hz are felt as a nuisance by most people. Other work on light flicker shows most people are maximally sensitive to flickers between 7 and 14 Hz. Light flicker at frequencies below 2,5 Hz and greater than 40 Hz are not perceived as a nuisance.

Problems caused by light flicker also occur in aviation. Propeller driven aircraft and helicopters have been known to give rise to light flicker which has caused people to become suddenly dizzy and disorientated. Seizures may be triggered by light flicker among people suffering from epilepsy.

From the literature on light flicker, it has been suggested that light flicker frequencies between 5 and 20 Hz should definitely be avoided. It is however suggested that to avoid light flicker, frequencies greater than 2,5 Hz should also be avoided. It should be borne in mind that these frequency thresholds do not apply to wind turbines specifically, but to the subject of light hindrance in general.⁽⁶²⁾

The zone in which shadow hindrance may occur can be accurately calculated taking into account the path of the sun, the wind direction, the time of day, time of wind and the position of the turbine.⁽⁶²⁾ Knowing the position of the intermittent shadow, it will be possible to assess whether or not the wind turbine will cause light flicker. If there is a chance of light flicker being caused and the turbine has a flicker frequency greater than an accepted threshold, say 2,5 Hz, the options of overcoming the light hindrance should be investigated. A wind turbine can be automatically stopped if light hindrance only occurs at certain times of the year, or dwellings can be fitted with blinds to minimize any light flicker.

7.5 ECOLOGICAL IMPACTS

The impact of wind turbines on the ecology can be divided into two sections, viz. the effect on the microclimate and the effect on birds and other flying life forms.

9.5.1 Microclimate

A wind turbine would introduce minor changes in :

1. Wind speed
2. Turbulence
3. Temperature
4. Available moisture
5. Other wind influenced atmospheric parameters, in the vicinity of the wind turbine.

The degree to which any of the above parameters would change will depend largely on the type of wind generator installed. It is, however, expected to be small. The small change in these atmospheric parameters has been confirmed by tests on the area surrounding a MOD-0 wind turbine. Since the change is expected to be very small, it can be assumed that these parameters will not introduce any measurable secondary effects on the flora and fauna in the area. The hazard to birds caused by the change in microclimate will be less than that created by tall buildings.

The enhanced turbulence at heights will still be less than the ambient ground level turbulence and will also be small in comparison with natural wind fluctuations. It has, however, been suggested that aircraft should not fly closer than six times the turbines diameter while the wind turbine is operating. The installation of a wind turbine at a particular site is expected to have little effect on the dispersion of flue gases from nearby chimneys. (50, 61)

9.5.2 Birds and other flying lifeforms

The significance of birds, bats and insects colliding with the rotating turbine blades or the tower, would depend on the location, time of year and the prevailing climatic conditions. From practical experience it is noticed that birds living close to wind turbines learn to avoid these obstacles in their own territory and are not at risk of being hit by a turbine blade. The main hazard a wind turbine may cause to birds is the threat it poses to migratory birds. Wind turbines should, however, have little or no effect on these birds during the day or on windless nights. It is also estimated that only 10-20% of all migratory birds fly below 200m and since the maximum height reached by a 100m diameter turbine is 175m, it is unlikely that a wind turbine would be a hazard to these birds. It has also been shown that even if birds do fly through the swept area of the turbine blades, the chances of them being hit are very small. (50, 81)

7.6 LAND USE RESTRICTIONS

A wind turbine itself utilizes very little land, but its installation may have to include the construction of a small building for instrumentation, a transformer and power lines. The construction of a road to the turbine site could have a greater land use impact than the wind turbine, but on the other hand it may be regarded by farmers as a benefit.

Areas of land which could probably be ruled out for the siting of wind turbines include :

1. Forests
2. Urban land
3. Military land
4. National and private parks and nature reserves
5. Areas of natural beauty.

The minimum distance a wind turbine should be placed from habitation will be largely determined by noise, electromagnetic interference, visual acceptability, light hindrance and safety. Sweden has adopted a minimum distance of 200m whereas in the U.K an arbitrary distance of 500m is being used. This distance is being assumed reasonable until more experience with wind turbines is gained. (50)

7.7 SAFETY

It is essential that the safety of an operating wind turbine should receive high priority during its design stages. Modern wind turbines have many safety features which often include crack detectors on turbine blades. These crack detectors are installed to reduce the possibility of a turbine blade becoming detached and flying off. The small possibility that a rotor or part of a rotor could fail and its implications should however be considered.

Studies done on blade failure consider the various modes of failure. It is estimated that a blade fragment will be thrown approximately 350m, for a particle shed near the blade tip at 10% overspeed, and tumbles, to over 2 000m for a fragment which adopts a stable flight configuration shed at the limiting runaway tip speed of 300m/s (1080 km/h!). Even within the range of particle or whole blade throw distances, the overall risk of an individual being struck, is extremely low and well below the probability of 10^{-7} per year associated with death by lightning strikes in the United Kingdom. (50, 63)

The safety of aircraft should also be considered especially when siting a large wind turbine close to an airfield.

7.8 THE AGULHAS SITE

From the foregoing discussion it is evident that if wind turbines were to cause any significant impact on the environment in a proposed area, it would be through electromagnetic interference, noise generation and visual acceptability.

Light hindrance would not cause any problems in this area for the windiest site, most suitable for siting a WECS, is at least 5km from the town of Cape Agulhas itself. Shadows caused by rotating turbine blades only cause hindrance problems in close proximity to wind turbines but there are no residences, including farmhouses, within 3km of this recommended site. This environmental impact has its greatest effect on the axis of the prevailing winds which is in the East-West direction at Cape Agulhas. It is however in these directions that residences in the area are most distant from the windiest site thus further reducing any possible light hindrance problems.

The impact that a wind turbine has on the ecology and its operational safety have been found to have very little, if any, impact at existing WECS sites. Cape Agulhas does not have any characteristics making it an exception, and it is therefore reasonable to suggest that these two factors would not have any impact if a wind generator were to be sited here.

The question of land use restrictions would also not play a role on the choice of a suitable site as all of the land in this area is privately owned and none of it is zoned as any type of restricted area. The land is used predominately for farming where the soil is fertile enough to support crops. The soil from the coast to approximately 10km inland is very sandy and unsuitable for agricultural purposes. Where the fertility of the soil increases, crops, such as wheat, are grown. This approximate distance of 10km varies along the coast but it is roughly the distance to the foot of

the hills that run parallel to the coast. It is inland of these hills that the fertility of the soil is high enough to support crops. From this aspect the strip of land along the coast would be well suited for wind turbine sites.

The generation of noise from a wind turbine cannot be prevented. By installing upwind horizontal axis machines, which are well sound proofed, the noise generation from both blade shadowing and mechanical movement can be minimized. The degree to which the noise generated from the turbine will effect inhabitants of the area will depend largely on the distance from the turbine site. Since the windiest site is 5km away from Cape Agulhas itself, it is unlikely that the noise generated will be audible from the town. The prevailing winds in the area are on average high and constant over time which would produce a relatively high background noise level, reducing the difference between non-operating and operating noise levels.

Television interference may occur in this area due to the scattering of television signals. Windy locations are the most suitable for siting WECS and these areas are usually found in remote locations. It is however in these areas that television interference is most likely to occur. This happens for the simple reason that people don't generally choose to live in areas having high winds and therefore television transmitter stations are not usually required in these remote areas. The fact that the area being investigated is close to the coast will reduce the likelihood of interference since the distance from an inland television transmitter station to a wind turbine would be approximately the same as that to the residences in the area. The use of the PAL transmission system in South Africa will also help to reduce the overall possibility of interference occurring. Television interference can, in most cases, be overcome by the installation of additional transmitting devices. The cost of returning the television signal to its original strength, if interference does occur, must then be included when calculating the cost of wind generated power.

The visual impact that a wind turbine has on the surrounding environment is extremely difficult to assess. The assessment of a turbine's visual acceptability incorporates many subjective viewpoints. If a large wind generator is installed in this area, it could become a tourist attraction, as has happened in many other countries, and could provoke favourable comment. To minimize any visual impact a generator might cause it would be necessary to keep the distance between it and any observers to a minimum. The worst case, a large wind generator on top of an isolated hill, would even tend to get lost in the surroundings at a distance of 3km. Since the most favourable site is very isolated, the siting of a turbine at this point would not draw a negative response.

The exploitation of the available wind energy potential would require a large number of installed wind turbines. From international experience it has been established that both the siting of wind turbines in wind parks, and the siting of isolated turbines, are environmentally acceptable, but that both arrangements do have minor associated environmental impacts.

CHAPTER EIGHT

8. CONCLUSIONS

The enhancement in the wind speed measured through both physical and numerical modeling was found to have a maximum value of approximately ten percent, although higher values for topographical wind enhancement were initially thought possible. The value for the reference velocity does however have a direct bearing on the absolute value for percentage wind enhancement. Throughout this project the velocity measured at the lighthouse was taken as the reference value and the percentage wind enhancement was expressed, relative to this velocity. If this reference velocity should change, the absolute values for wind enhancement in the investigated area would change, although the relative enhancement would remain the same. Bearing this in mind it can be concluded that there are areas in the Cape Agulhas region with wind speeds of the order of five percent greater than those recorded by the Weather Bureau at the lighthouse.

The reason for the point of maximum wind enhancement occurring close to the summit of the northern ridge as opposed to the center of the valley, as initially expected, is due to the valley not being deep and constricted enough. Since the shape of the valley is not ideal for producing increased wind velocities, the airflow is enhanced to a greater extent by the surrounding ridges. This result is in accordance with the theory on topographical wind enhancement discussed in chapter one. The hill that produces the maximum wind enhancement lies parallel to the prevailing wind direction which is not the ideal orientation for maximum enhancement over a hill. The same hill shape would be expected to produce greater enhancement if it were orientated perpendicular to the wind direction

The fact that the airflow over the investigated region varied considerably close to the ground but became more uniform as the

height increased, is clearly visible from all the results. This characteristic implies that the airflow over a hill is influenced predominantly by the overall hill shape as height increases, than by localized changes in topography.

The investigated site does not possess any factors making it environmentally unsuitable for siting WECS. The environmental impact that a wind turbine imposes on its surroundings will probably be less in the area surrounding Cape Agulhas than the majority of other windy locations in South Africa. Although the wind enhancement in the investigated area was, at maximum, only higher by ten percent with respect to the lighthouse wind data, this region is an area of high annual wind speeds. The daily wind speed curve and the results from the numerical modelling exercise both indicate that there would be a high percentage utilization of the winds resulting in a high wind energy production. The fact that the daily wind speed curve is relatively flat also allows for a simple matching procedure between the prevailing winds and available wind turbines. By considering both the environmental aspects and the wind energy statistics for the Agulhas site it can be concluded that this region is a suitable WECS site.

CHAPTER NINE

9. RECOMMENDATIONS

The following recommendations are made in the light of the work done for this project and other work done on the feasibility of wind turbines in South Africa.

1. Accurate wind speed and direction data should be gathered for the Cape Agulhas area. This could be done either by installing an anemometer or by having access to the wind data recorded by other organisations in the vicinity of Cape Agulhas (eg. from ESCOM's nuclear siting programme or Armscor's test range). These statistics are essential for the correct matching between the prevailing winds and available wind turbines.
2. The numerical model should be re-run for the Soetanysberg mountain range which lies approximately 15km west of the Cape Agulhas lighthouse. The comparison between the results of this exercise and those yielded from this project would give the best overall wind turbine site in this area.
3. Vertical velocity profiles should be taken at a few points over the area investigated in this project to examine the accuracy with which the numerical model predicts vertical velocity profiles
4. After establishing the optimum position for a wind turbine and knowing the absolute values of wind speeds in this area, a detailed costing analysis should be completed. The cost of wind generated power should not however be the major criterion for establishing its feasibility but rather the fact that it is essential to gain experience with alternative energy production methods for their efficient operation, should be of prime consideration

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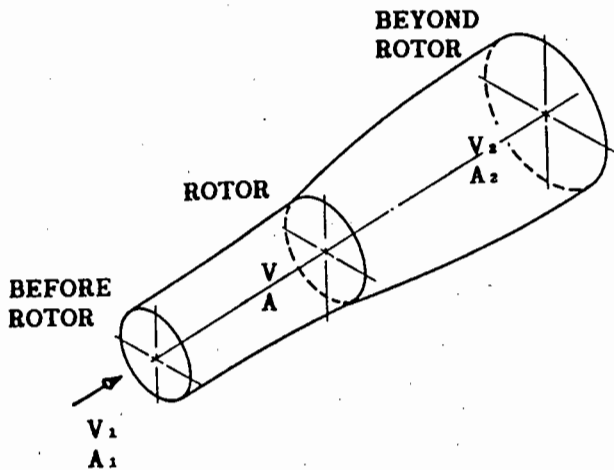
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APPENDIX 1.1

DERIVATION OF THE BETZ LIMIT

Consider the following arrangement:



- V_1 = Velocity upstream of the wind turbine
- V = Velocity through the rotor
- V_2 = Velocity downstream of the wind turbine
- A_1 = Area of the flowstream upwind of the wind turbine
- A = Area of the flowstream through the rotor
- A_2 = Area of the flowstream downwind of the wind turbine

To develop mechanical energy from the wind implies the extraction of kinetic energy

$$\therefore V_2 < V_1 \dots \dots \dots (\text{equ.1})$$

and from continuity $m_1 = m_2 = m$

$$\therefore \rho A_1 V_1 = \rho A_2 V_2 \dots \dots \dots (\text{equ.2})$$

It then also follows that $A_2 > A_1 \dots \dots \dots (\text{equ.3})$

The force exerted on the wind turbines rotor can be expressed as:

$$F = \rho A V (V_1 - V_2) \dots \dots \dots (\text{equ.4})$$

APPENDIX 1.1

and the Power extracted:

$$P = F V = \rho A V^2 (V_1 - V_2) \dots\dots\dots(\text{equ.5})$$

The change in kinetic energy is give by:

$$\begin{aligned} \delta KE &= \frac{1}{2} m_1 V_1^2 - \frac{1}{2} m_2 V_2^2 \\ &= \frac{1}{2} \rho A V V_1^2 - \frac{1}{2} \rho A V V_2^2 \\ &= \frac{1}{2} \rho A V (V_1^2 - V_2^2) \dots\dots\dots(\text{equ.6}) \end{aligned}$$

But the change in kinetic energy = the power extracted

$$\begin{aligned} \therefore \rho A V^2 (V_1 - V_2) &= \frac{1}{2} \rho A V (V_1^2 - V_2^2) \\ V (V_1^2 - V_2^2) &= \frac{1}{2} (V_1 - V_2)(V_1 + V_2) \\ \therefore V &= \frac{1}{2} (V_1 + V_2) \dots\dots\dots(\text{equ.7}) \end{aligned}$$

Now from equation 4 $F = \rho A V (V_1 - V_2)$
and from equation 7 $V = \frac{1}{2} (V_1 + V_2)$

$$\therefore F = \frac{1}{2} \rho A (V_1^2 - V_2^2) \dots\dots\dots(\text{equ.8})$$

From equation 5 $P = F V$

$$\begin{aligned} \therefore P &= \frac{1}{2} \rho A (V_1^2 - V_2^2) \frac{1}{2} (V_1 + V_2) \\ &= \frac{1}{4} \rho A (V_1^3 - V_1^2 V_2 - V_1 V_2^2 - V_2^3) \dots\dots\dots(\text{equ.9}) \end{aligned}$$

By differentiating this power function w.r.t. V_2 we get:

$$dp/dV_2 = \frac{1}{4} \rho A (V_1^2 - 2 V_1 V_2 - 3 V_2^2) \dots\dots\dots(\text{equ.10})$$

APPENDIX 1.1

By setting this derivative equal to zero we can establish the maximum extractable power.

$$\frac{1}{4} \rho A (V_1^2 - 2 V_1 V_2 - 3 V_2^2) = 0$$

$$\therefore \text{either } V_2 = -V_1 \quad (\text{this has no meaning})$$

$$\text{or } V_2 = 1/3 V_1 \quad \dots\dots\dots(\text{equ.11})$$

by substituting this value for V_2 in the equation for power, (equation 9) we get:

$$\begin{aligned} P &= \frac{1}{4} \rho A (V_1^3 + 1/3 V_1^3 - 1/9 V_1^3 - 1/27 V_1^3) \\ &= 8/27 \rho A V_1^3 \quad \dots\dots\dots(\text{equ.12}) \end{aligned}$$

This value for the maximum extractable power is 59,3 % of the theoretical power available in the wind and is known as the Betz limit.

APPENDIX 2.1.

THE NINE SITES USED IN ROBERTS' STUDY WITH AVERAGE WIND SPEEDS

SITE	MEAN WIND SPEED (ms^{-1})	
	ROBERTS	WEATHER BUREAU
Alexander Bay	4,3	4,1
Cape Town (D.F. Malan)	4,3	4,0
Durban	3,2	3,3
East London	4,3	4,7
Johannesburg	3,0	3,3
Kimberley	3,0	3,6
Pietersburg	2,4	2,6
Port Elizabeth	4,4	4,3
Pretoria	1,5	1,8

(Source: Ref.7.)

APPENDIX 2.2.

BEAUFORT SCALE FOR PREDICTING WIND SPEEDS

BEAUFORT NUMBER	WIND SPEED			DESCRIPTIVE TERMS
	knots	ms ⁻¹	km/hr	
0	1	0.0-0.4	<1	CALM
1	1-3	0.5-1.5	1-6	LIGHT AIR
2	4-5	2.0-3.0	7-11	LIGHT BREEZE
3	7-10	3.5-5.0	12-19	GENTLE BREEZE
4	11-16	5.5-8.0	20-28	MODERATE BREEZE
5	17-21	8.1-10.9	29-38	FRESH BREEZE
6	22-27	11.4-13.9	39-49	STRONG BREEZE
7	28-33	14.1-16.9	50-61	NEAR GALE
8	34-40	17.4-20.4	62-74	GALE
9	41-47	20.5-23.9	75-88	STRONG GALE
10	48-55	24.4-28.0	89-102	STORM
11	56-63	28.4-32.5	103-117	VIOLENT STORM
12	64-71	32.6-35.9	118-133	HURRICANE

(Source: Ref. 1,6)

APPENDIX 2.2.

BEAUFORT NUMBER	SEA CRITERION	LAND CRITERION
0	Sea is like a mirror.	Smoke rises vertically
1	Ripples with the appearance of scales are formed but without forming crests.	The wind inclines the smoke but weathercocks do not rotate.
2	Small wavelets, still short but more pronounced. Crests have a glassy appearance and do not break.	The leaves quiver. One can feel the wind blowing on one's face.
3	Large wavelets. Crests begin to break. Foam of glassy appearance. Perhaps scattered with white horses.	Leaves and little branches move gently.
4	Small waves, becoming longer. Fairly frequent white horses.	The wind blows dust and leaves onto the roads. Branches move
5	Moderate waves, taking a more pronounced long form; many white horses are formed.	Little trees begin to sway.
6	Large waves begin to form; the white foam crests are more extensive everywhere. (Probably some spray.)	Big branches move. Electrical wires vibrate. It becomes difficult to use an umbrella.

APPENDIX 2.2.

BEAUFORT NUMBER	SEA CRITERION	LAND CRITERION
7	Sea leaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind.	Trees sway. Walking against the wind becomes unpleasant.
8	Moderately high waves of greater length; edges of crests begin to break into spindrift. The foam is blown in well marked streaks along the direction of the wind.	Little branches break. It is difficult to walk outside.
9	High waves. Dense streaks of foam along the direction of the wind. Crests of waves begin to topple, tumble and roll over. Spray may affect visibility.	Branches of trees break.
10	Very high waves with long overhanging crests. The resulting foam in great patches is blown in dense white streaks along the direction of the wind. The whole surface of the sea takes on a white appearance. The tumbling of the sea becomes heavy and shock-like. Visibility affected.	Trees are uprooted and roofs are damaged.

APPENDIX 2.2.

BEAUFORT NUMBER	SEA CRITERION	LAND CRITERION
11	Exceptionally high waves. The sea is completely covered with long white patches of foam lying along the direction of the wind. Everywhere the edges of the wave crests are blown into froth. Visibility affected.	Extensive destruction. Roofs are torn off. Houses are destroyed and so on.
12	The air is filled with foam and spray. Sea completely white driving spray; visibility very seriously affected.	

(Source: Ref. 1,6)

APPENDIX 2.3.

THE COST OF WIND GENERATED ELECTRICITY AT NINE SITES

WIND TURBINE STATION	WIND SPEED	ENERGY COST (cents/kW-hr)			
		DVI 15-3	WTS-75	WINDANE 29	WINDANE 9
Port Elizabeth	4.4	22.6	20.8	25.3	15.6
Alexander Bay	4.3	22.8	22.3	23.9	16.0
Cape Town	4.3	22.3	20.9	25.0	16.3
East London	4.3	28.3	25.3	30.2	18.9
Durban	3.2	34.2	30.9	37.6	23.6
Kimberley	3.0	67.3	53.4	64.5	37.6
Johannesburg	3.0	94.1	70.0	85.7	47.2
Pietersburg	2.4	117.3	86.9	104.7	56.8
Pretoria	1.5	1493.4	901.9	814.6	423.9

DVI 15-3 = 15 kW rated turbine (Vertical Axis)

WTS-75 = 2000 kW rated turbine

Windane 29 = 265 kW rated turbine

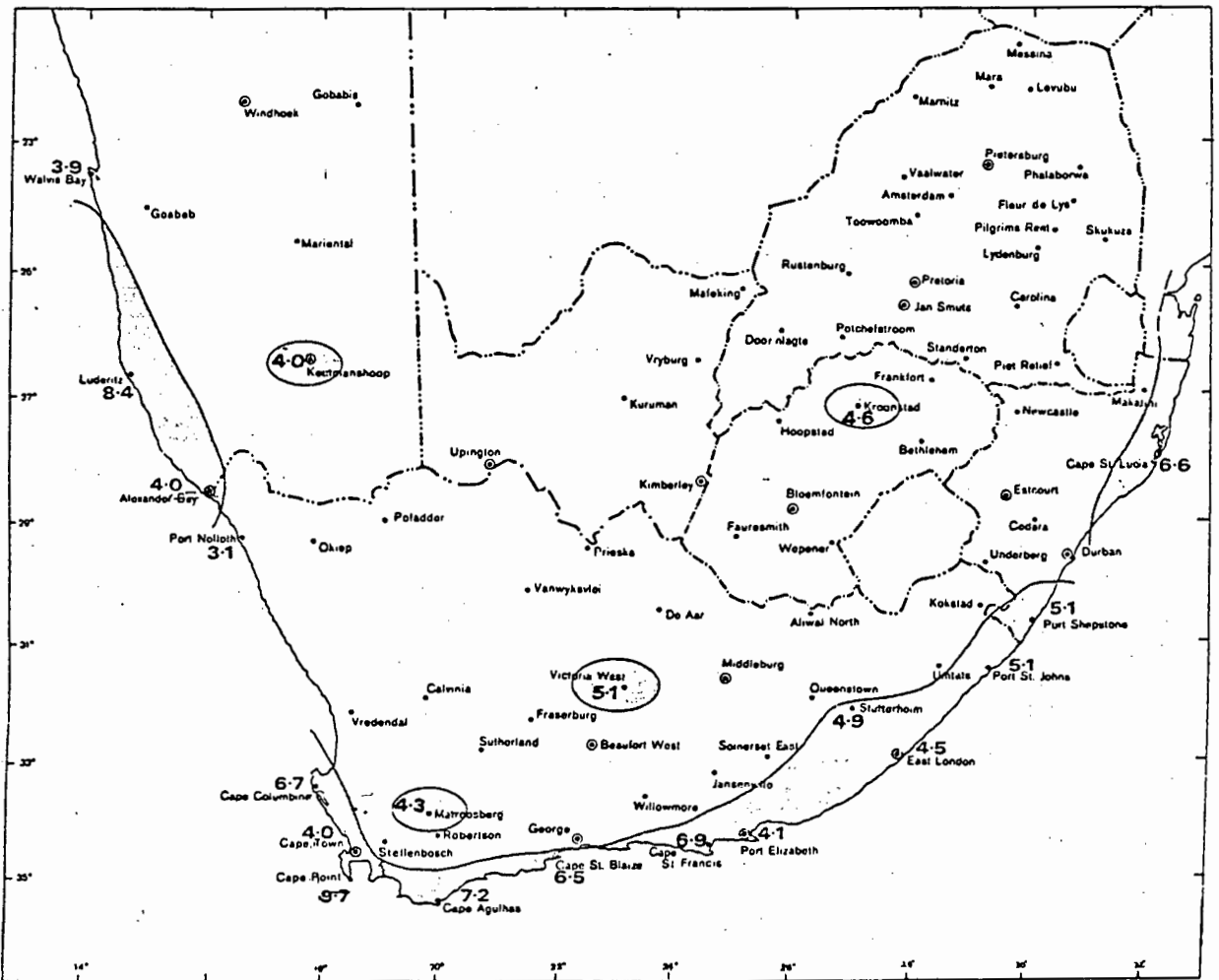
Windane 9 = 15.7 kW rated turbine

(Source: Ref. 7.)

APPENDIX 2.4.

MAP SHOWING THE WIND ENERGY POTENTIAL OVER SOUTH AFRICA

Areas with Mean Annual Wind Speeds (normalised to 10 m above ground) Greater Than 4 m/sec.



(Source Ref. 12)

APPENDIX 2.5.

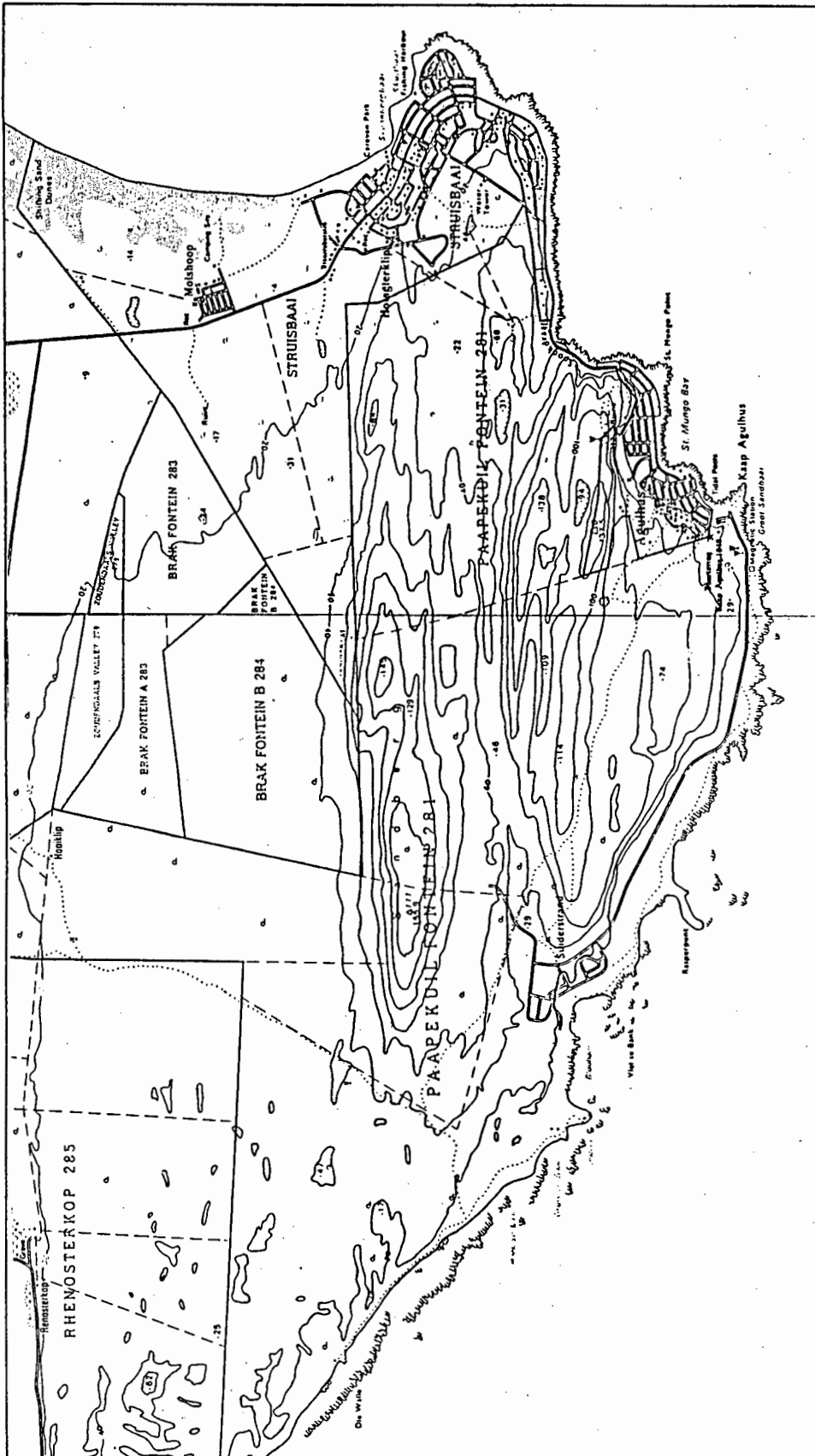
TABLE SHOWING MONTHLY WIND SPEED VALUES FOR SELECTED SITES OVER SOUTH AFRICA.

TOWN	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Alexander Bay	5.3	4.6	4.0	3.1	2.6	2.8	2.8	3.4	4.0	4.7	5.2	5.2	4.0
Cape Point	10.5	10.5	10.5	10.0	8.2	8.6	8.5	9.0	9.5	10.1	11.1	10.0	9.7
D.F. Malan	4.9	4.6	4.1	3.4	3.2	3.3	3.3	3.6	3.9	4.2	5.0	5.3	4.1
Cape Agulhus	7.8	7.5	7.1	6.9	6.3	6.2	6.5	6.9	7.7	8.2	7.6	7.7	7.2
Cape St. Francis	7.4	6.9	6.4	6.4	6.1	5.8	6.5	6.9	7.7	7.8	7.2	7.7	6.9
Port Elizabeth	4.6	4.4	3.9	3.6	3.1	3.0	3.2	3.9	4.4	4.9	4.8	4.5	4.0
East London	4.6	4.6	4.3	4.2	4.1	4.4	4.4	4.7	4.8	5.0	4.9	4.7	4.6

(Source: Ref. 21)

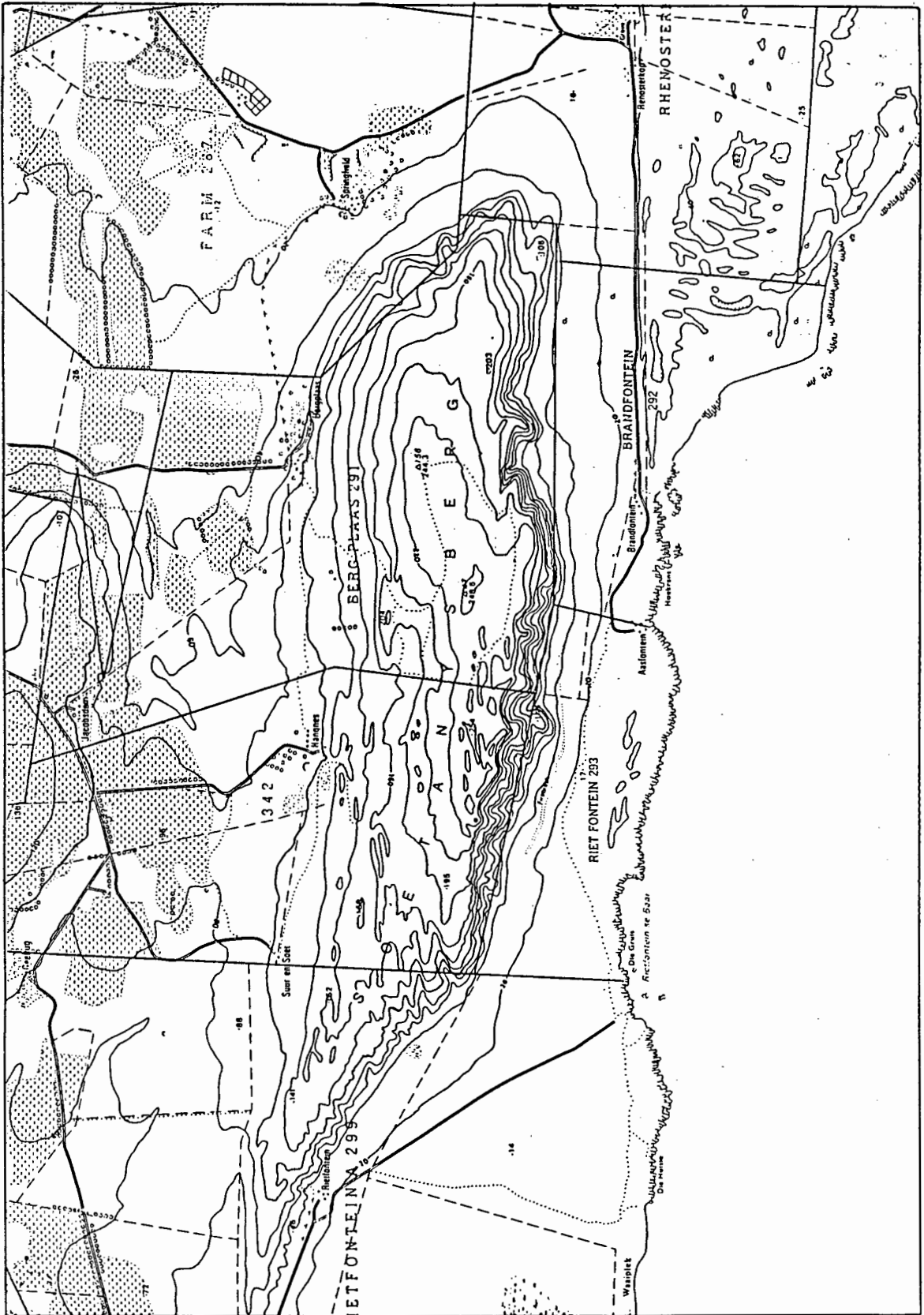
APPENDIX 4.2. (a)

POSSIBLE AREAS TO BE MODELLED: (a) The Sandberg Area



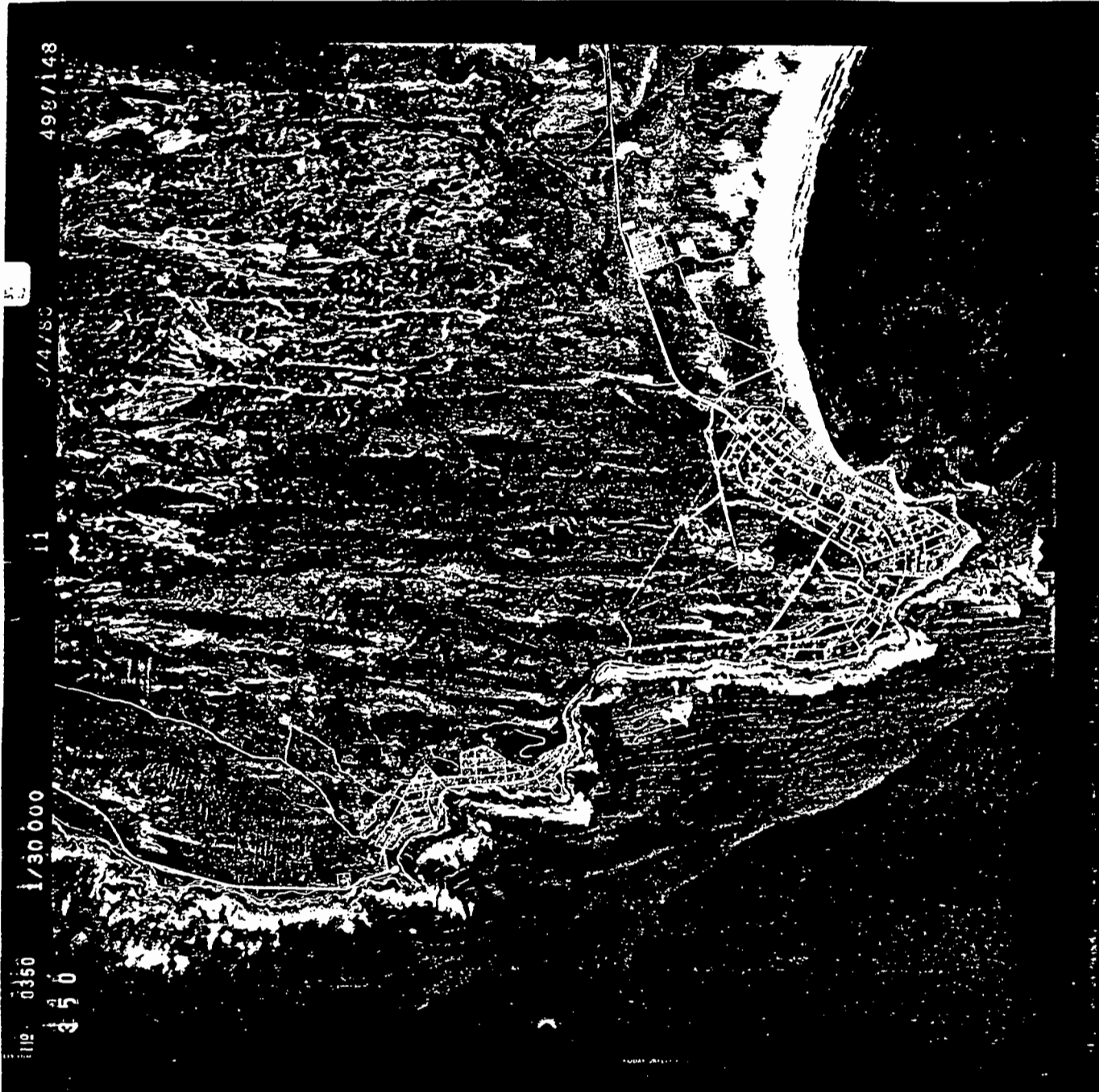
APPENDIX 4.2. (b)

POSSIBLE AREAS TO BE MODELLED: (b) The Soetansberg Area



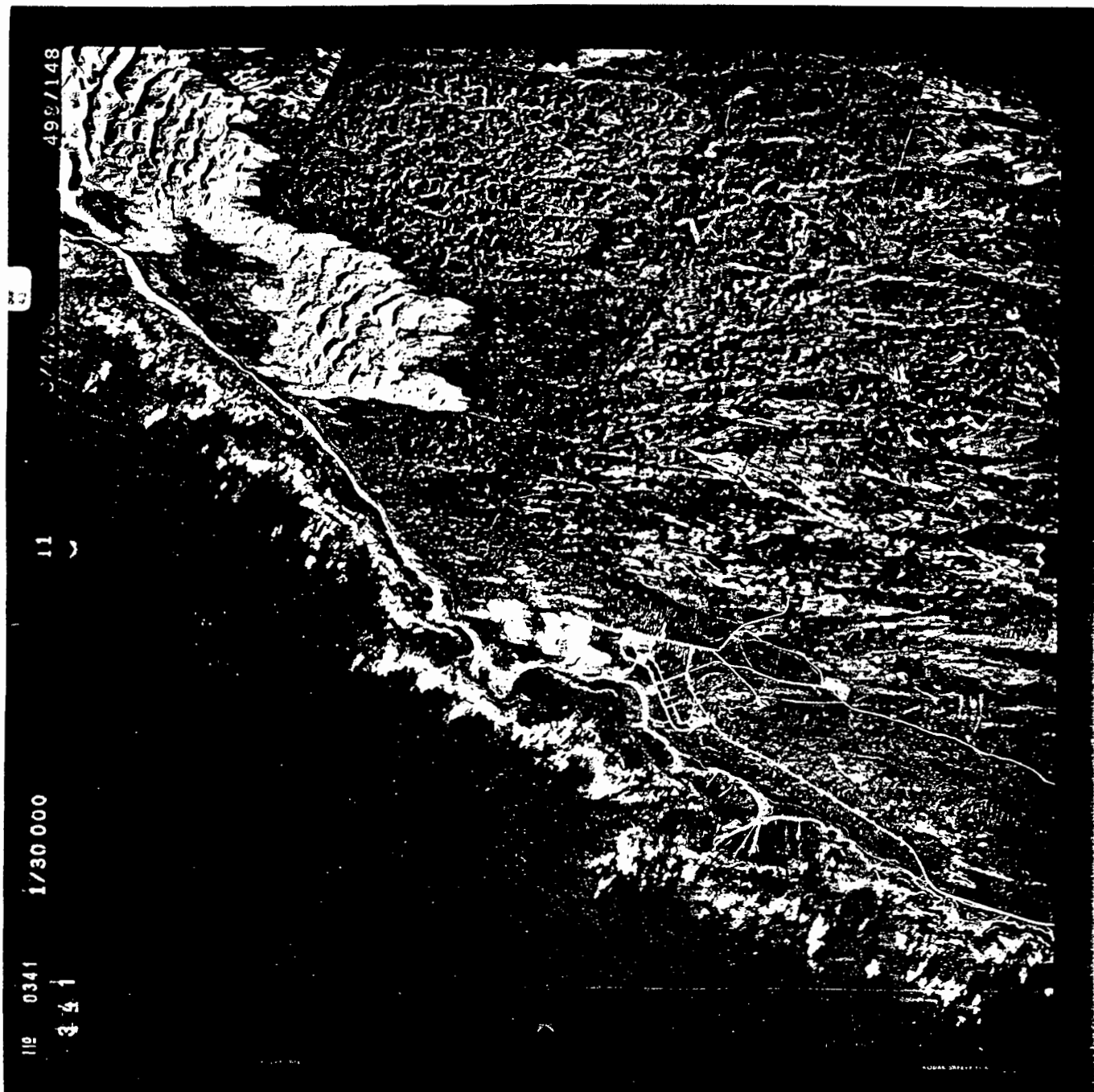
APPENDIX 4.3. (a)

AERIAL PHOTOGRAPHS VIEWED: (a) East end of the Sandberg Area



APPENDIX 4.3. (b)

AERIAL PHOTOGRAPHS VIEWED: (b) West end of the Sandberg Area



APPENDIX 4.3. (c)

AERIAL PHOTOGRAPHS VIEWED: (c) East end of the Soetansberg Area



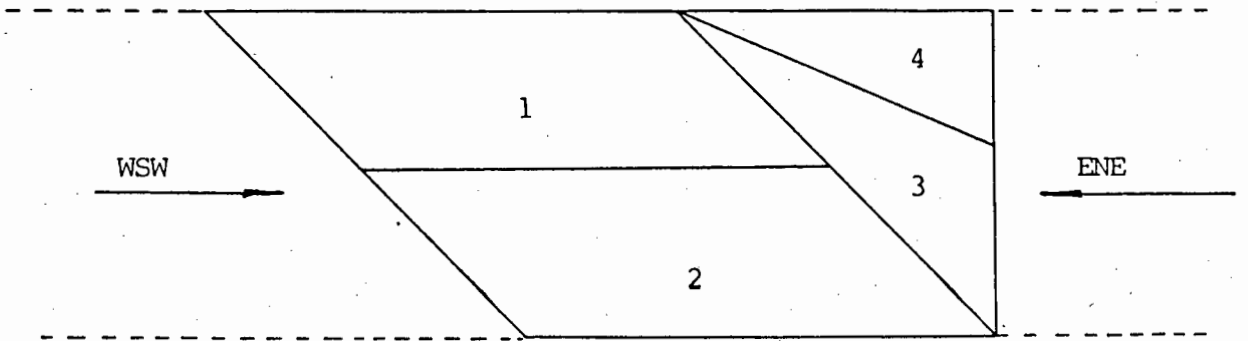
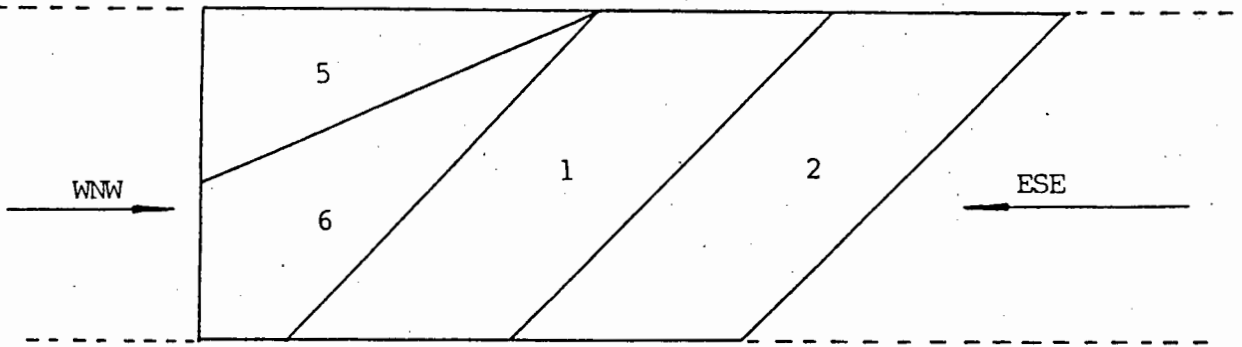
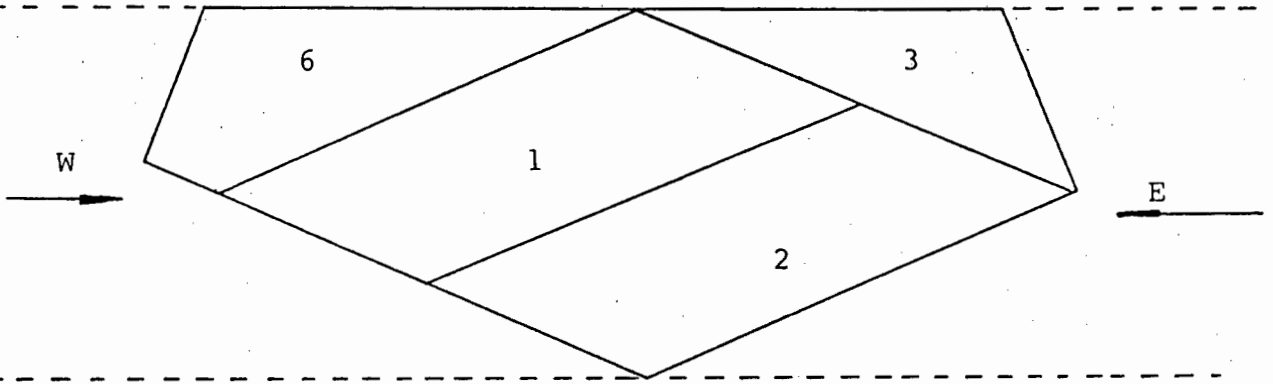
APPENDIX 4.3. (d)

AERIAL PHOTOGRAPHS VIEWED: (d) West end of the Soetansberg Area



APPENDIX 4.4.

POSSIBLE MODEL ARRANGEMENTS IN THE WIND TUNNEL



APPENDIX 4.5.

EQUATIONS FOR THE CALIBRATION OF THE PROBE

2nd Order Equation:

$$\text{Velocity} = 15,090 - 13,770*V + 3,142*V^2$$

3rd Order Equation:

$$\text{Velocity} = -17,498 + 21,940*V - 9,436*V^2 + 1,432*V^3$$

4th Order Equation:

$$\text{Velocity} = 33,943 - 52,912*V + 30,389*V^2 - 7,779*V^3 + 0,783*V^4$$

5th Order Equation:

$$\text{Velocity} = 42,446 - 56,887*V + 24,904*V^2 - 2,970*V^3 - 0,531*V^4 + 0,121*V^5$$

Where V = Probe Voltage

APPENDIX 5.1.

THE DIGITIZING PROGRAMME

```

100  REM:  DIGITIZING PROGRAMME
110  REM:
120  WINDOW 0,1100,0,1100
130  DIM X(750),Y(750)
140  PRINT "Please enter first file to be used for data storage."
150  INPUT C
160  PRINT "File number ";C
170
180  PRINT "Enter a origin from the digitizer  "
190  INPUT @2:A,R,V
200  PRINT "Enter a contour level for this file:"
210  INPUT H
220  FIND C
230  PRINT @33:H
240  PRINT "L"
250  PRINT "N  X    Y    Z"
260  PRINT "GG","Ready to go....start digitizing:"
270
280  C = C + 1          'incremental file numbers
280
290          ***INPUT LOOP***
300
310  FOR I=1 TO 500
320      N=I
330      INPUT @2:A,X(I),Y(I),S
340      PRINT "^";I;X(I);Y(I);H
350      MOVE X(I),Y(I)
360      DRAW X(I),Y(I)
370      IF X(I) > 1100 THEN 420
380      IF I <> 480 THEN 400
390      PRINT "GGOnly 20 points to go !!GG"

```

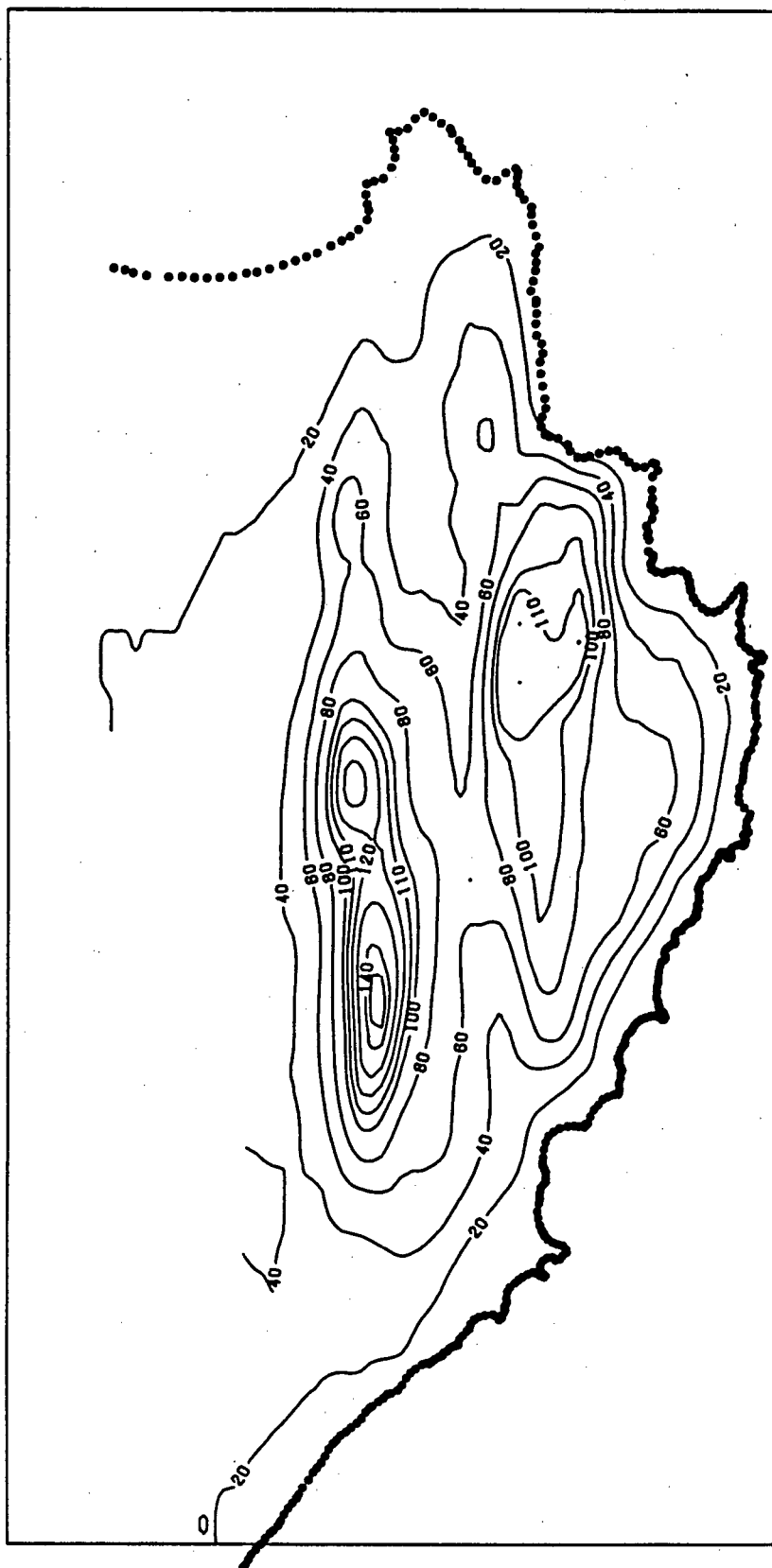
APPENDIX 5.1.

THE DIGITIZING PROGRAMME

```
400     NEXT I
410
420         ***OUTPUT LOOP***
430
440     PRINT "L"
450     PRINT "GPlease wait:  loading data to cartridge...G"
460     FOR I=1 TO N
470         IMAGE 6D.1D,6D.1D,6D.1D
480         X(I) = X(I)-R
490         Y(I) = Y(I)-V
500         PRINT @33:X(I),Y(I),H
510     NEXT I
520
530     PRINT "GGfinishedGG:  Digitize more points ? (Y/N)";
540     INPUT Y$
550     IF Y$ = "Y" THEN 160
560     IF Y$ = "y" THEN 160
570     PRINT "GGOK.  End of programme."
580     END
```

APPENDIX 5.2.

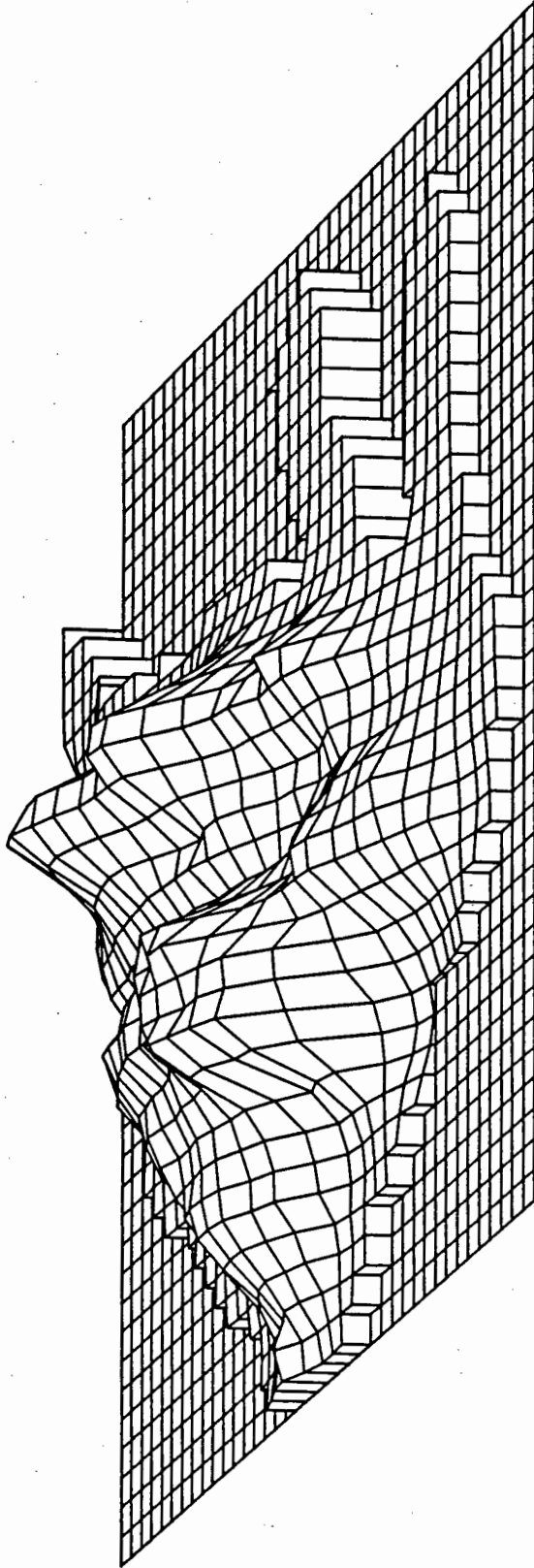
CONTOUR MAP OF THE DIGITIZED POINTS



CAPE AGULHAS

APPENDIX 5.3.

3D PLOT OF THE DIGITIZED POINTS



CAPE AGULHAS

APPENDIX 5.4. (a)

SUMMARY OF HISTORICAL WIND DATA: (a) Wind data for 1980 and 1981

Summary of data in file : C:\WASP\1980WIND.PRN (per mille)
 Number of observations : 1099 Observations skipped: 0
 Number of reading errors: 39 Wind speed bin width: 1.0 m/s

Sect	Freq	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17	A	k
0:	1.9	107	0	347	0	50	198	0	248	0	0	0	0	50	0	6.0	1.77
30:	0.2	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	10.34
60:	15.2	20	62	93	31	25	205	56	161	37	180	62	0	50	19	8.3	2.03
90:	16.7	35	28	73	6	17	237	23	254	62	147	79	17	23	0	8.4	2.67
120:	10.0	68	19	273	47	47	254	38	132	47	47	28	0	0	0	6.1	2.49
150:	0.2	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	10.34
180:	5.3	56	107	125	18	71	356	71	107	0	89	0	0	0	0	6.2	3.57
210:	0.2	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	10.34
240:	25.6	15	18	122	37	26	203	89	173	41	181	66	0	18	11	8.1	2.36
270:	20.1	15	5	141	47	14	150	70	178	52	225	66	0	33	5	8.5	2.46
300:	4.3	70	22	288	44	66	244	0	89	0	133	22	0	22	0	6.0	1.67
330:	0.3	684	0	0	0	0	0	0	316	0	0	0	0	0	0	2.3	0.87
Total		39	28	139	32	28	211	57	175	42	158	57	3	25	7	7.7	2.17

Number of calms (included): 26 Mean wind speed: 6.4 m/s

DUMP DOS RETURN
 RAWDATA>

Summary of data in file : C:\WASP\1981WIND.PRN (per mille)
 Number of observations : 1096 Observations skipped: 0
 Number of reading errors: 35 Wind speed bin width: 1.0 m/s

Sect	Freq	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17	A	k
0:	2.8	102	0	399	0	33	133	100	166	66	0	0	0	0	0	5.1	2.10
30:	0.3	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	10.34
60:	18.2	16	0	98	0	41	114	73	176	135	259	83	0	5	0	8.8	3.49
90:	12.7	23	0	111	7	7	141	81	215	148	237	30	0	0	0	8.3	4.51
120:	13.8	21	0	116	0	89	246	171	199	96	27	27	0	7	0	7.0	2.92
150:	0.3	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	10.34
180:	5.9	49	0	206	0	79	190	190	190	63	16	16	0	0	0	6.5	3.52
210:	0.3	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	10.34
240:	20.7	14	0	114	0	68	123	127	164	186	173	23	0	9	0	8.1	3.62
270:	21.1	14	0	85	0	67	210	125	179	125	134	54	0	9	0	7.9	2.93
300:	3.5	83	0	135	0	81	297	81	216	54	54	0	0	0	0	6.4	3.42
330:	0.3	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	10.34
Total		35	0	118	1	57	168	117	182	129	148	40	0	6	0	7.8	3.17

Number of calms (included): 37 Mean wind speed: 6.3 m/s

DUMP DOS RETURN
 RAWDATA>

APPENDIX 5.4. (b)

SUMMARY OF HISTORICAL WIND DATA: (b) Wind data for 1982 and 1983

Summary of data in file : C:\WASP\1982WIND.PRN [per mille]
 Number of observations : 1096 Observations skipped: 0
 Number of reading errors: 76 Wind speed bin width: 1.0 m/s

Sect	Freq	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17	A	k
0:	2.1	241	0	379	0	190	47	47	95	0	0	0	0	0	0	3.3	1.37
30:	0.5	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	10.34
60:	18.7	27	16	99	0	52	126	110	183	99	209	37	0	42	0	8.5	2.73
90:	10.2	49	0	96	0	48	86	183	259	96	106	58	10	10	0	8.1	3.27
120:	12.6	47	0	141	8	125	219	195	172	62	31	0	0	0	0	6.4	3.75
150:	0.5	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	10.34
180:	5.5	91	0	196	0	196	178	143	107	36	36	0	0	18	0	6.0	2.28
210:	0.7	718	0	0	0	0	141	0	0	0	0	0	0	0	141	2.6	0.67
240:	27.9	18	7	113	11	106	116	81	232	134	127	39	11	7	0	8.0	3.47
270:	14.3	35	14	55	14	68	157	130	185	137	151	21	7	27	0	8.1	2.99
300:	6.6	76	0	119	0	194	209	134	89	75	89	15	0	0	0	6.4	2.43
330:	0.5	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	10.34

Total 61 7 112 6 97 140 123 187 100 119 27 5 16 1 7.6 2.69

Number of calms (included): 61 Mean wind speed: 6.0 m/s

DUMP DOS RETURN
 RAWDATA>

Summary of data in file : C:\WASP\1983WIND.PRN [per mille]
 Number of observations : 1096 Observations skipped: 0
 Number of reading errors: 42 Wind speed bin width: 1.0 m/s

Sect	Freq	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17	A	k
0:	1.8	516	0	108	161	108	54	0	54	0	0	0	0	0	0	2.7	1.35
30:	1.6	578	60	121	60	0	181	0	0	0	0	0	0	0	0	1.9	1.04
60:	14.2	64	0	167	60	47	114	100	247	0	147	53	0	0	0	7.3	2.73
90:	13.1	69	0	115	72	87	180	130	231	14	94	7	0	0	0	6.7	2.95
120:	11.1	82	0	146	154	103	274	94	120	0	26	0	0	0	0	5.5	3.15
150:	3.1	294	0	153	123	246	92	31	61	0	0	0	0	0	0	4.0	2.10
180:	5.7	158	0	264	132	99	83	66	116	0	66	17	0	0	0	4.7	1.49
210:	1.6	578	0	181	181	0	0	0	0	0	60	0	0	0	0	2.3	0.98
240:	22.5	40	4	135	88	59	143	118	135	17	164	55	0	42	0	7.5	1.97
270:	16.5	55	0	104	52	40	115	98	219	12	213	69	0	23	0	8.3	2.76
300:	7.6	120	0	239	63	38	113	113	63	0	176	50	0	25	0	6.6	1.73
330:	1.3	706	74	74	74	74	0	0	0	0	0	0	0	0	0	0.9	0.81

Total 109 3 148 87 68 141 98 159 8 126 37 0 15 0 6.7 2.04

Number of calms (included): 115 Mean wind speed: 5.4 m/s

DUMP DOS RETURN
 RAWDATA>

APPENDIX 5.4. (c)

SUMMARY OF HISTORICAL WIND DATA: (c) Wind data for 1984 and 1985

Summary of data in file : C:\WASP\1984WIND.PRN [per mille]
 Number of observations : 1099 Observations skipped: 0
 Number of reading errors: 45 Wind speed bin width: 1.0 m/s

Sect	Freq	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17	A	k
0:	1.2	762	0	159	79	0	0	0	0	0	0	0	0	0	0	0.7	0.77
30:	1.6	578	0	60	60	121	121	60	0	0	0	0	0	0	0	2.5	1.19
60:	9.3	98	0	123	154	143	123	92	92	51	113	10	0	0	0	5.8	2.05
90:	19.8	46	0	77	115	158	134	115	139	67	105	34	0	10	0	6.8	2.26
120:	10.1	90	0	150	159	131	131	94	113	19	66	19	0	28	0	5.9	1.73
150:	2.2	406	0	212	85	85	85	85	42	0	0	0	0	0	0	3.1	1.40
180:	3.2	285	0	208	268	60	89	60	0	0	30	0	0	0	0	3.7	1.69
210:	3.4	269	28	169	197	169	28	112	0	0	28	0	0	0	0	3.9	1.83
240:	11.5	79	0	156	156	156	164	107	66	74	33	8	0	0	0	5.5	2.28
270:	20.5	44	0	65	111	88	139	194	166	78	69	37	0	5	5	7.2	2.69
300:	15.3	59	0	149	198	179	68	105	105	31	80	25	0	0	0	5.4	1.74
330:	1.9	489	0	357	51	102	0	0	0	0	0	0	0	0	0	2.2	1.76

Total 109 1 122 144 135 117 118 106 49 70 22 0 6 1 5.9 1.98

Number of calms (included): 115 Mean wind speed: 4.9 m/s

DUMP DOS RETURN
 RAWDATA>

Summary of data in file : C:\WASP\1985WIND.PRN [per mille]
 Number of observations : 1096 Observations skipped: 0
 Number of reading errors: 38 Wind speed bin width: 1.0 m/s

Sect	Freq	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17	A	k
0:	1.7	602	0	114	171	114	0	0	0	0	0	0	0	0	0	1.8	1.21
30:	1.9	514	0	194	146	97	49	0	0	0	0	0	0	0	0	2.4	1.56
60:	11.6	86	0	131	114	122	139	114	82	106	82	24	0	0	0	6.3	2.24
90:	14.7	68	0	45	122	116	161	141	109	116	103	19	0	0	0	6.8	2.67
120:	14.4	69	0	92	190	125	144	164	59	52	72	33	0	0	0	6.1	2.25
150:	4.1	243	46	115	229	207	23	46	69	23	0	0	0	0	0	4.1	2.04
180:	3.3	306	0	173	145	231	29	87	29	0	0	0	0	0	0	3.8	1.98
210:	1.9	514	0	0	97	291	0	97	0	0	0	0	0	0	0	3.1	1.56
240:	11.5	87	0	164	164	181	107	123	99	25	41	8	0	0	0	5.3	2.09
270:	17.5	57	0	70	92	145	135	167	119	70	97	48	0	0	0	6.9	2.69
300:	15.7	64	0	157	199	175	133	72	79	24	66	30	0	0	0	5.3	1.75
330:	1.7	602	0	227	57	57	0	0	0	57	0	0	0	0	0	2.0	1.00

Total 120 2 111 147 149 120 119 82 58 67 25 0 0 0 5.8 2.03

Number of calms (included): 127 Mean wind speed: 4.7 m/s

DUMP DOS RETURN
 RAWDATA>

APPENDIX 5.5.

COMBINED SUMMARY OF ALL HISTORICAL WIND DATA USED

Summary of data in file : C:\WASP\1985WIND.PRN (per mille)
 Number of observations : 6582 Observations skipped: 0
 Number of reading errors: 275 Wind speed bin width: 1.0 m/s

Sect	Freq	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17	A	k
0:	1.9	334	0	275	58	83	83	33	108	17	0	0	0	8	0	3.3	1.18
30:	1.0	625	16	109	78	62	94	16	0	0	0	0	0	0	0	1.8	1.01
60:	14.5	48	14	116	47	63	137	90	165	75	177	49	0	17	3	7.9	2.54
90:	14.6	48	5	84	60	78	161	107	195	82	131	38	4	8	0	7.5	2.75
120:	12.0	61	3	147	93	104	210	132	132	49	45	19	0	5	0	6.3	2.59
150:	1.7	364	18	136	145	173	55	45	55	9	0	0	0	0	0	3.6	1.70
180:	4.8	135	20	197	76	118	168	109	105	20	43	7	0	3	0	5.4	2.15
210:	1.3	471	12	106	141	141	24	71	0	0	24	0	0	0	12	3.2	1.11
240:	19.9	34	6	128	58	85	145	104	160	84	136	39	2	15	2	7.5	2.41
270:	18.4	35	3	88	53	70	153	131	173	79	147	50	1	16	2	7.8	2.58
300:	8.8	74	2	171	129	144	140	90	95	29	94	27	0	5	0	5.9	1.87
330:	1.0	646	16	193	48	64	0	0	16	16	0	0	0	0	0	1.4	0.90

Total 79 7 125 70 89 150 105 149 64 115 35 1 11 1 6.9 2.19

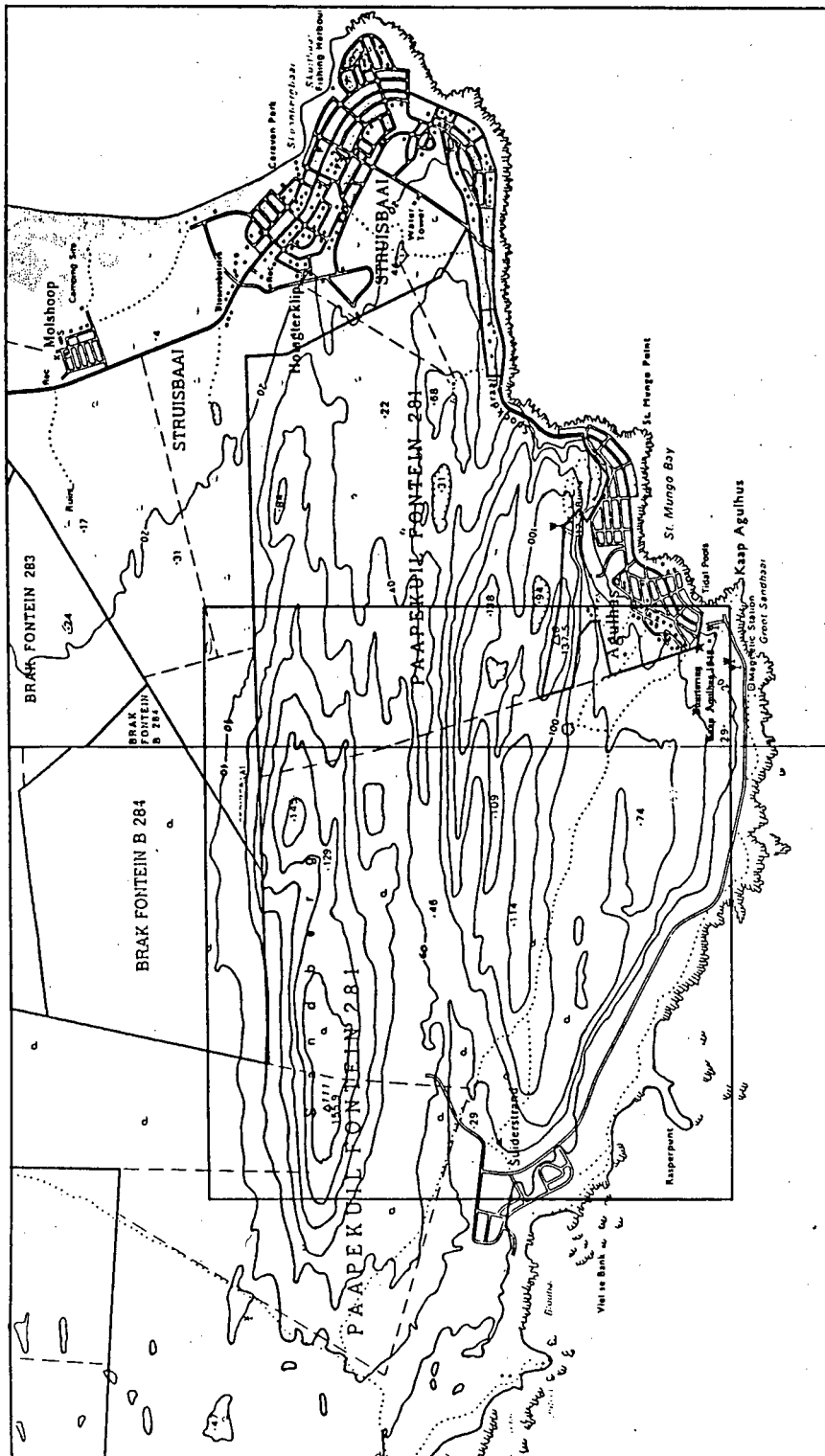
Number of calms (included): 481 Mean wind speed: 5.6 m/s

DUMP DOS RETURN
 RAWDATA>

APPENDIX 6.1.

TOPOGRAPHICAL MAP OF INVESTIGATED AREA

(The blocked area is that used in depicting the results)



APPENDIX 6.2.

TYPICAL DISPLAY OF INPUT DATA FROM THE NUMERICAL MODEL

```

ATLAS-----
:CAPE AGULHUS WIND DATA '80-85
:
    
```

```

OROGRAPHY-----
C:\WASP\AGLMAP.MAP          :+AGULHUS , CARTESIAN CU-ORDINATES
(1950,550)                  :19 m a.s.l. . . , @ : 2.8, 1.58E+04 m
ROUGHNESS-----
C:\WASP\COORDS\LIGHTHOU.RDS :LIGHTHOUSE
C:\WASP\COORDS\LIGHTHOUSE.RDS :LIGHTHOUSE
OBSTACLE-----
:LIGHTHOUSE
:
    
```

```

RAWDATA-(2 m a.g.l.)----- WECS-----
C:\WASP\1985WIND.FRN          :
:                               :
C:\WASP\AGLWIND.TAB          :
AGULHUS WIND DATA '80-85    : = C:\WASP\COORDS
    
```

HEIGHT DATA OBSTACLE ROUGHNESS OROGRAPHY ATLAS
 WECS FREQUENCY TEXT DISPLAY RETURN DDS HELP STOP
 WASP>

```

ATLAS-----
:CAPE AGULHUS WIND DATA '80-85
:
    
```

```

OROGRAPHY-----
C:\WASP\AGLMAP.MAP          :+AGULHUS , CARTESIAN CU-ORDINATES
(0,3000)                    :59.8 m a.s.l. . . , @ : 2.1, 1.16E+04 m
ROUGHNESS-----
C:\WASP\COORDS\POINT110.RDS :POINT J10
:                               :
OBSTACLE-----
:POINT J10
:
    
```

```

RAWDATA-(2 m a.g.l.)----- WECS-----
C:\WASP\1985WIND.FRN          :
:                               :
C:\WASP\AGLWIND.TAB          :
AGULHUS WIND DATA '80-85    : = C:\WASP\COORDS
    
```

HEIGHT DATA OBSTACLE ROUGHNESS OROGRAPHY ATLAS
 WECS FREQUENCY TEXT DISPLAY RETURN DDS HELP STOP
 WASP>

APPENDIX 6.3. (a)

TYPICAL DISPLAY OF RESULTS FROM THE NUMERICAL MODEL

(a) Results for the lighthouse at 2m and 10m a.g.l.

CAPE AGULHUS WIND DATA '80-85							29/ 5/88 12:12				
LIGHTHOUSE							Height: 2.0 m a.g.l.				
Sect	Rch	Input	Obstacle	Drography	A	k	%	E%			
0:	0	0.0%	0°	0.0%	-3.5%	10°	:	3.2	1.15	2.0	0.8
30:	1	0.0%	0°	0.0%	16.8%	12°	:	5.3	1.62	3.6	2.9
60:	2	0.0%	0°	0.0%	21.8%	3°	:	6.9	2.20	11.6	14.5
90:	0	0.0%	0°	0.0%	18.1%	-5°	:	6.7	2.39	13.8	14.5
120:	0	0.0%	0°	0.0%	5.1%	-10°	:	5.9	2.21	9.9	7.7
150:	0	0.0%	0°	0.0%	-8.3%	-4°	:	4.8	1.86	3.6	1.8
180:	0	0.0%	0°	0.0%	-6.1%	7°	:	4.8	1.83	3.9	2.1
210:	0	0.0%	0°	0.0%	8.6%	9°	:	5.9	1.85	5.5	5.1
240:	0	0.0%	0°	0.0%	19.5%	3°	:	7.0	2.12	16.7	22.4
270:	1	0.0%	0°	0.0%	26.4%	-7°	:	6.5	2.20	16.2	17.2
300:	0	0.0%	0°	0.0%	-10.2%	-13°	:	5.9	1.84	9.5	9.0
330:	0	0.0%	0°	0.0%	-7.5%	-5°	:	4.4	1.56	3.7	1.9
N= 5.5 m/s E= 194. W/m ²					6.2		1.99				

HEIGHT DATA OBSTACLE ROUGHNESS DROGRAPHY ATLAS
 WECS FREQUENCY TEXT DISPLAY RETURN DOS HELP STOP
 WAsP>

CAPE AGULHUS WIND DATA '80-85							29/ 5/88 12:14				
LIGHTHOUSE							Height: 10.0 m a.g.l.				
Sect	Rch	Input	Obstacle	Drography	A	k	%	E%			
0:	0	0.0%	0°	0.0%	-5.0%	8°	:	5.4	1.30	2.1	1.3
30:	1	0.0%	0°	0.0%	10.5%	9°	:	8.4	1.85	3.8	4.8
60:	2	0.0%	0°	0.0%	15.9%	2°	:	9.0	2.42	11.1	12.9
90:	0	0.0%	0°	0.0%	12.7%	-4°	:	8.3	2.65	12.9	11.3
120:	0	0.0%	0°	0.0%	3.0%	-6°	:	7.5	2.45	10.7	7.3
150:	0	0.0%	0°	0.0%	-5.1%	-2°	:	6.4	2.04	4.0	2.0
180:	0	0.0%	0°	0.0%	-2.5%	4°	:	6.5	2.01	4.3	2.2
210:	0	0.0%	0°	0.0%	7.8%	6°	:	7.7	2.05	5.7	4.9
240:	0	0.0%	0°	0.0%	14.9%	2°	:	8.7	2.33	15.9	17.6
270:	1	0.0%	0°	0.0%	14.9%	-5°	:	9.3	2.46	15.4	20.1
300:	0	0.0%	0°	0.0%	2.6%	-10°	:	8.8	2.10	10.2	12.5
330:	0	0.0%	0°	0.0%	-10.0%	-3°	:	7.1	1.76	3.9	3.2
N= 7.4 m/s E= 427. W/m ²					8.3		2.19				

HEIGHT DATA OBSTACLE ROUGHNESS DROGRAPHY ATLAS
 WECS FREQUENCY TEXT DISPLAY RETURN DOS HELP STOP
 WAsP>

APPENDIX 6.3. (b)

TYPICAL DISPLAY OF RESULTS FROM THE NUMERICAL MODEL

(b) Results for the lighthouse at 20m and 50m a.g.l.

CAPE AGULHUS WIND DATA '80-85							29/ 5/88 12:15				
Lighthouse							Height: 20.0 m a.g.l.				
Sect	Rch	Input	Obstacle	Orography	A	k	%	E%			
0:	0	0.0%	0°	0.0%	-3.8%	7°	:	6.4	1.33	2.2	1.7
30:	1	0.0%	0°	0.0%	8.7%	7°	:	9.9	1.95	3.9	5.9
60:	2	0.0%	0°	0.0%	13.3%	1°	:	9.5	2.45	10.9	11.8
90:	0	0.0%	0°	0.0%	10.3%	-3°	:	8.7	2.65	12.5	9.8
120:	0	0.0%	0°	0.0%	1.7%	-5°	:	7.9	2.46	10.9	6.8
150:	0	0.0%	0°	0.0%	-4.8%	-1°	:	6.9	2.04	4.1	1.9
180:	0	0.0%	0°	0.0%	-1.9%	4°	:	7.0	2.02	4.4	2.2
210:	0	0.0%	0°	0.0%	7.0%	5°	:	8.2	2.06	5.7	4.6
240:	0	0.0%	0°	0.0%	12.7%	1°	:	9.1	2.33	15.5	15.5
270:	1	0.0%	0°	0.0%	11.2%	-4°	:	10.3	2.48	15.0	20.3
300:	0	0.0%	0°	0.0%	1.7%	-8°	:	10.1	2.18	10.7	15.2
330:	0	0.0%	0°	0.0%	-8.3%	-2°	:	8.5	1.81	4.1	4.3
M= 8.0 m/s E= 543. W/m ²							9.0 2.18				

HEIGHT DATA OBSTACLE ROUGHNESS OROGRAPHY ATLAS
 WECS FREQUENCY TEXT DISPLAY RETURN DOS HELP STOP
 WASP>

CAPE AGULHUS WIND DATA '80-85							29/ 5/88 12:17				
Lighthouse							Height: 50.0 m a.g.l.				
Sect	Rch	Input	Obstacle	Orography	A	k	%	E%			
0:	0	0.0%	0°	0.0%	-2.4%	5°	:	7.8	1.37	2.3	2.1
30:	1	0.0%	0°	0.0%	6.3%	5°	:	11.9	2.08	4.0	7.1
60:	2	0.0%	0°	0.0%	10.3%	1°	:	10.2	2.48	10.7	10.2
90:	0	0.0%	0°	0.0%	7.6%	-3°	:	9.2	2.66	12.3	8.1
120:	0	0.0%	0°	0.0%	0.3%	-4°	:	8.5	2.46	11.0	6.0
150:	0	0.0%	0°	0.0%	-4.8%	-1°	:	7.4	2.04	4.1	1.8
180:	0	0.0%	0°	0.0%	-2.0%	3°	:	7.5	2.01	4.5	2.0
210:	0	0.0%	0°	0.0%	5.5%	4°	:	8.8	2.06	5.8	4.1
240:	0	0.0%	0°	0.0%	10.1%	1°	:	9.6	2.32	15.3	13.0
270:	1	0.0%	0°	0.0%	7.9%	-3°	:	11.9	2.49	14.4	21.6
300:	0	0.0%	0°	0.0%	0.5%	-5°	:	11.9	2.28	11.1	18.0
330:	0	0.0%	0°	0.0%	-6.0%	-1°	:	10.5	1.89	4.4	5.9
M= 8.8 m/s E= 753. W/m ²							10.0 2.13				

HEIGHT DATA OBSTACLE ROUGHNESS OROGRAPHY ATLAS
 WECS FREQUENCY TEXT DISPLAY RETURN DOS HELP STOP
 WASP>

APPENDIX 6.3. (c)

TYPICAL DISPLAY OF RESULTS FROM THE NUMERICAL MODEL

(c) Results for the lighthouse at 75m and 100m a.g.l.

CAPE AGULHUS WIND DATA '80-85										29/ 5/88 12:19	
LIGHTHOUSE										Height: 75.0 m a.g.l.	
Sect	Rch	Input	Obstacle	Orography		A	k	%	E%		
0:	0	0.0%	0°	0.0%	-2.5%	4°	:	8.4	1.38	2.3	2.2
30:	1	0.0%	0°	0.0%	5.1%	4°	:	12.9	2.14	4.0	7.6
60:	2	0.0%	0°	0.0%	9.1%	1°	:	10.6	2.50	10.6	10.0
90:	0	0.0%	0°	0.0%	6.6%	-3°	:	9.4	2.66	12.2	7.6
120:	0	0.0%	0°	0.0%	-0.2%	-4°	:	8.7	2.47	11.1	5.7
150:	0	0.0%	0°	0.0%	-4.8%	-1°	:	7.7	2.04	4.2	1.7
180:	0	0.0%	0°	0.0%	-2.2%	3°	:	7.8	2.01	4.5	2.0
210:	0	0.0%	0°	0.0%	4.7%	4°	:	9.0	2.06	5.8	3.8
240:	0	0.0%	0°	0.0%	8.9%	1°	:	9.9	2.32	15.3	12.0
270:	1	0.0%	0°	0.0%	6.8%	-3°	:	12.5	2.50	14.3	21.9
300:	0	0.0%	0°	0.0%	-0.1%	-4°	:	12.8	2.33	11.3	19.1
330:	0	0.0%	0°	0.0%	-5.6%	-1°	:	11.4	1.93	4.5	6.5
N=		9.2 m/s		E=		869. W/m ²		10.4		2.11	

HEIGHT DATA OBSTACLE ROUGHNESS OROGRAPHY ATLAS
 WECS FREQUENCY TEXT DISPLAY RETURN DOS HELP STOP
 WAsP>

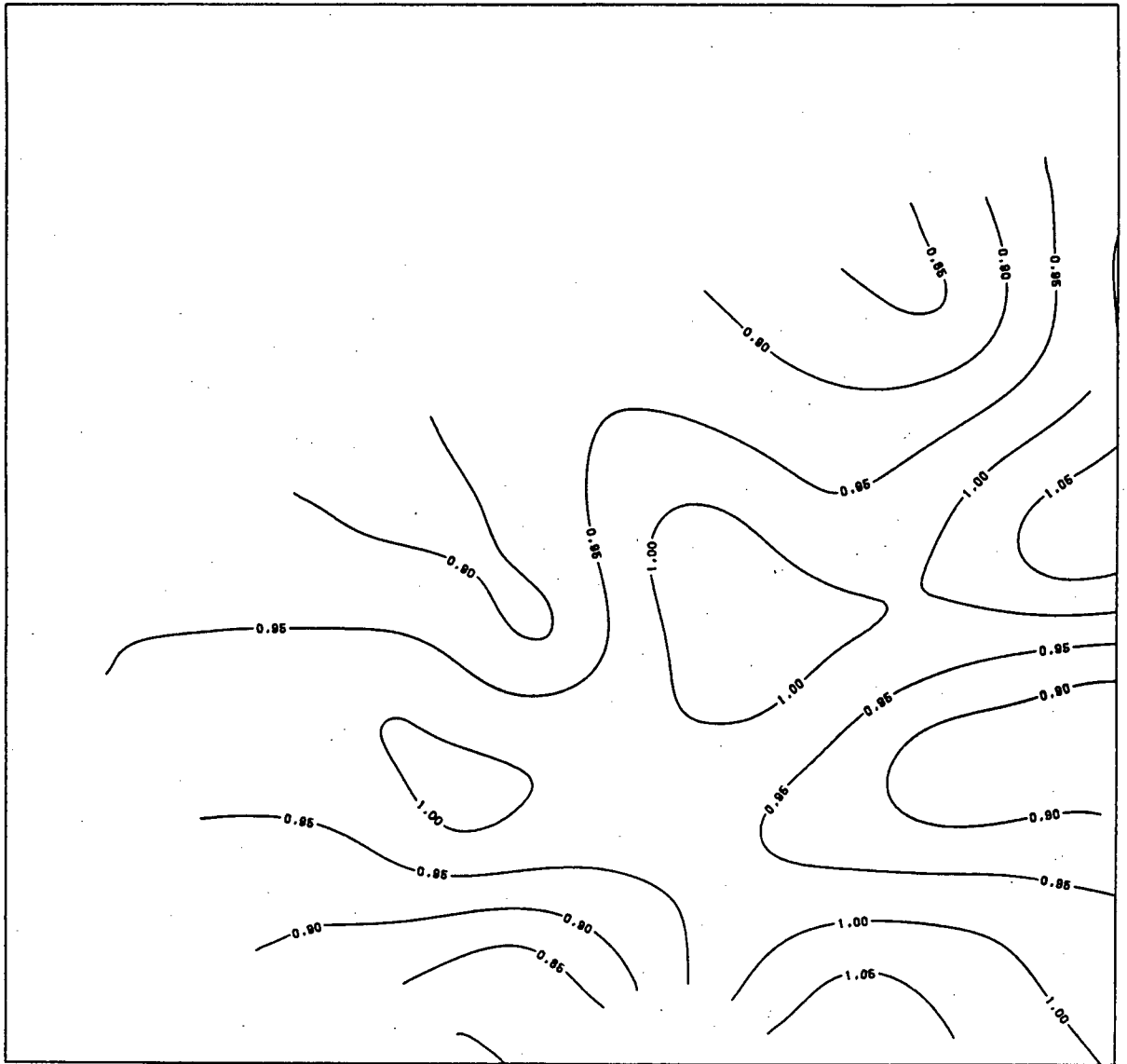
CAPE AGULHUS WIND DATA '80-85										29/ 5/88 12:20	
LIGHTHOUSE										Height: 100.0 m a.g.l.	
Sect	Rch	Input	Obstacle	Orography		A	k	%	E%		
0:	0	0.0%	0°	0.0%	-2.7%	3°	:	8.8	1.40	2.3	2.3
30:	1	0.0%	0°	0.0%	4.4%	4°	:	13.6	2.18	4.0	8.1
60:	2	0.0%	0°	0.0%	8.2%	1°	:	10.9	2.51	10.6	9.9
90:	0	0.0%	0°	0.0%	5.9%	-3°	:	9.5	2.67	12.2	7.2
120:	0	0.0%	0°	0.0%	-0.4%	-3°	:	8.9	2.46	11.1	5.6
150:	0	0.0%	0°	0.0%	-4.7%	-1°	:	7.8	2.04	4.2	1.7
180:	0	0.0%	0°	0.0%	-2.3%	3°	:	7.9	2.01	4.5	1.9
210:	0	0.0%	0°	0.0%	4.1%	3°	:	9.2	2.06	5.7	3.7
240:	0	0.0%	0°	0.0%	8.1%	1°	:	10.0	2.32	15.2	11.4
270:	1	0.0%	0°	0.0%	6.0%	-3°	:	12.8	2.50	14.2	21.1
300:	0	0.0%	0°	0.0%	-0.5%	-4°	:	13.4	2.36	11.3	20.1
330:	0	0.0%	0°	0.0%	-5.4%	-1°	:	12.0	1.96	4.6	7.0
N=		9.5 m/s		E=		946. W/m ²		10.7		2.10	

HEIGHT DATA OBSTACLE ROUGHNESS OROGRAPHY ATLAS
 WECS FREQUENCY TEXT DISPLAY RETURN DOS HELP STOP
 WAsP>

APPENDIX 6.4. (a)

RESULTS FROM THE PHYSICAL MODEL: FOR AN ENE WIND DIRECTION

(a) Relative velocities at 20m a.g.l.

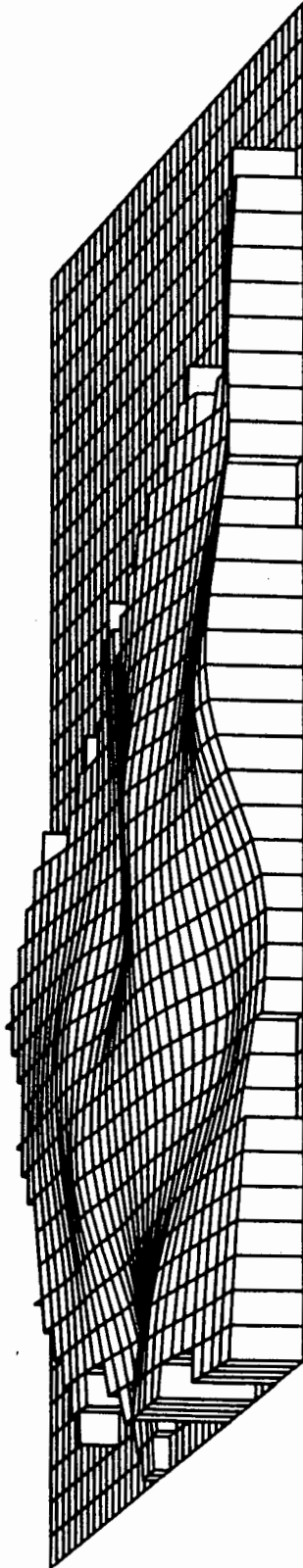


VELOCITY. H=20M A.G.L

APPENDIX 6.4. (a)

RESULTS FROM THE PHYSICAL MODEL: FOR AN ENE WIND DIRECTION

(a) Relative velocities at 20m a.g.l.

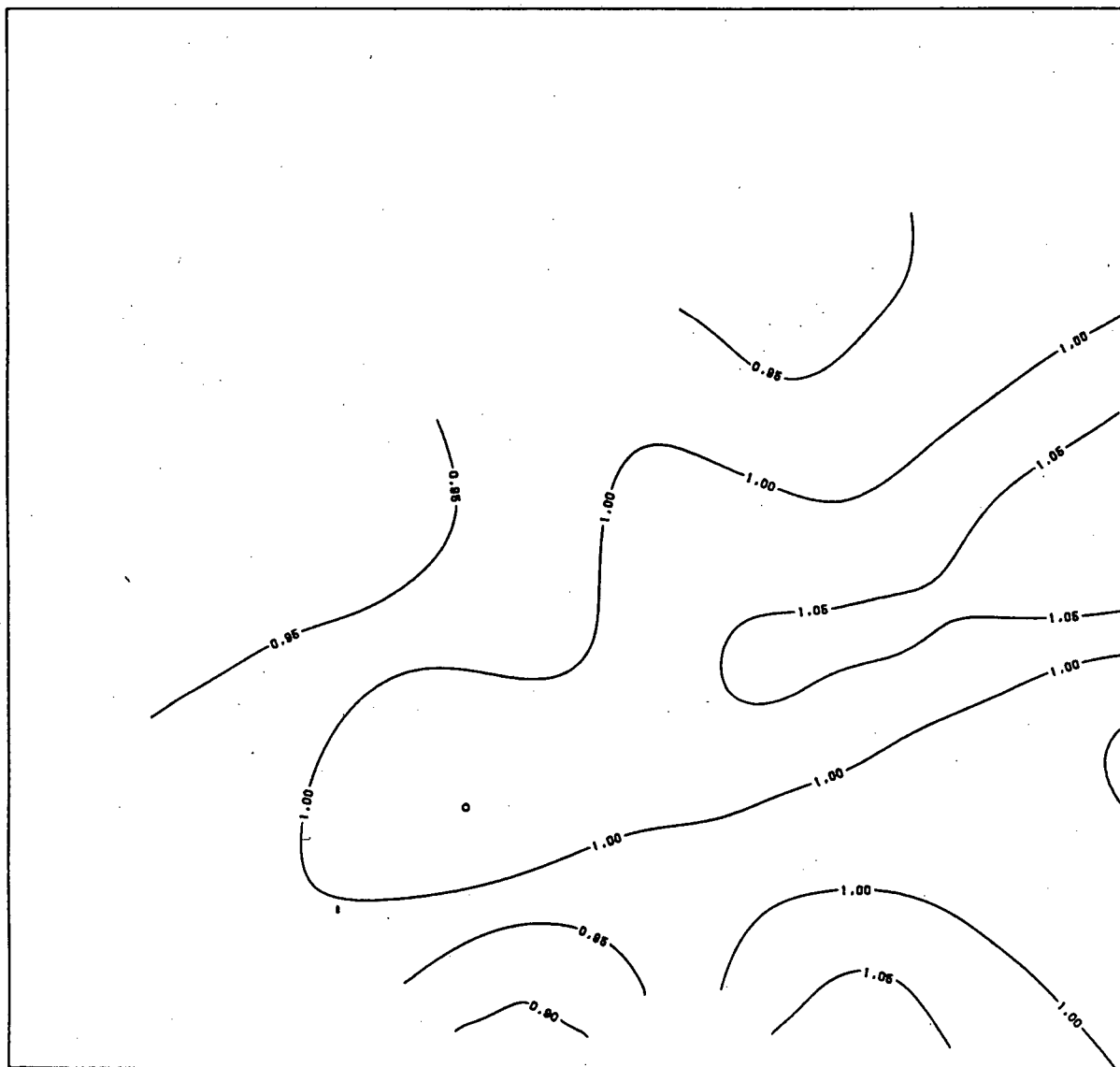


VELOCITY. H=20M A.G.L.

APPENDIX 6.4. (b)

RESULTS FROM THE PHYSICAL MODEL: FOR AN ENE WIND DIRECTION

(b) Relative velocities at 50m a.g.l.

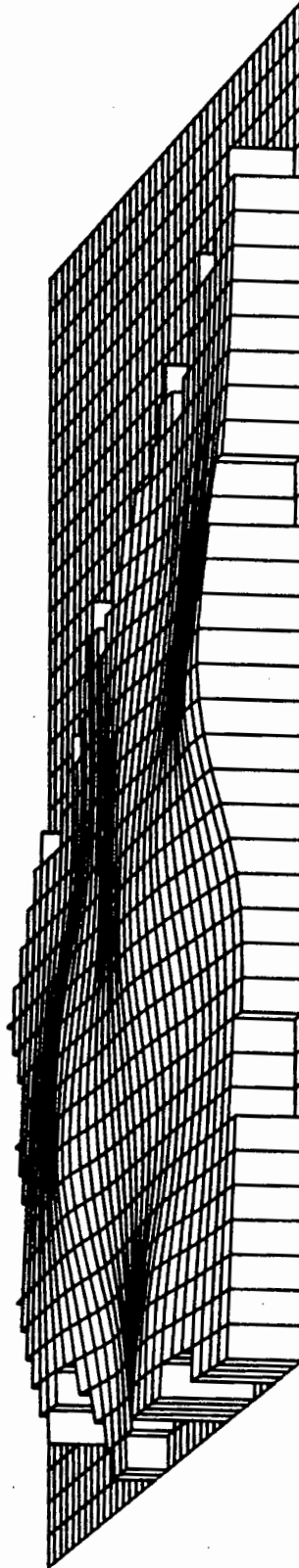


VELOCITY. H=50M A.G.L.

APPENDIX 6.4. (b)

RESULTS FROM THE PHYSICAL MODEL: FOR AN ENE WIND DIRECTION

(b) Relative velocities at 50m a.g.l.

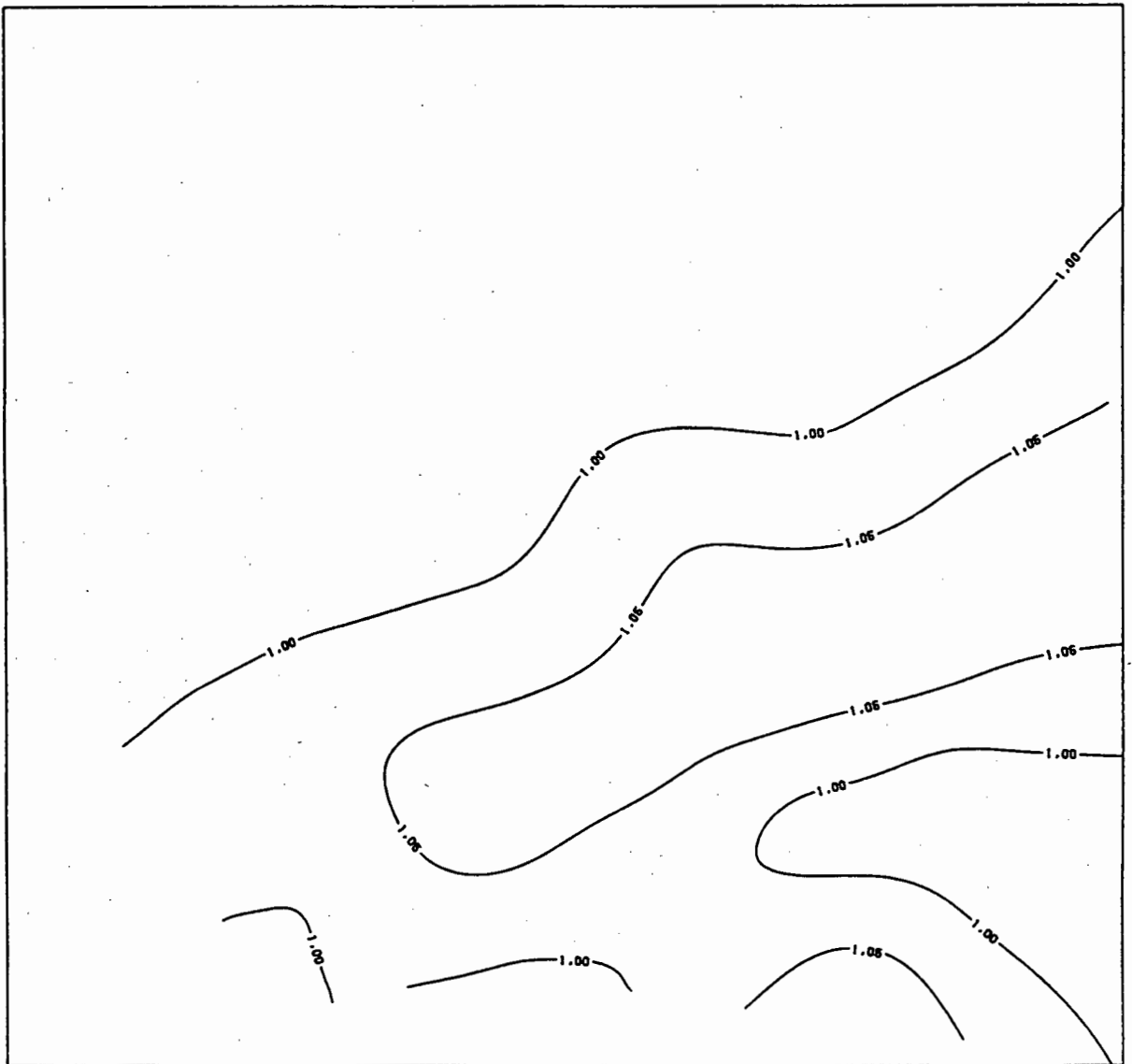


VELOCITY . H=50M A.G.L.

APPENDIX 6.4. (c)

RESULTS FROM THE PHYSICAL MODEL: FOR AN ENE WIND DIRECTION

(c) Relative velocities at 100m a.g.l.

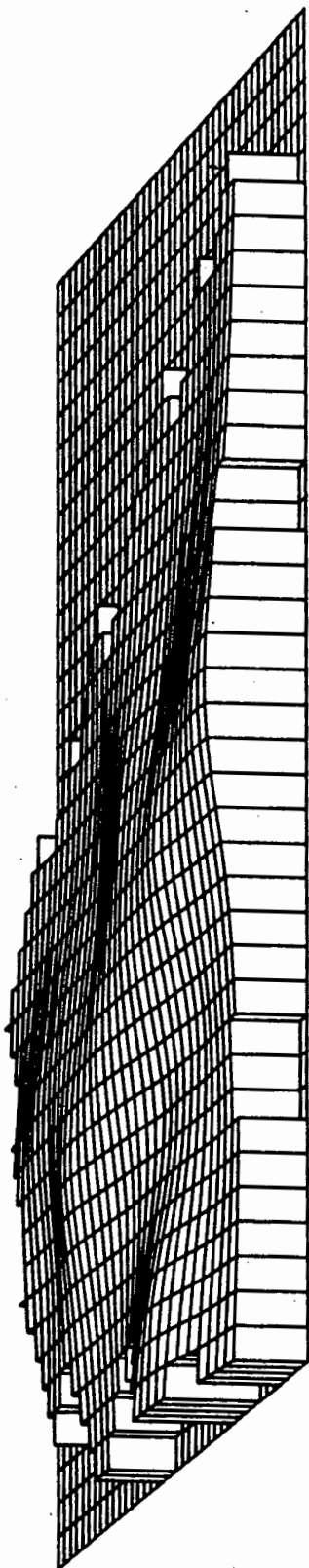


VELOCITY. H=100M A.G.L

APPENDIX 6.4. (c)

RESULTS FROM THE PHYSICAL MODEL: FOR AN ENE WIND DIRECTION

(c) Relative velocities at 100m a.g.l.



VELOCITY. H=100M A.G.L.

APPENDIX 6.5. (a)

RESULTS FROM THE NUMERICAL MODEL: FOR AN ENE WIND DIRECTION

(a) Relative velocities at 20m a.g.l.

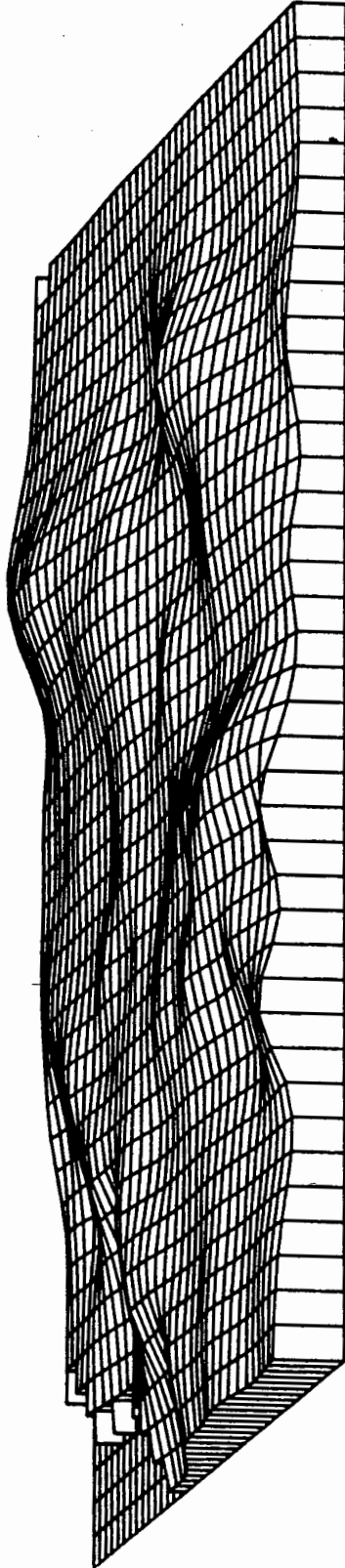


VELOCITY. H=20M A.G.L

APPENDIX 6.5. (a)

RESULTS FROM THE NUMERICAL MODEL: FOR AN ENE WIND DIRECTION

(a) Relative velocities at 20m a.g.l.



VELOCITY . H=20M A.G.L.

APPENDIX 6.5. (b)

RESULTS FROM THE NUMERICAL MODEL: FOR AN ENE WIND DIRECTION

(b) Relative velocities at 50m a.g.l.

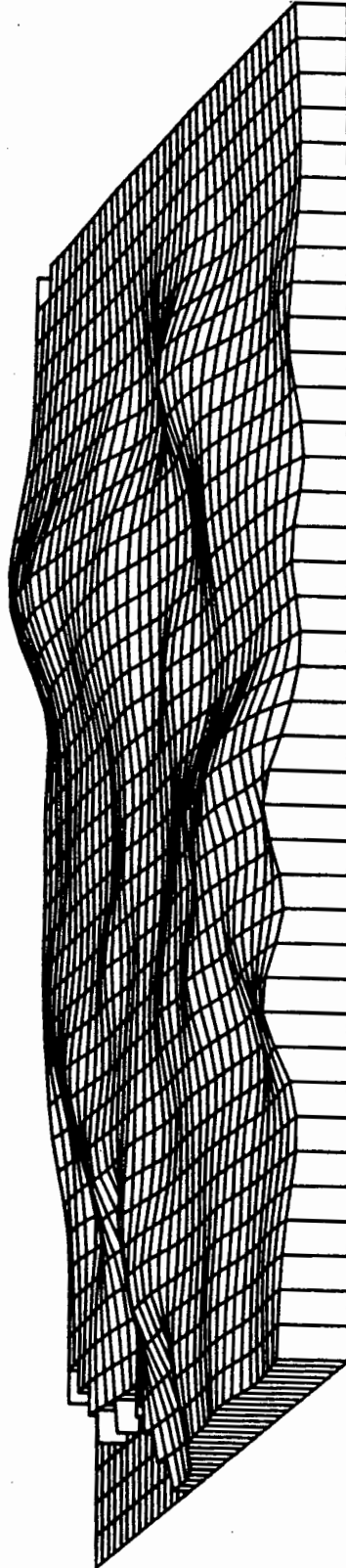


VELOCITY. H=50M A.G.L

APPENDIX 6.5. (b)

RESULTS FROM THE NUMERICAL MODEL: FOR AN ENE WIND DIRECTION

(b) Relative velocities at 50m a.g.l.

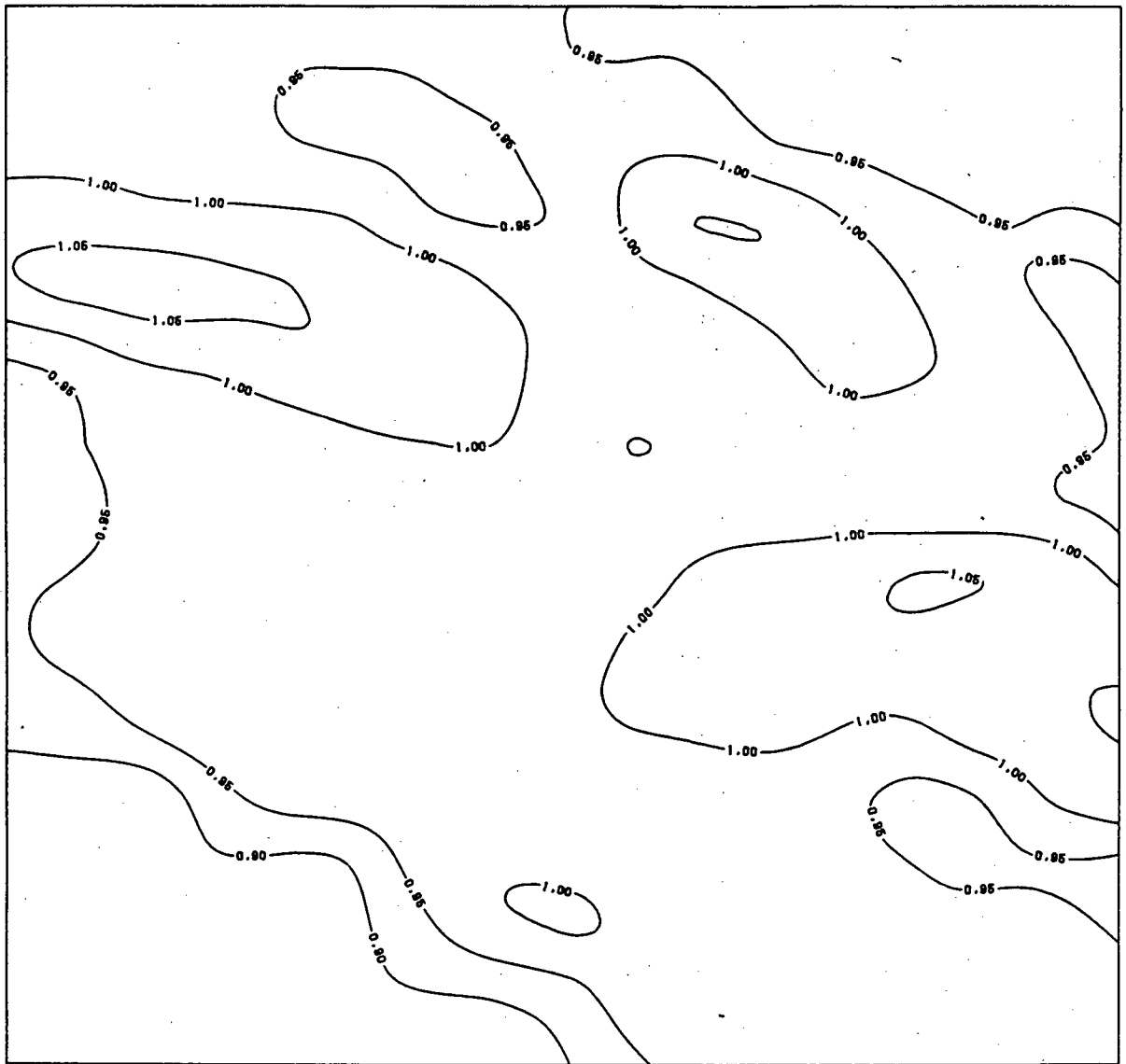


VELOCITY . H=50M A.G.L.

APPENDIX 6.5. (c)

RESULTS FROM THE NUMERICAL MODEL: FOR AN ENE WIND DIRECTION

(c) Relative velocities at 100m a.g.l.

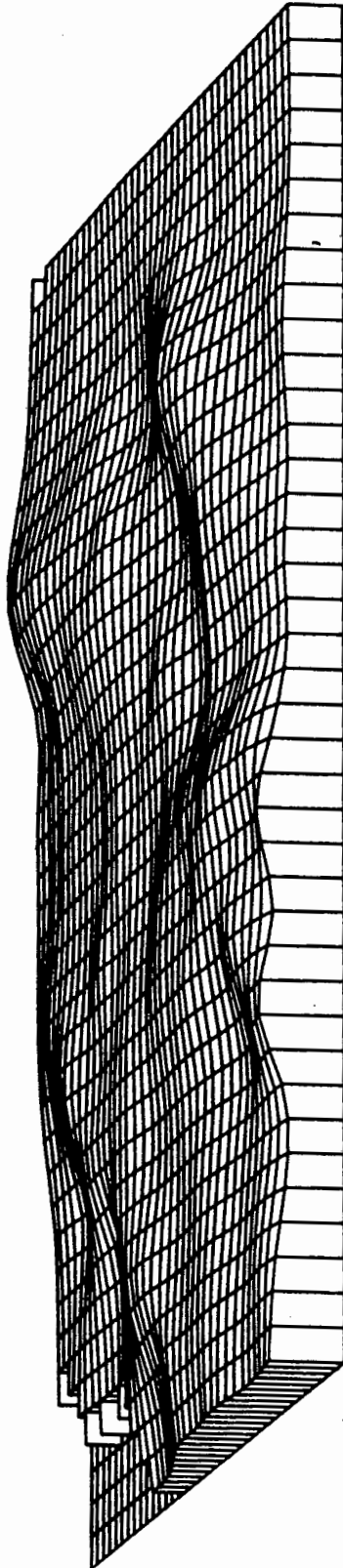


VELOCITY. H=100M A.G.L

APPENDIX 6.5. (c)

RESULTS FROM THE NUMERICAL MODEL: FOR AN ENE WIND DIRECTION

(c) Relative velocities at 100m a.g.l.

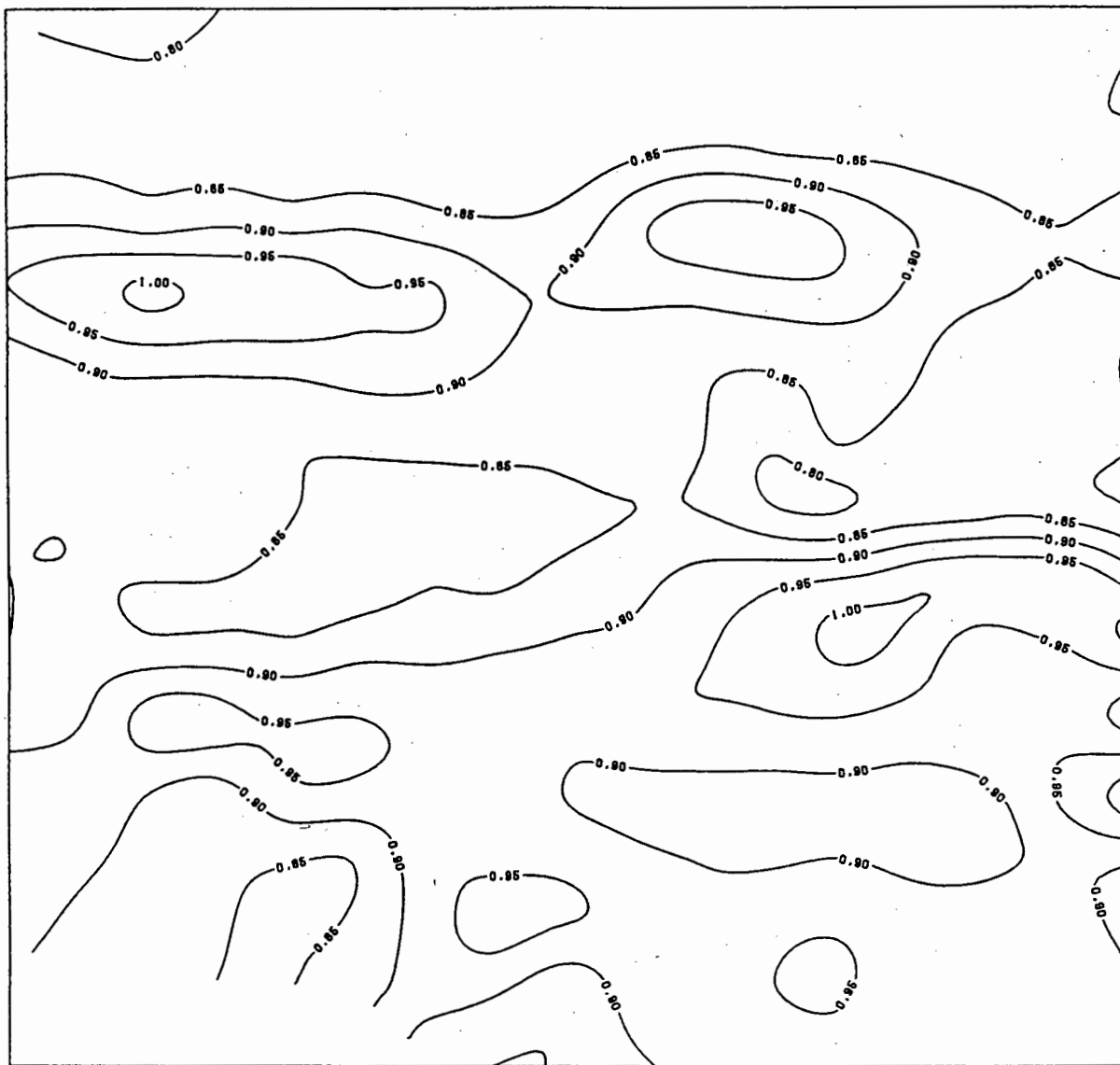


VELOCITY . H=100M A.G.L.

APPENDIX 6.6. (a)

RELATIVE ANNUAL AVERAGE WIND SPEEDS. RESULTS FROM NUMERICAL MODEL

(a) Relative annual average velocity at 20m a.g.l.

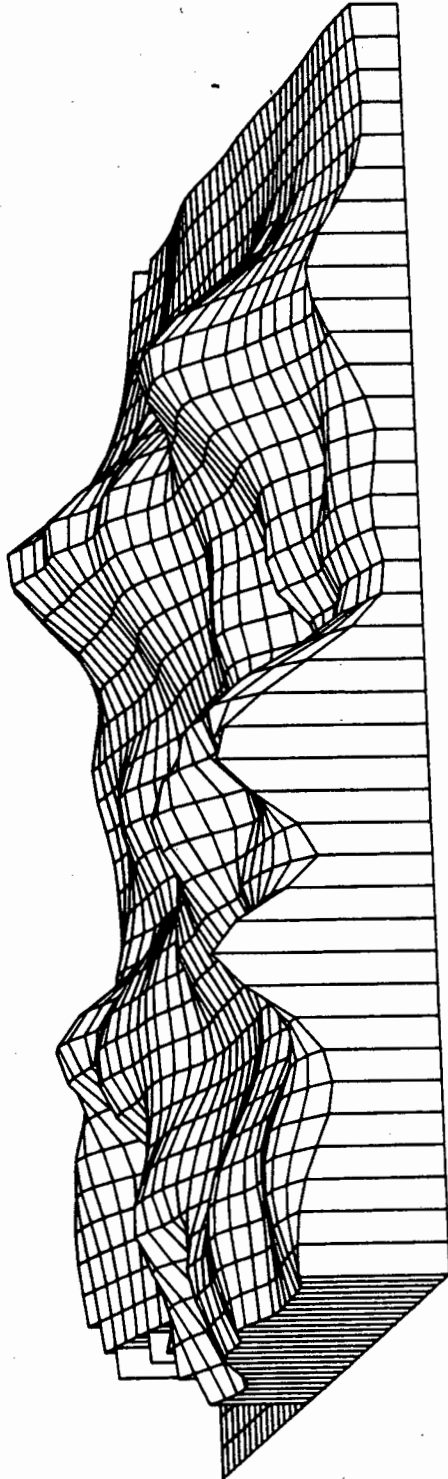


VELOCITY. H=20M A.G.L.

APPENDIX 6.6. (a)

RELATIVE ANNUAL AVERAGE WIND SPEEDS. RESULTS FROM NUMERICAL MODEL

(a) Relative annual average velocity at 20m a.g.l.

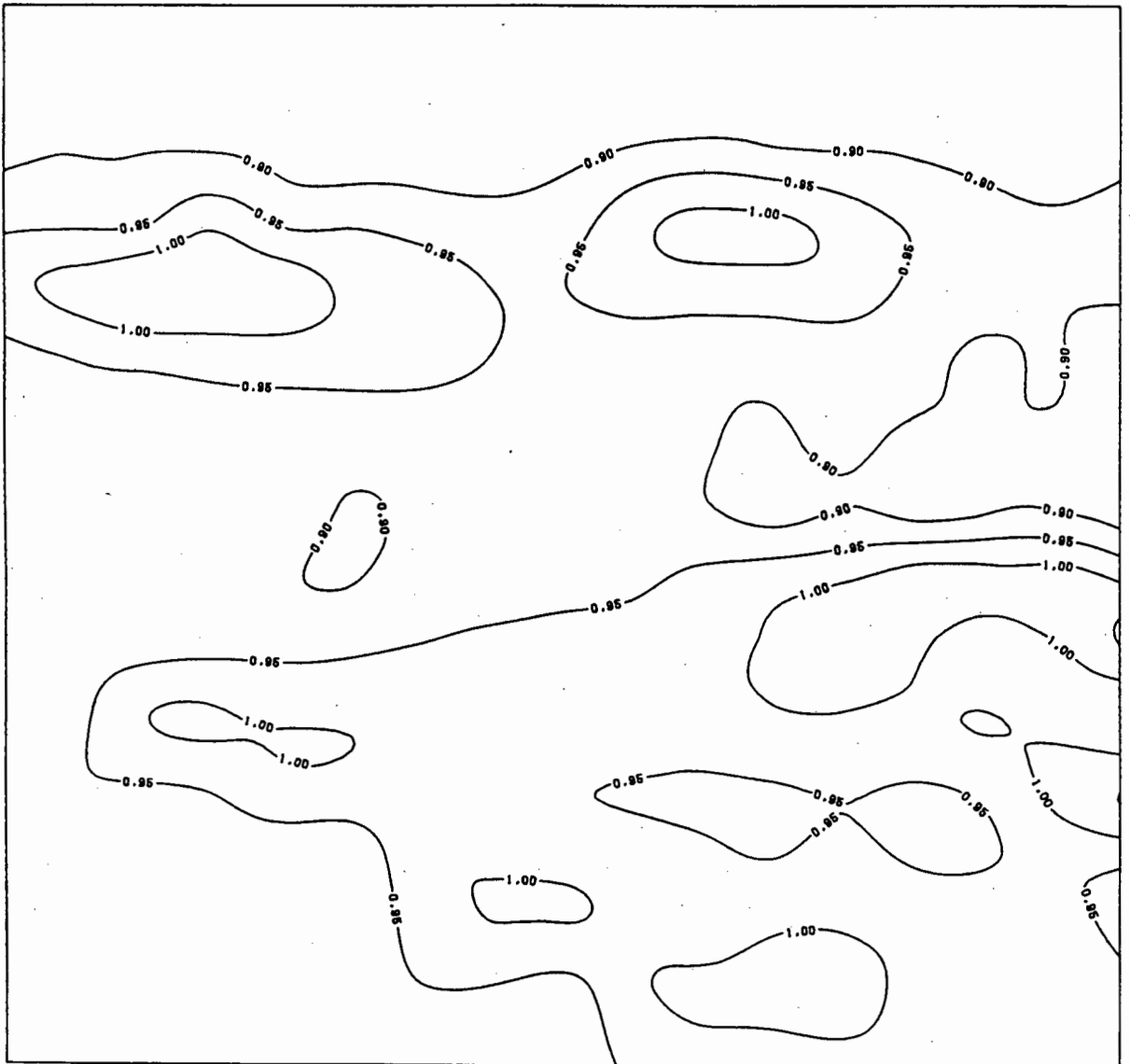


VELOCITY . H=20M A.G.L.

APPENDIX 6.6. (b)

RELATIVE ANNUAL AVERAGE WIND SPEEDS. RESULTS FROM NUMERICAL MODEL

(b) Relative annual average velocity at 50m a.g.l.

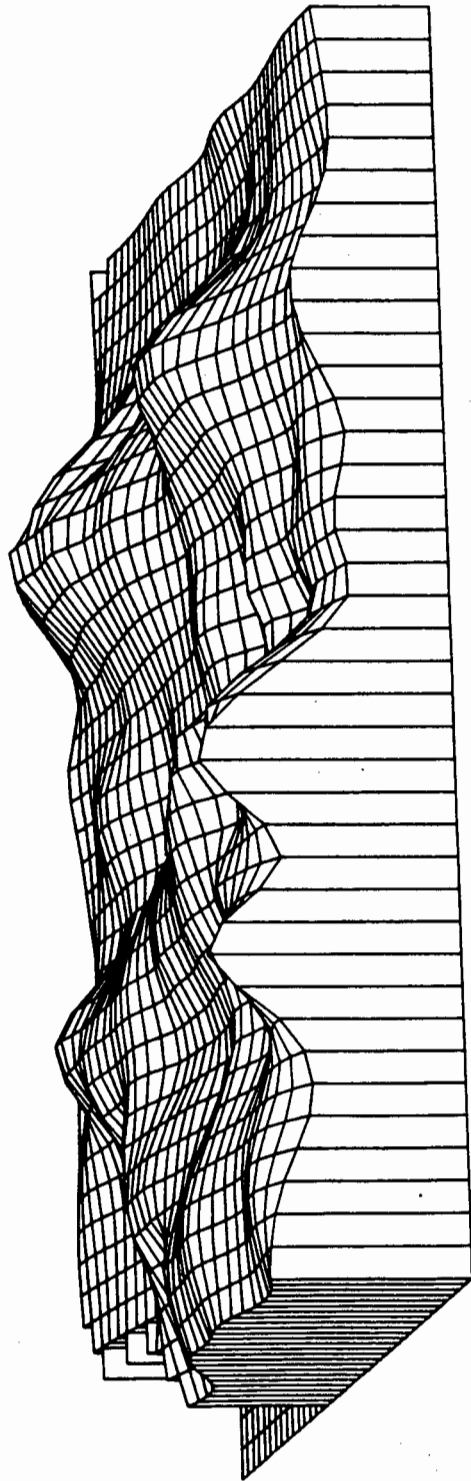


VELOCITY. H=50M A.G.L.

APPENDIX 6.6. (b)

RELATIVE ANNUAL AVERAGE WIND SPEEDS. RESULTS FROM NUMERICAL MODEL

(b) Relative annual average velocity at 50m a.g.l.

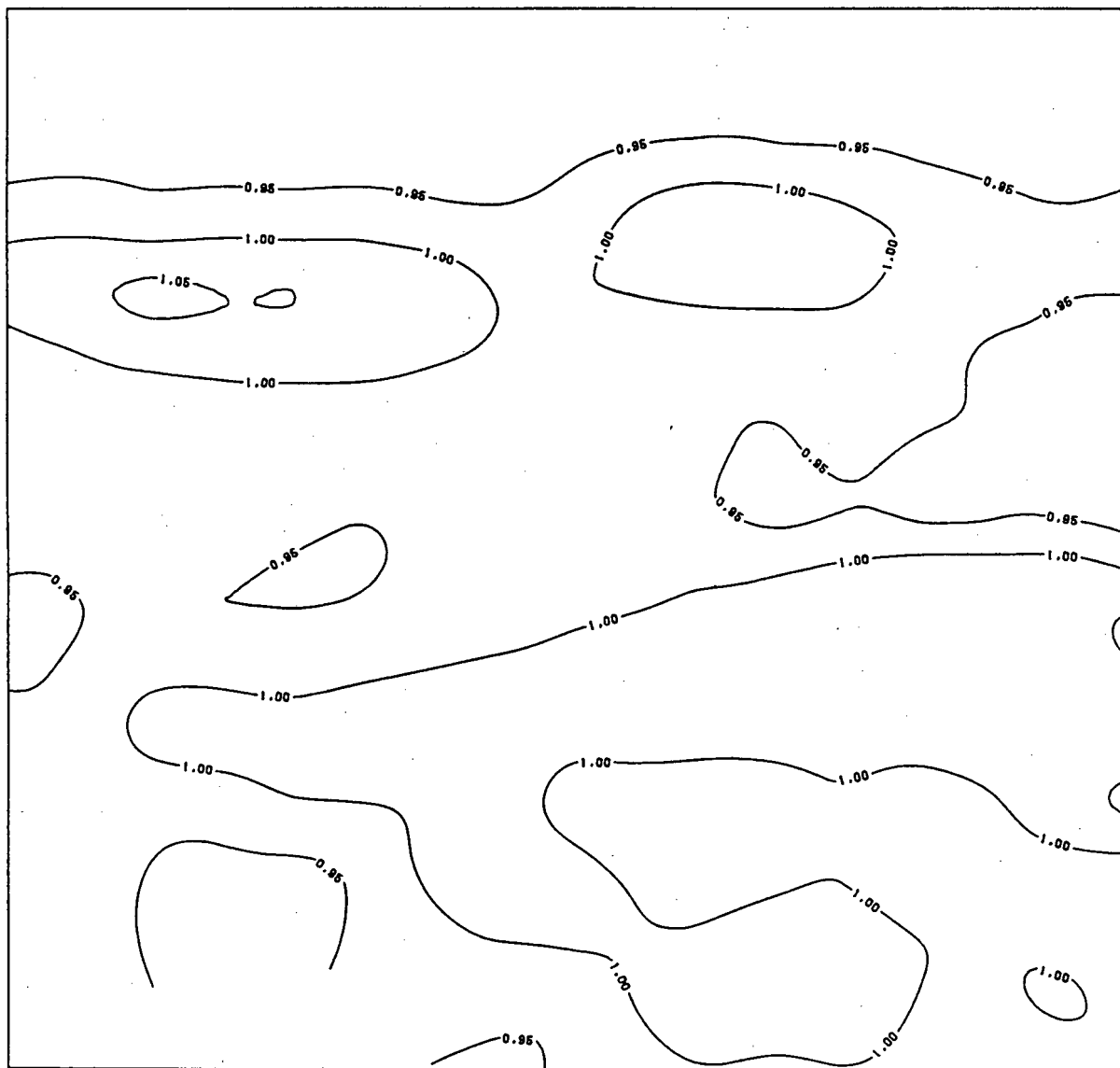


VELOCITY • H=50M A.G.L.

APPENDIX 6.6. (c)

RELATIVE ANNUAL AVERAGE WIND SPEEDS. RESULTS FROM NUMERICAL MODEL

(c) Relative annual average velocity at 100m a.g.l.

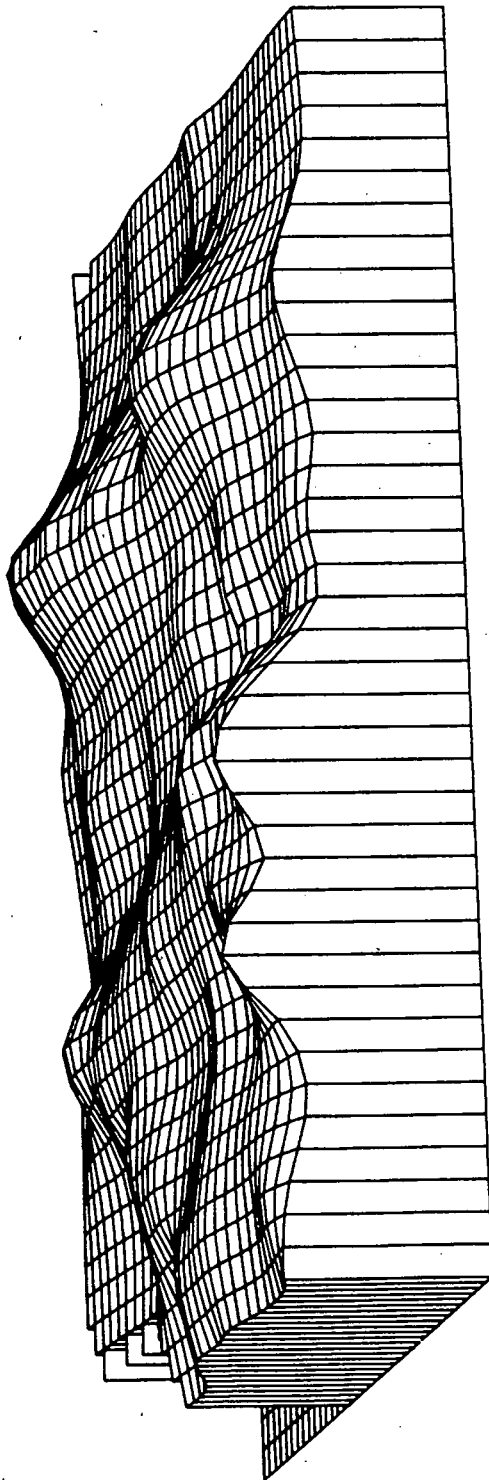


VELOCITY. H=100M A.G.L.

APPENDIX 6.6. (c)

RELATIVE ANNUAL AVERAGE WIND SPEEDS. RESULTS FROM NUMERICAL MODEL

(c) Relative annual average velocity at 100m a.g.l.

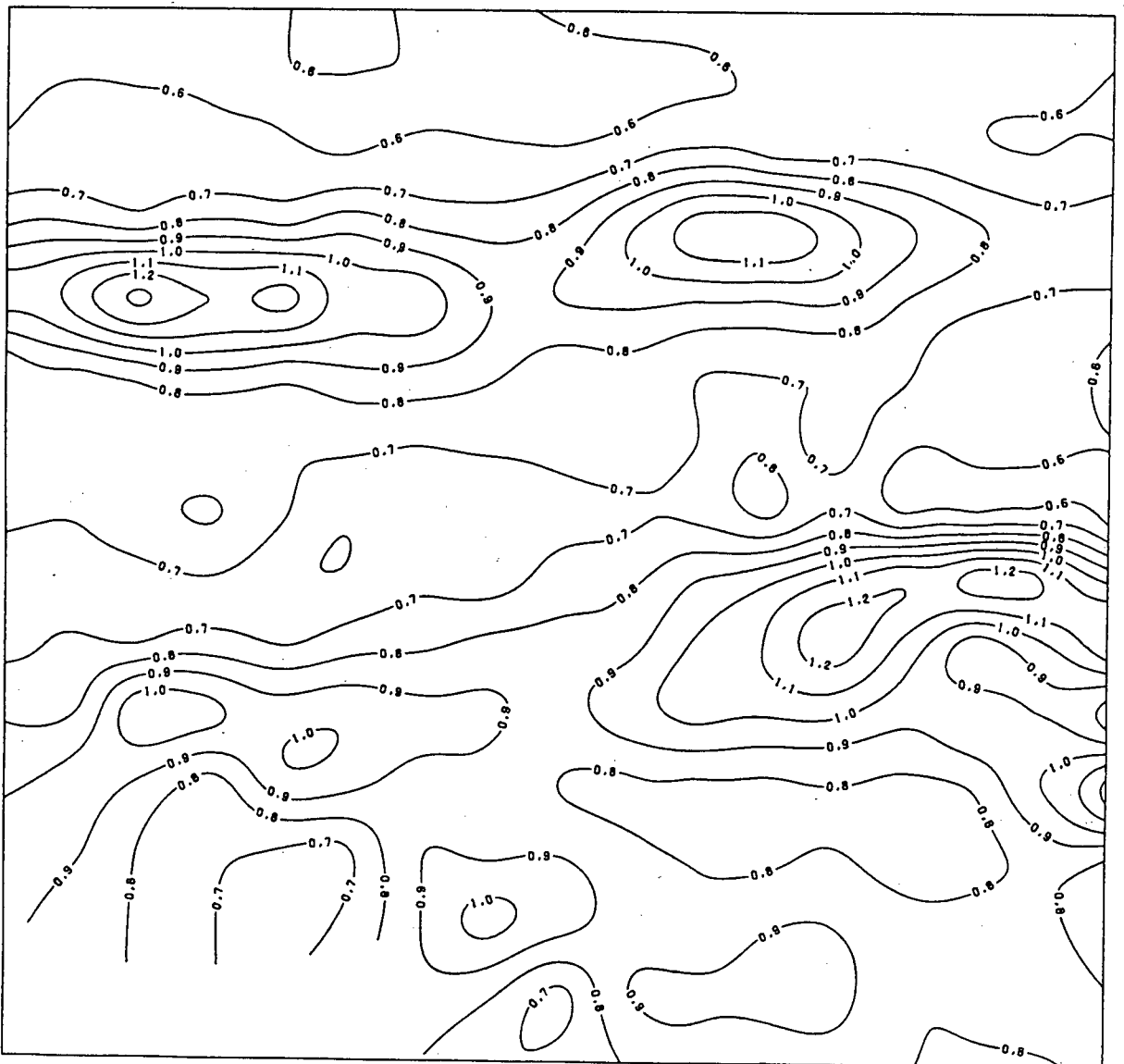


VELOCITY • H=100M A.G.L.

APPENDIX 6.7. (a)

RELATIVE ANNUAL AVERAGE ENERGY DENSITY. RESULTS FROM NUMERICAL MODEL

(a) Relative annual average energy density at 20m a.g.l.

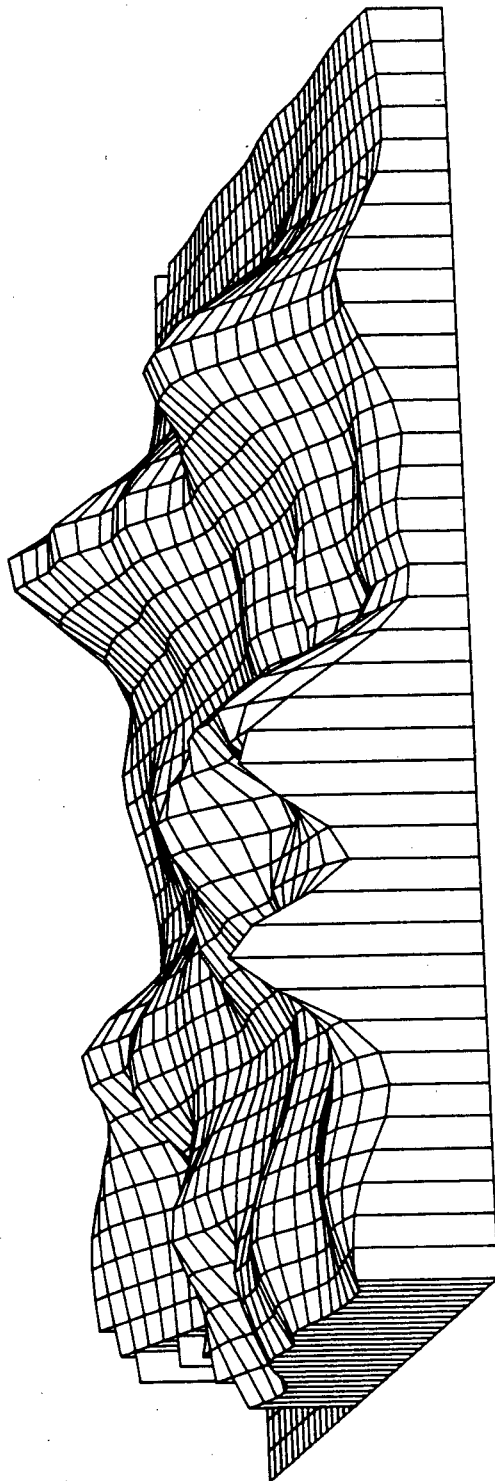


ENERGY DENSITY. H=20M A.G.L

APPENDIX 6.7. (a)

RELATIVE ANNUAL AVERAGE ENERGY DENSITY. RESULTS FROM NUMERICAL MODEL

(a) Relative annual average energy density at 20m a.g.l.

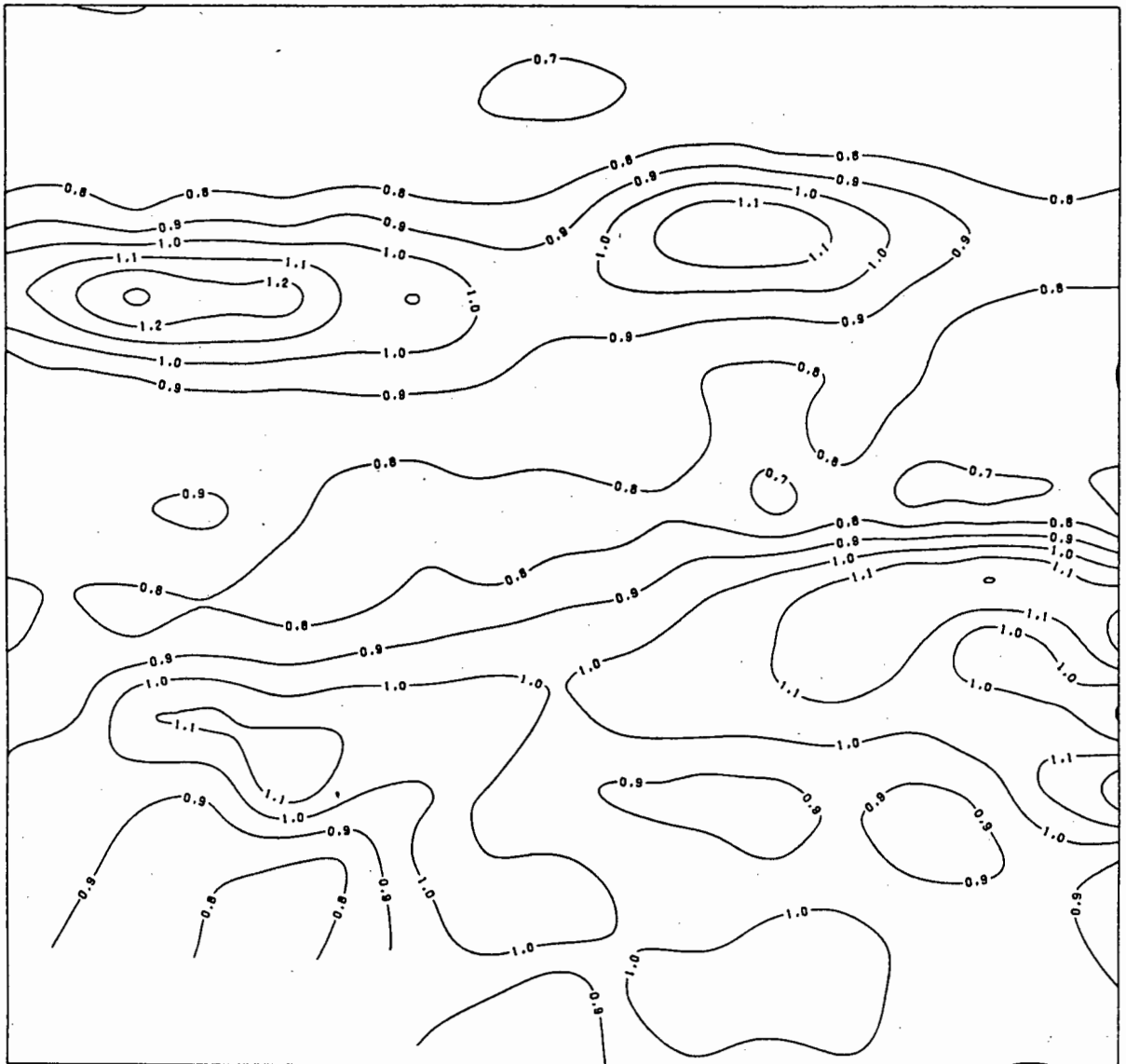


ENERGY DENSITY. H=20M A.G.L.

APPENDIX 6.7. (b)

RELATIVE ANNUAL AVERAGE ENERGY DENSITY. RESULTS FROM NUMERICAL MODEL

(b) Relative annual average energy density at 50m a.g.l.

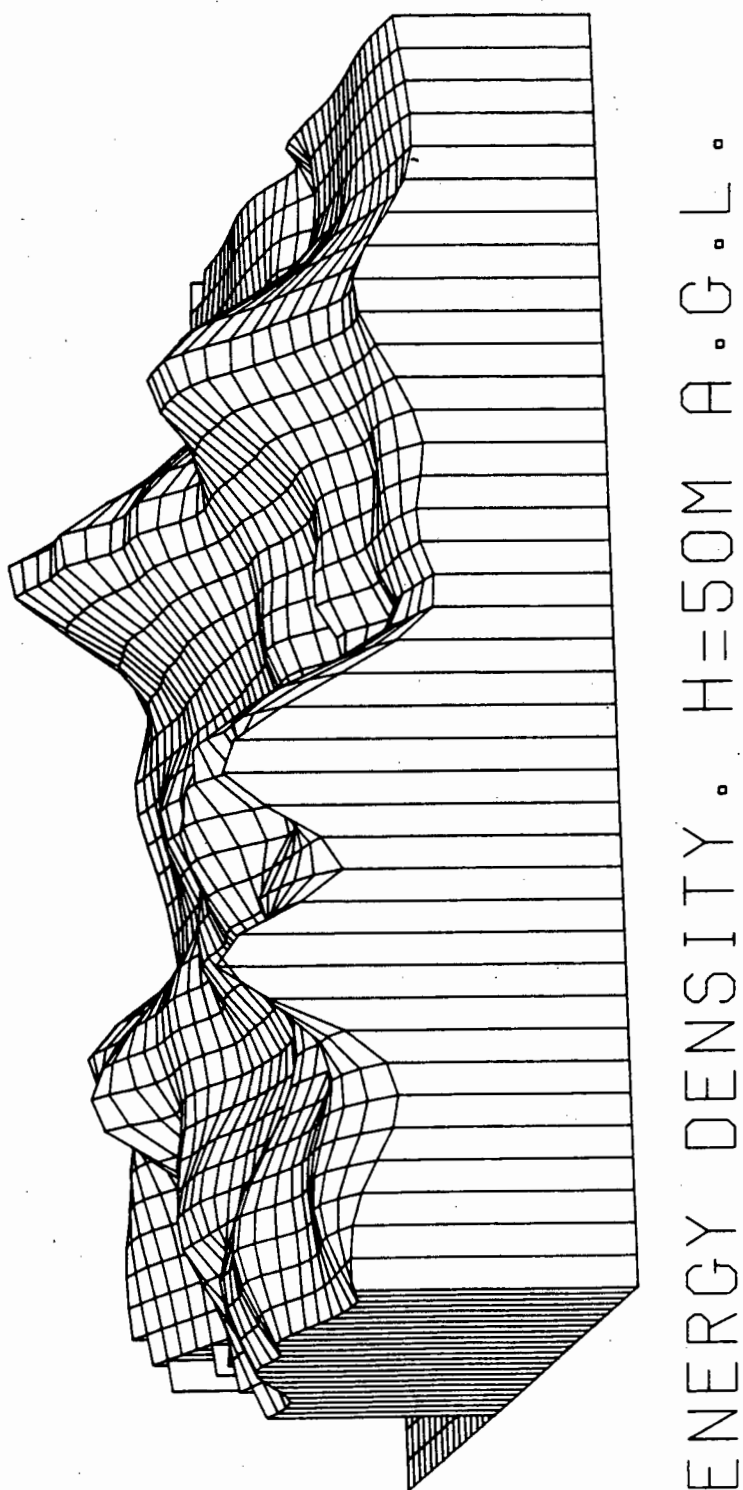


ENERGY DENSITY. H=50M A.G.L

APPENDIX 6.7. (b)

RELATIVE ANNUAL AVERAGE ENERGY DENSITY. RESULTS FROM NUMERICAL MODEL

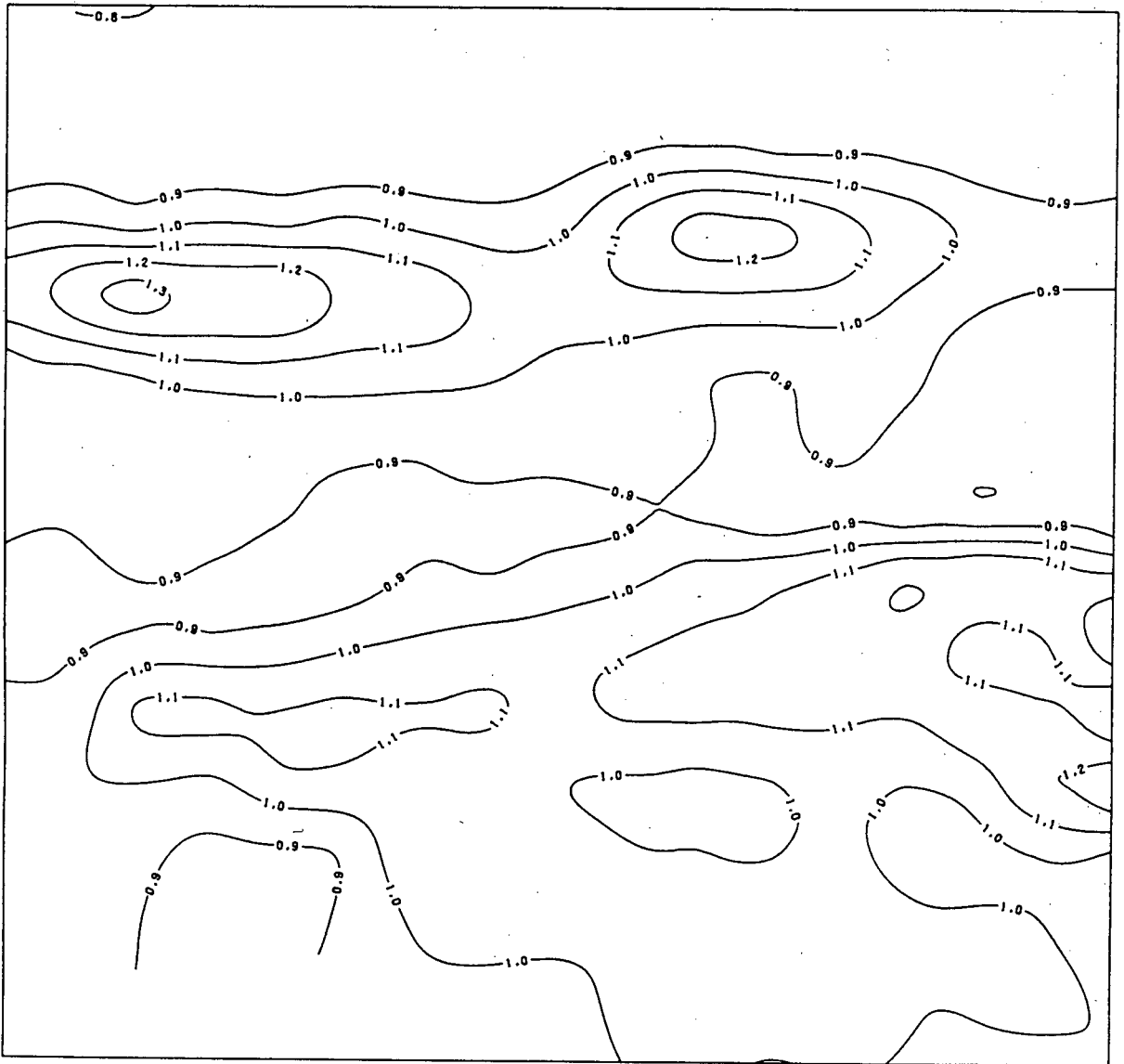
(b) Relative annual average energy density at 50m a.g.l.



APPENDIX 6.7. (c)

RELATIVE ANNUAL AVERAGE ENERGY DENSITY. RESULTS FROM NUMERICAL MODEL

(c) Relative annual average energy density at 100m a.g.l.

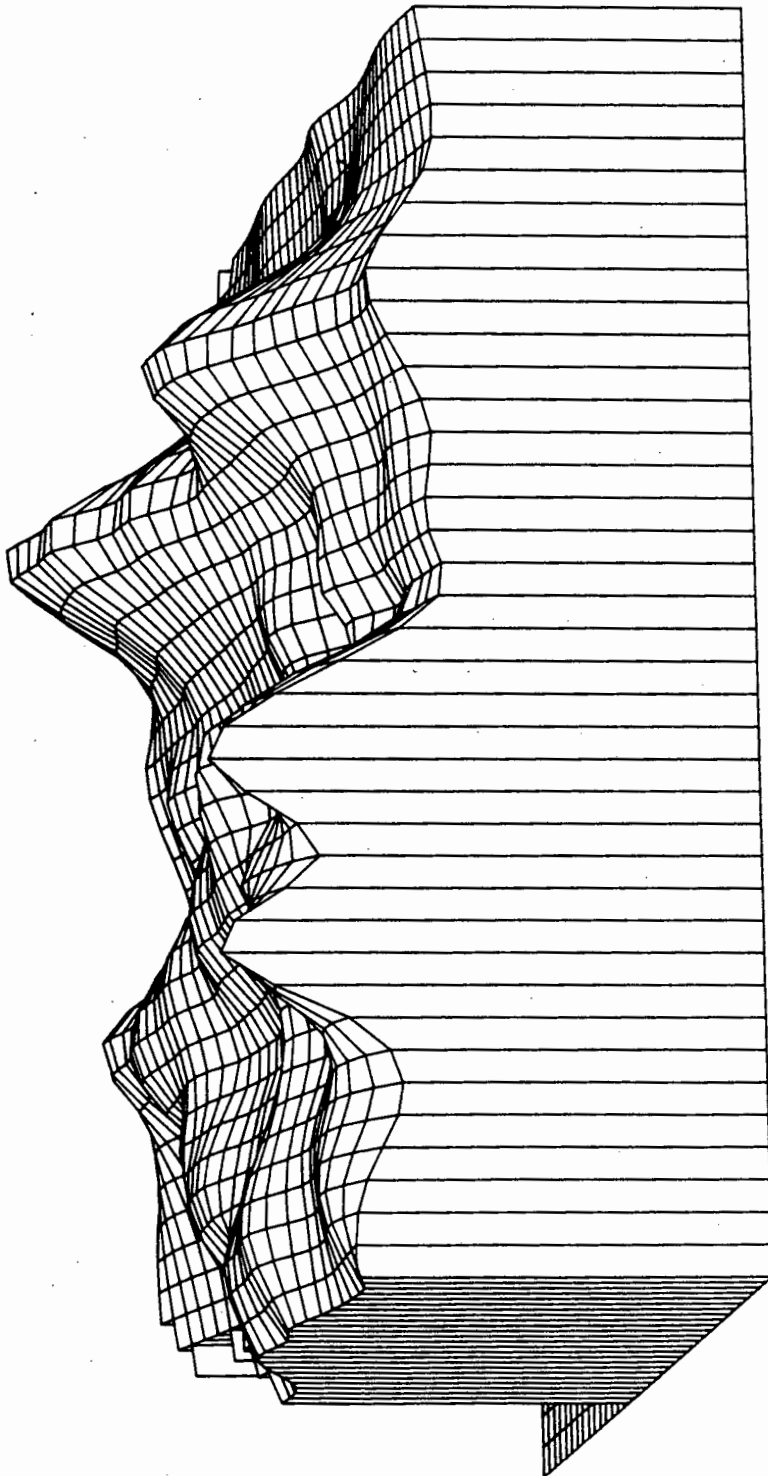


ENERGY DENSITY. H=100M A.G.L

APPENDIX 6.7. (c)

RELATIVE ANNUAL AVERAGE ENERGY DENSITY. RESULTS FROM NUMERICAL MODEL.

(c) Relative annual average energy density at 100m a.g.l.

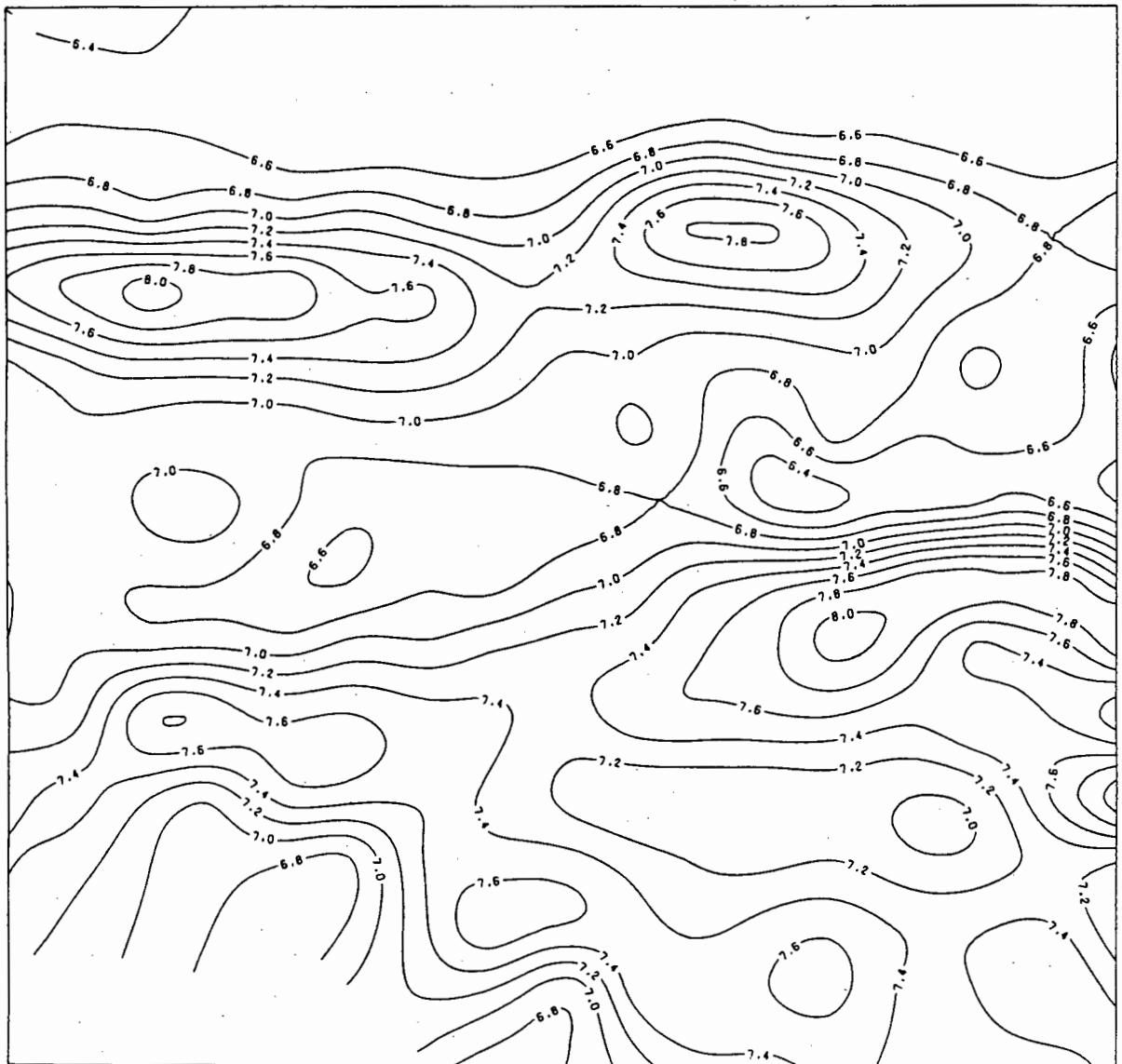


ENERGY DENSITY. H=100M A.G.L.

APPENDIX 6.8. (a)

TRUE ANNUAL AVERAGE WIND SPEED. RESULTS FROM NUMERICAL MODEL

(a) True annual average wind speed at 20m a.g.l.

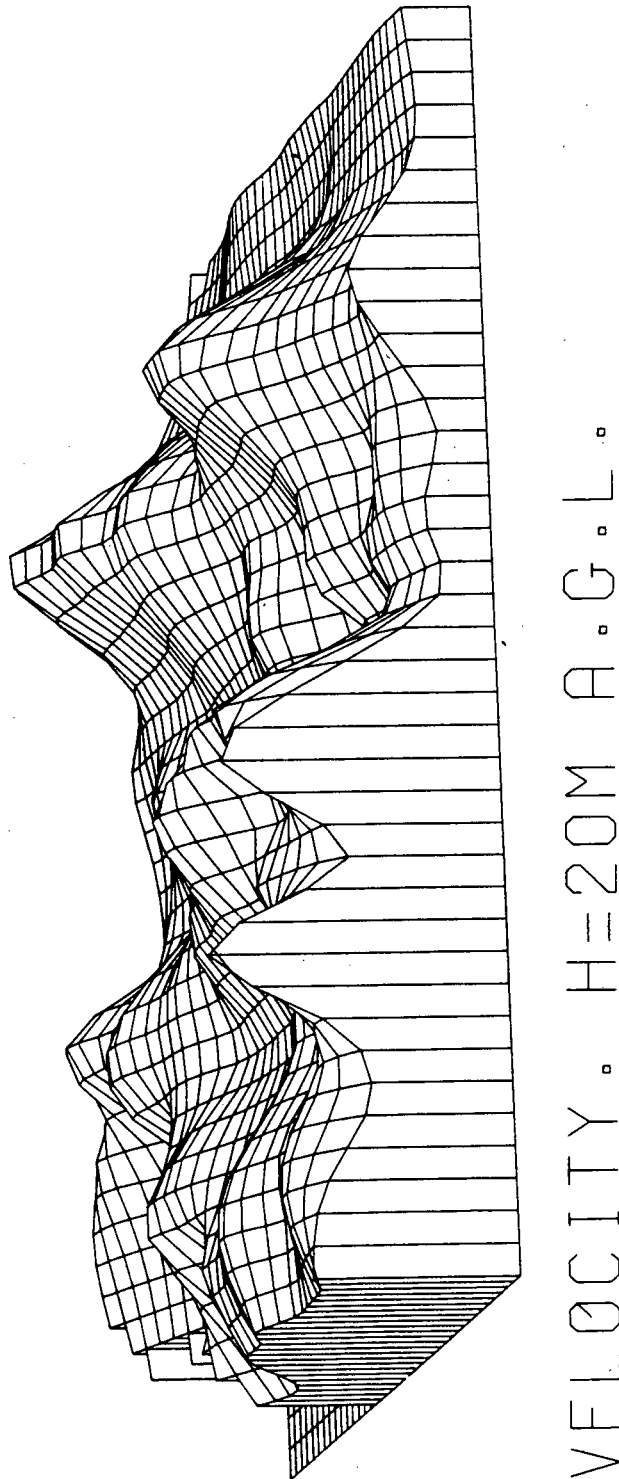


VELOCITY. H=20M A.G.L.

APPENDIX 6.8. (a)

TRUE ANNUAL AVERAGE WIND SPEED. RESULTS FROM NUMERICAL MODEL.

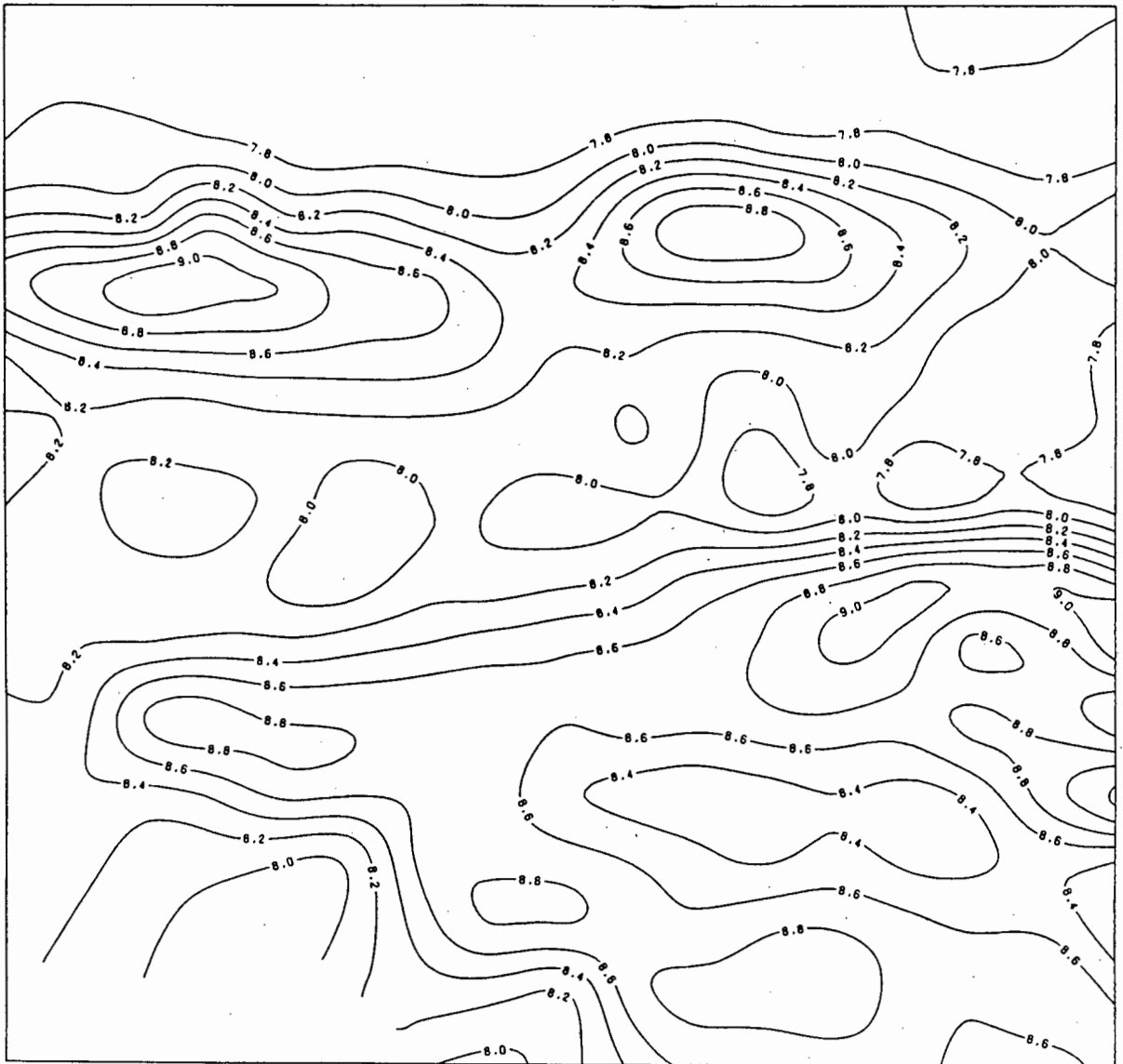
(a) True annual average wind speed at 20m a.g.l.



APPENDIX 6.8. (b)

TRUE ANNUAL AVERAGE WIND SPEED. RESULTS FROM NUMERICAL MODEL

(b) True annual average wind speed at 50m a.g.l.

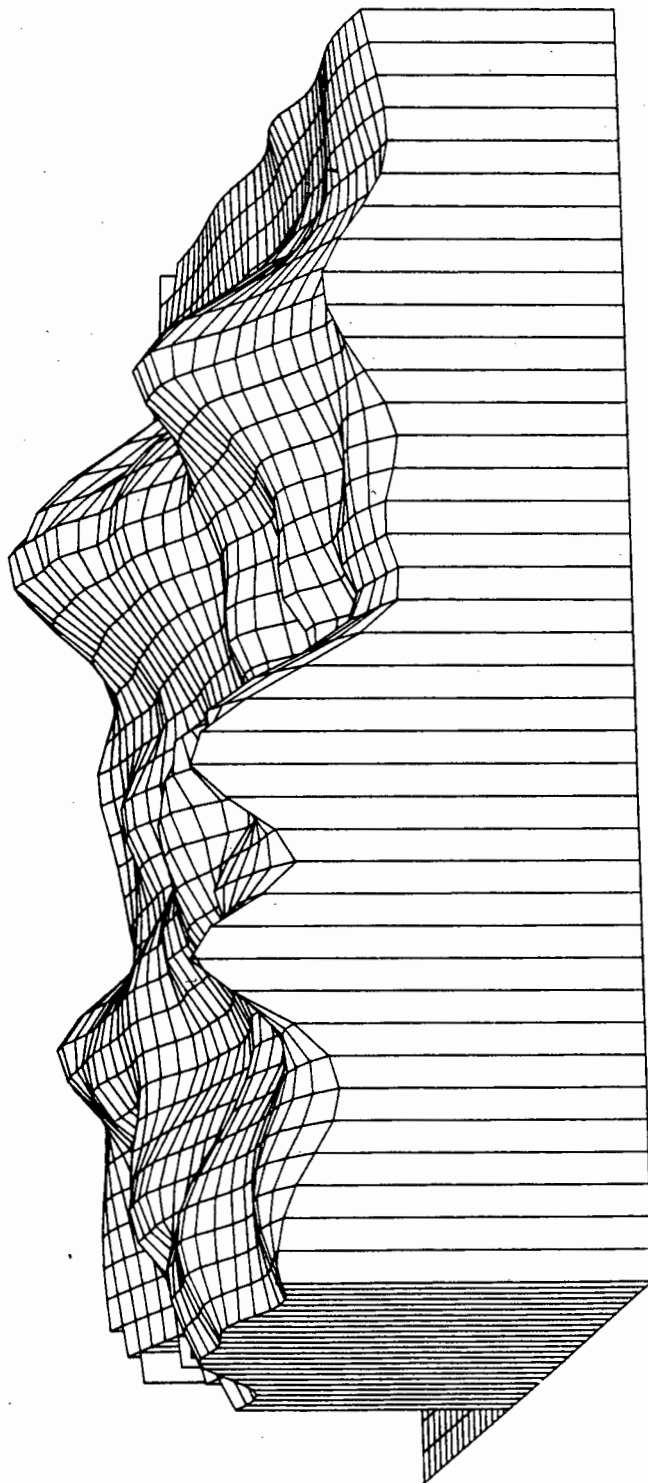


VELOCITY. H=50M A.G.L

APPENDIX 6.8. (b)

TRUE ANNUAL AVERAGE WIND SPEED. RESULTS FROM NUMERICAL MODEL

(b) True annual average wind speed at 50m a.g.l.

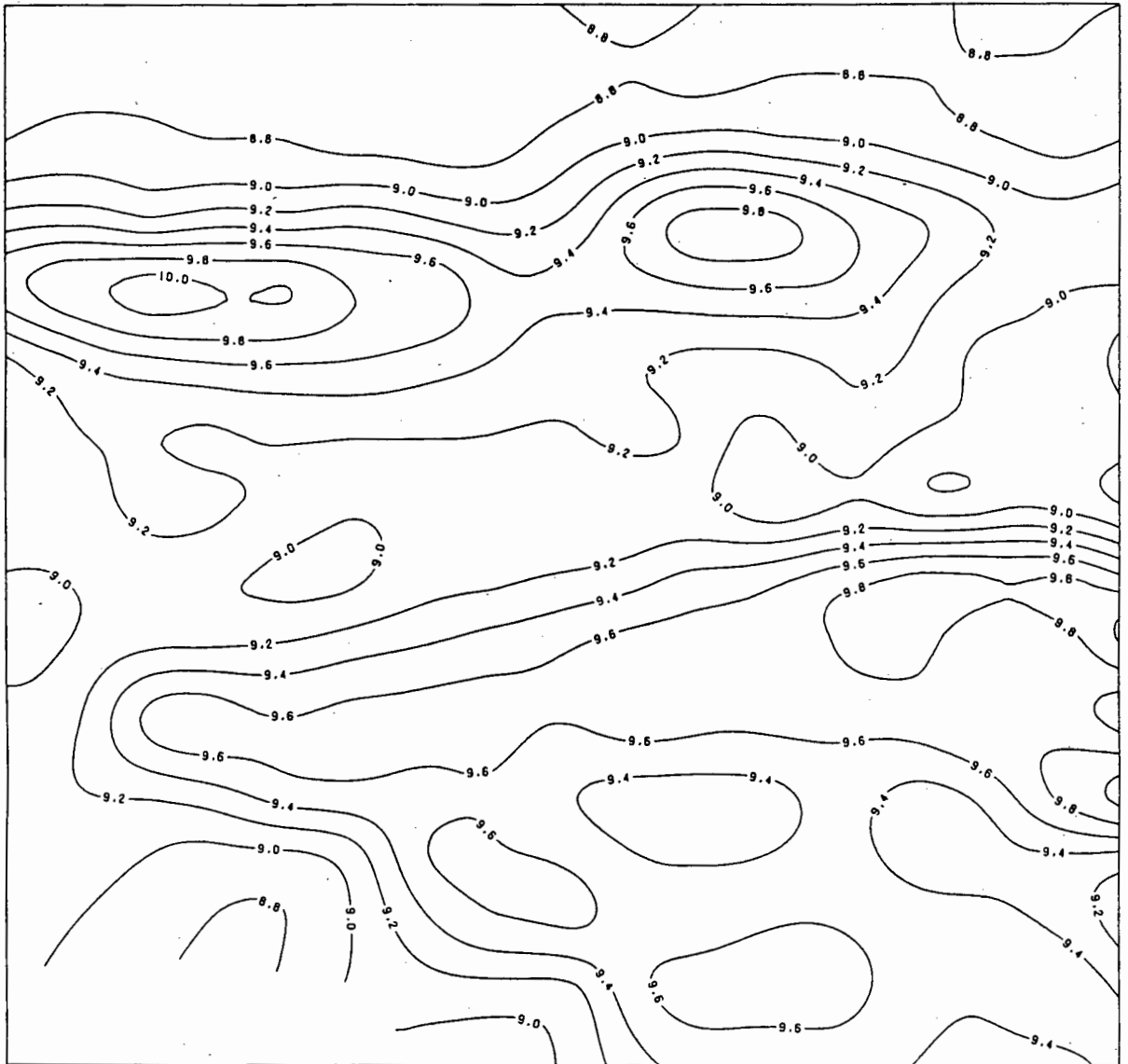


VELOCITY . H=50M A.G.L.

APPENDIX 6.8. (c)

TRUE ANNUAL AVERAGE WIND SPEED. RESULTS FROM NUMERICAL MODEL

(c) True annual average wind speed at 100m a.g.l.

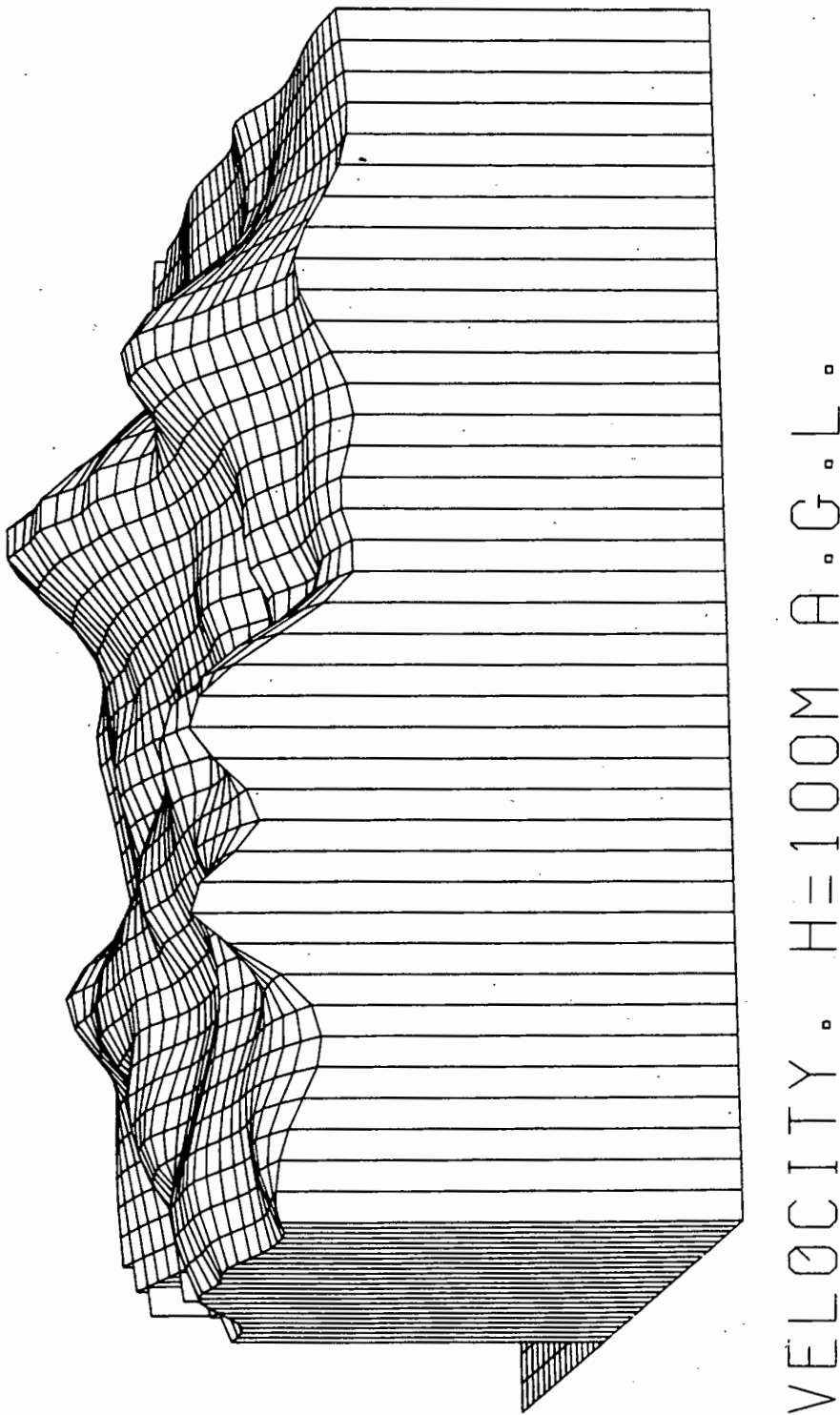


VELOCITY. H=100M A.G.L

APPENDIX 6.8. (c)

TRUE ANNUAL AVERAGE WIND SPEED. RESULTS FROM NUMERICAL MODEL.

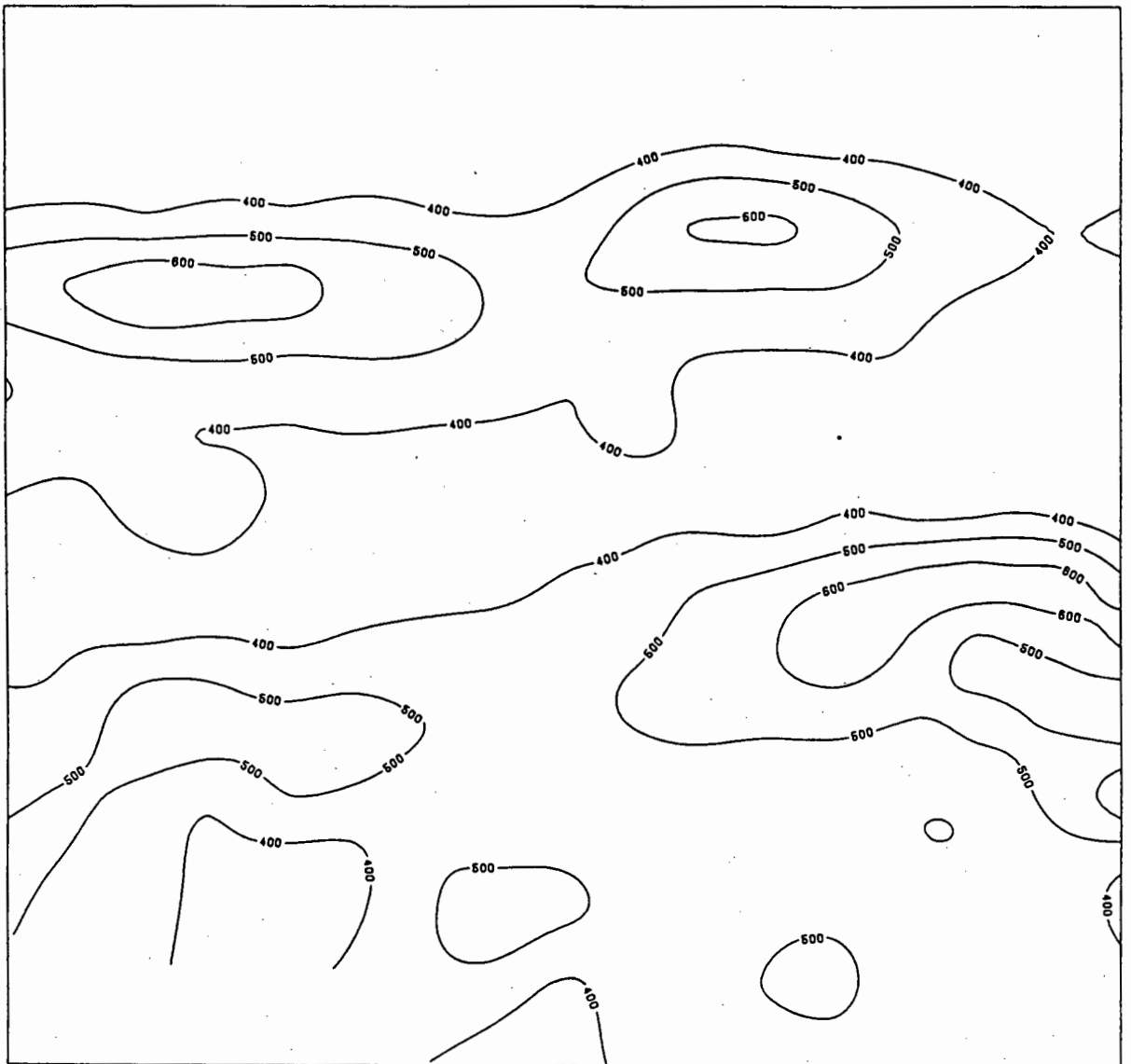
(c) True annual average wind speed at 100m a.g.l.



APPENDIX 6.9. (a)

TRUE ANNUAL AVERAGE ENERGY DENSITY. RESULTS FROM NUMERICAL MODEL

(a) True annual average energy density at 20m a.g.l.

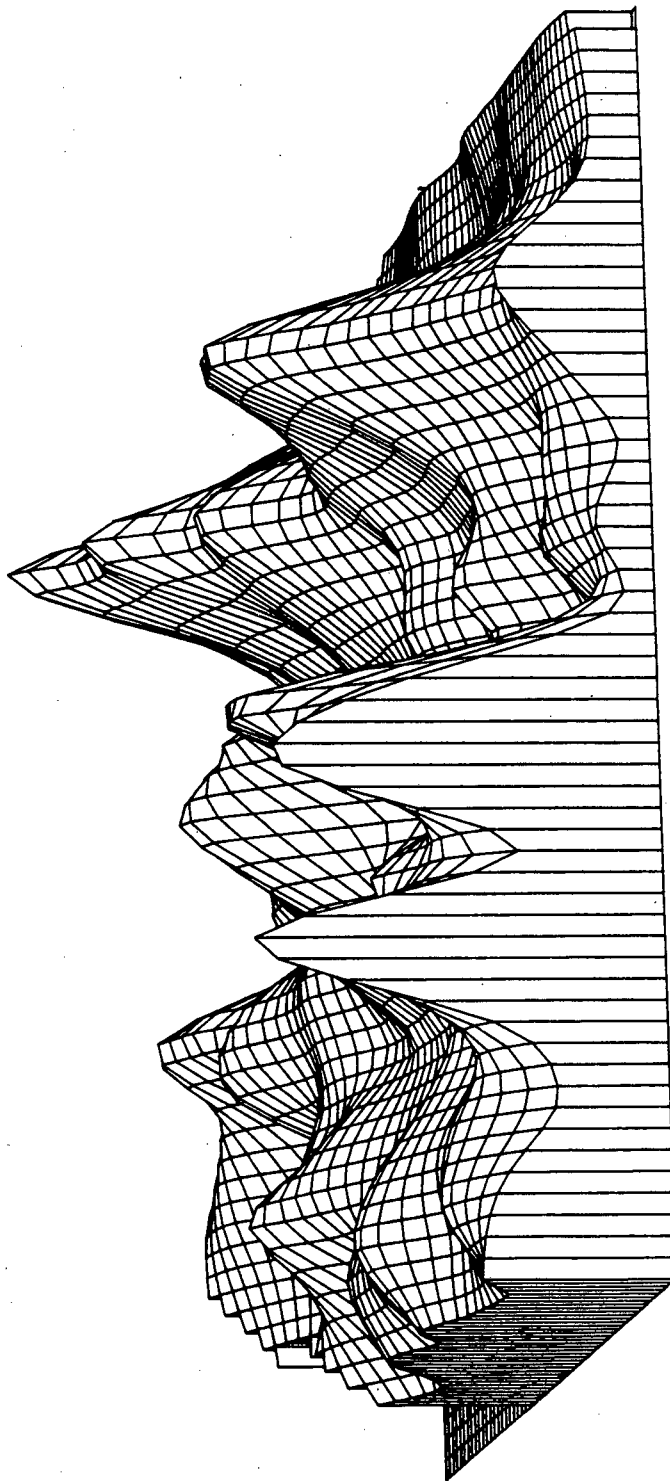


ENERGY DENSITY. H=20M A.G.L

APPENDIX 6.9. (a)

TRUE ANNUAL AVERAGE ENERGY DENSITY. RESULTS FROM NUMERICAL MODEL.

(a) True annual average energy density at 20m a.g.l.

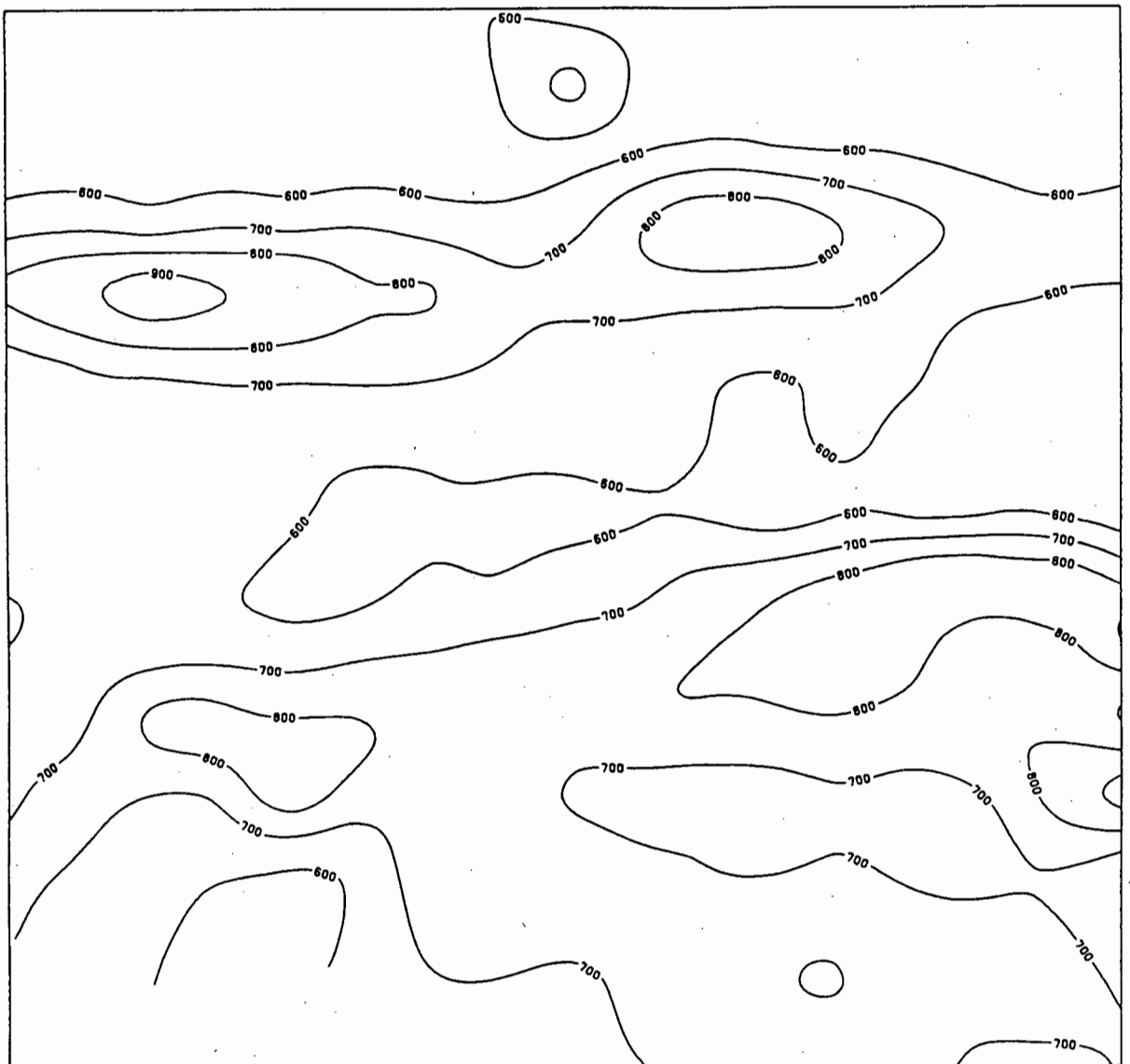


ENERGY DENSITY. H=20M A.G.L.

APPENDIX 6.9. (b)

TRUE ANNUAL AVERAGE ENERGY DENSITY. RESULTS FROM NUMERICAL MODEL.

(b) True annual average energy density at 50m a.g.l.

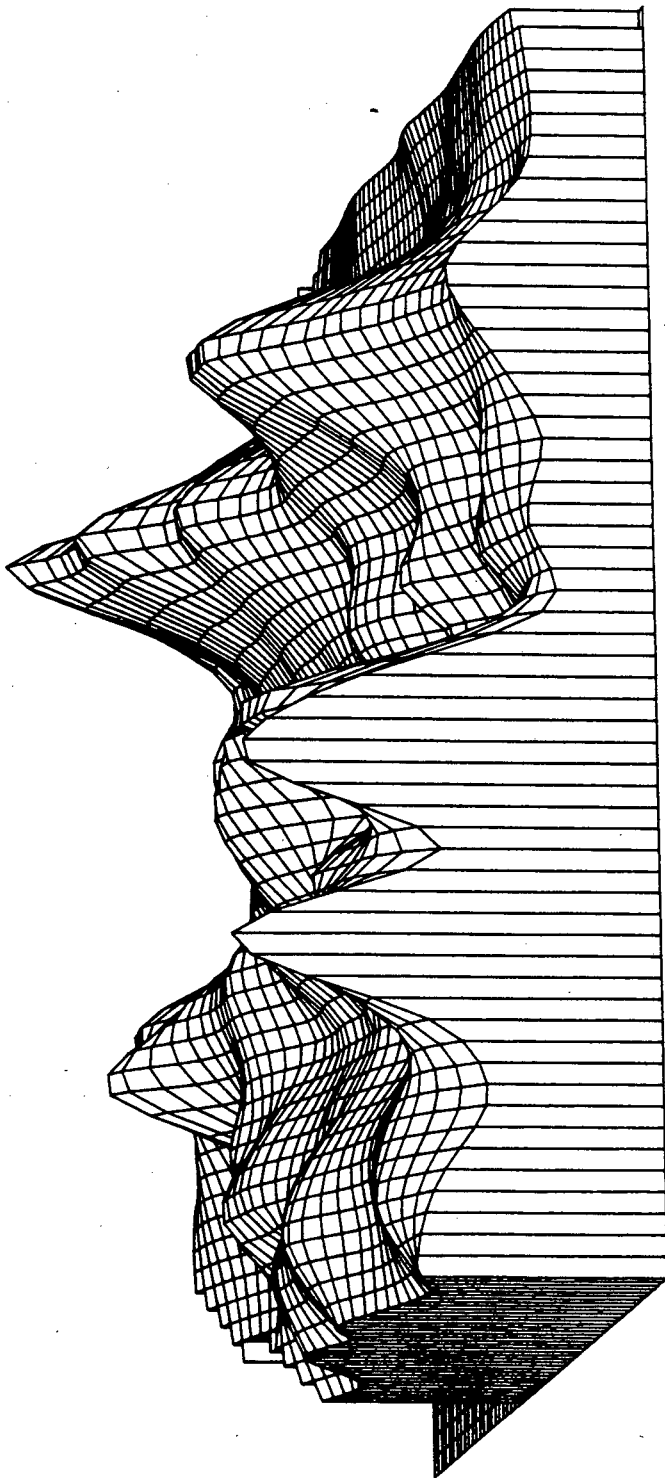


ENERGY DENSITY. H=50M A.G.L

APPENDIX 6.9. (b)

TRUE ANNUAL AVERAGE ENERGY DENSITY. RESULTS FROM NUMERICAL MODEL.

(b) True annual average energy density at 50m a.g.l.

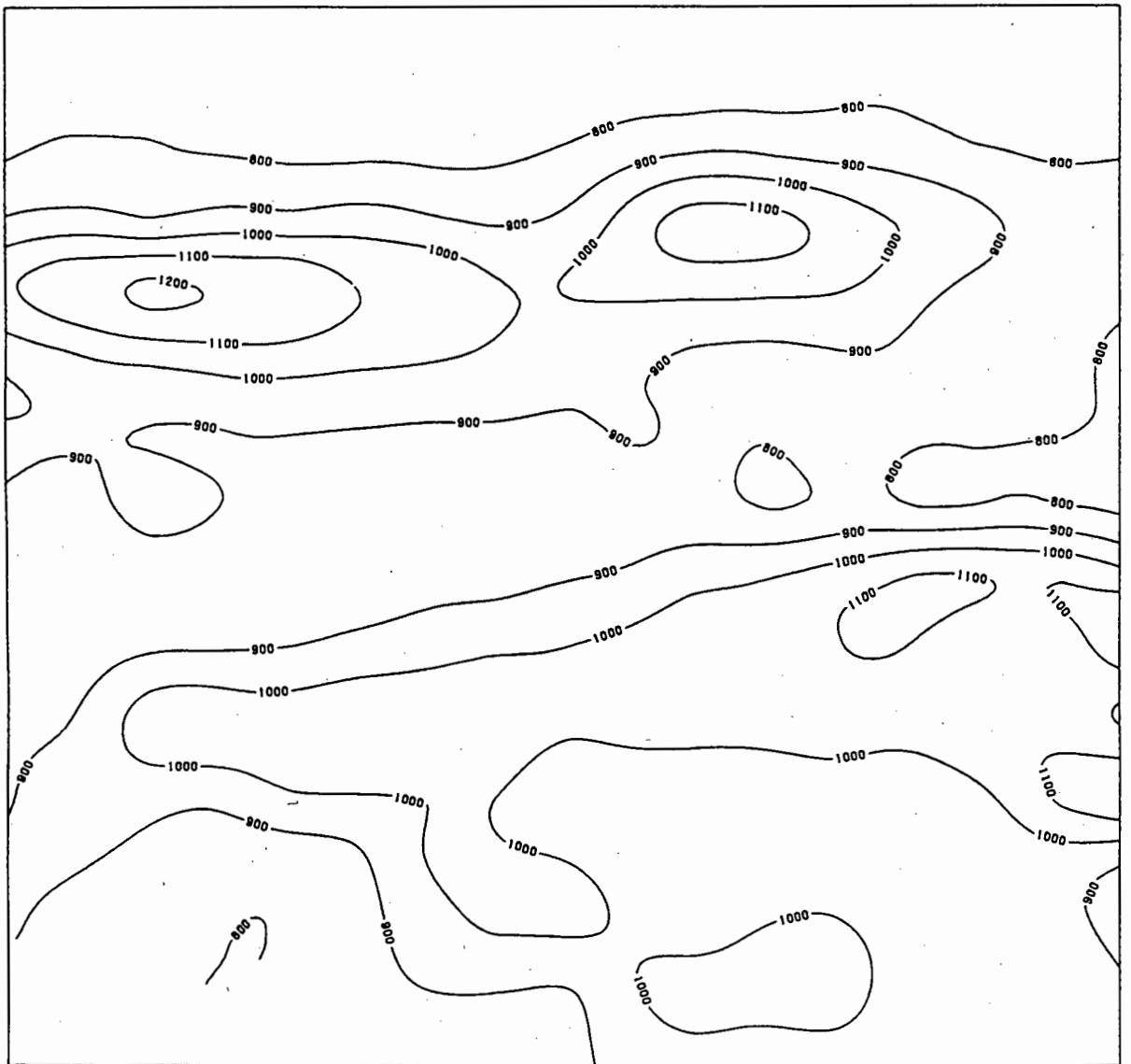


ENERGY DENSITY. H=50M A.G.L.

APPENDIX 6.9. (c)

TRUE ANNUAL AVERAGE ENERGY DENSITY. RESULTS FROM NUMERICAL MODEL

(c) True annual average energy density at 100m a.g.l.



ENERGY DENSITY. H=100M A.G.L

APPENDIX 6.9. (c)

TRUE ANNUAL AVERAGE ENERGY DENSITY. RESULTS FROM NUMERICAL MODEL

(c) True annual average energy density at 100m a.g.l.

