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AN INVESTIGATION OF THE AREAS OF POTENTIAL WIND EROSION IN THE CAPE PROVINCE, REPUBLIC OF SOUTH AFRICA

BY

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ABSTRACT

Soil erosion is regarded as a serious problem throughout the world. Erosion is caused by both water and wind. Although the two usually occur together, wind erosion has received little attention with the exception of the problems associated with croplands. Wind erosion can, however, also be a serious problem in natural grazing lands.

In this research project an attempt is made to determine the areas of potential wind erosion in the Cape Province through the use of two different models. The models used were developed and applied in semi-arid areas and thus were considered to be applicable in South Africa. The models used are: The Wind Erosion Equation developed by Chepil, Woodruff and Siddoway in the United States; and Lynch and Edward's Model for the Analysis of Limited Climatic Data, developed in Australia.

There are two aspects to soil erosion by wind - the erodibility of the soil as determined by moisture, grains size, aggregates, plant cover and surface topography; and soil erosivity as determined by wind strength and duration. Methods to control wind erosion are based on decreasing erosivity through the establishment of shelterbelts and by decreasing erodibility through improving plant cover, aggregate stability and moisture retention properties.

Efforts at wind erosion measurement are generally ineffective. A number of models have been developed to overcome these difficulties and to allow for prediction of soil loss. Two of these models are applied to conditions in the Cape Province. This area covers a wind range of climatic, soil and agricultural conditions and as such provides an appropriate area for their application.

It is, however, concluded that neither of these models can be directly applied to conditions in the Cape Province. The seasonal rainfall distribution and the uneven distribution of the data points contribute to the ineffectiveness of the models. The greatest problem, however, is the importance of management in determining whether or not wind erosion occurs. As a result, although the models illustrate the general climatic trends affecting the susceptibility of an area to wind erosion, the lack of a management factor accounts for the lack of detail.

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CHAPTER ONE

INTRODUCTION

> "By the late 1970s, soil erosion exceeded soil formation on abut a third of US cropland, much of it in the midwestern agricultural heartland. In Canada, soil degradation has been costing farmers $1 billion a year. In the USSR, the extension of cultivation to the so-called Virgin Lands was a major plank of agricultural policy, but now it is believed that much of this land is marginal. In India, soil erosion affects 25-30 per cent of the total land under cultivation. Without conservation measures, the total area of rainfed cropland in developing countries in Asia, Africa and Latin America will shrink by 544 million hectares over the long term because of soil erosion and degradation, according to the Food and Agriculture Organization (FAO)." (World Commission on Environment and Development 1987, p. 125)).

As the above quotation indicates, soil erosion is a serious problem throughout the world. Even in the the United States where "nearly $15 billion has been spent on soil conservation since the mid-1930's, the erosion of croplands by wind and water ... remains one of the biggest, most pervasive environmental problems the nation faces" (Carter 1977, 409).

The increasing intensity of land exploitation in both the developed and the developing world has resulted in a growing misuse of this limited resource. Agriculture has had to expand into increasingly marginal areas which has resulted in increased loss of soil by erosion and degradation. Of particular concern is desertification, which is defined as the impoverishment of terrestrial ecosystems under the impact of man so that ultimately desert-like conditions remain (Dregne 1985). Soil erosion by wind and water, timber cutting, vegetation destruction, salinization and waterlogging are all causes of desertification. Dregne (1985) estimates that 80% of the drylands in Africa south of the Sahara are at least moderately desertified. It thus appears that soil erosion is not only a problem on its own, but that it is also a significant factor in the broader and self-sustaining problem of desertification.

Soil erosion, itself, is a complex and far reaching problem. Erosion reduces the water holding capacity of the soil as well as its inherent fertility as soil nutrients are depleted. Soil depth and thus the root zone, is decreased. Eroded topsoil is deposited in rivers, lakes and reservoirs, silting up waterways and ports, reducing reservoir storage capacity and increasing the incidence and severity of floods. Wind transported soil can damage buildings and equipment and give rise to air pollution.

Yet despite the severity and extent of the problems which arise as a consequence of erosion, it must be placed in context, as it is a natural and ongoing geomorphological process. It is through an understanding of these basic geomorphological principles that the nature and severity of accelerated erosion can be assessed. It is thus erosion, exacerbated by human activity, which constitutes the problem. Accelerated erosion exceeds the natural soil forming processes and there is a net decrease in the quality and volume of soil.

There are two forms of sediment transport other then soil erosion, *viz*: mass movement and solution. Under natural conditions, the relative importance of each of these processes depends on the geological,topographical and climatic conditions of an area. These processes seldom act in isolation, as the effects of soil erosion or solution may give rise to mass movement and in turn, the scars on the landscape resulting from mass movement are readily eroded further. Sediment transport by solution requires infiltration and chemical breakdown of rock or soil material, whereas in areas where overland flow is dominant, soil erosion is the main denudation process. Human activity can play a significant role in increasing the amount of overland flow by compacting the soil and removing the vegetation. It can thus be seen that their is a complex network of factors and feedback mechanisms associated with soil loss.

Soil particles may be dislodged and transported by both wind and water. Wind erosion losses of 10 mm yr^{-1} were recorded in Kansas for a period of 20 years prior to the implementation of soil conservation practices (Kirkby 1980). Rates of water erosion are seldom this extreme. Although losses of 1 mm yr^{-1} by water erosion have been recorded in some semi-arid areas, in Britain erosion rates rarely exceed 1 um yr^{-1} (Kirkby 1980). The extent of erosion is, however, highly dependent on vegetation cover.

Current soil conservation practice is based on acceptable erosion rates of 2 - 10 tons $acre^{-1}$ yr^{-1} which is equivalent to a loss of 0.2 to 1 mm yr^{-1} (Kirkby 1980). This rate is argued to keep pace with the rate of chemical weathering forming new soil.

South Africa is largely a semi-arid country in which soil erosion is a serious problem. In the past, however, much of the attention has been focused on water erosion and gullying or donga formation. Wind erosion has received little direct attention with the exception of the cropped areas of the Transvaal and the Orange Free State, as in the marginal agricultural areas of the western Free State and western Transvaal, wind erosion is considered to be a prominent economic problem (Roux 1986). Roux (*pers. comm.*) also considers wind erosion to be one of the most serious problems facing the Karoo. There has been virtually no research, except in cultivated areas to determine which areas are particularly prone to wind erosion and which factors are the most important in giving rise to erosion by wind. This has been identified as a research priority by the Department of Agriculture (Roux 1986).

Although rates of soil loss by wind erosion can be high it is an insidious problem as it seldom gives rise to such obvious scars as dongas. Dust storms are capable of transporting huge volumes of soil, although this is not always apparent to the observer and, as a result the problem is often disregarded. In addition, the actual effects of cumulative wind erosion in terms of lost fertility are often masked by the increased use of fertilizers and pesticides, and the problem continues.

It was thus considered an appropriate and necessary research project to assess the wind erosion hazard in South Africa and the obvious initial task was seen to be the production of a map showing the susceptibility of different areas to wind erosion. A variety of models for the determination of the risk of wind erosion are available and it was decided to test the usefulness of two of these models for South African conditions. Both of the models were developed and applied in semi arid conditions and as such they were considered to be potentially applicable in a semi arid country such as South Africa. The models are: the Wind Erosion Equation developed by Chepil, Woodruff and Siddoway in the United States, and Lynch and Edward's model for the analysis of limited climatic data, developed in Australia.

There are thus two aims in this research project; to produce a map of the wind erosion hazard, and to test the applicability of the above mentioned models to conditions in South Africa. An assessment of wind erosion by means of aerial photography and a postal survey was undertaken in order to test the effectiveness of the models in describing actual conditions.

The structure of this report is as follows. Chapter 2 contains a description of the nature of the wind erosion hazard globally and regionally, and the problems associated with it, such as changes in soil fertility, crop damage and atmospheric pollution. The actual processes of wind transport of soil particles and the means of controlling wind erosion are described in Chapter 3. The procedure for the measurement of wind erosion and its associated problems, and the different approaches to modelling wind erosion are discussed in Chapter 4. These chapters contain the required background which has formed the foundation on which this research was undertaken. The description of the geographical limitations of the study are contained in Chapter 5. The methodological approach taken in the implementation of this research project is found in Chapter 6. Chapter 7 contains the results. Chapter 8 is a discussion of these results and the final Chapter documents the overall conclusions.

CHAPTER TWO

THE SIGNIFICANCE OF SOIL EROSION BY WIND

Wind erosion in agricultural areas has been recorded for hundreds of years, however, the significance of wind erosion only received international attention in the 1930's as a result of the dust bowl conditions in the Western Great Plains of the United States of America. In the fifty years since then, land damaged annually throughout the United States has ranged from a low of 405 thousand ha to a high of 6 million ha (Kimberlin *et al* 1977). Much of this damage has occurred in the Great Plains, although other parts of the country have also been affected.

Over the years wind erosion has been shown to be a problem on all continents, especially in the drier areas. Wind erosion is very common in the steppe areas of the U.S.S.R. (Holy 1980); the 'Black Storms' of the Ukraine have even been known to cause starvation. In 1891, for example, crop damage was so extensive that the population of entire villages starved to death (Holy 1980).

The barren, sandy soils of the arid regions are most susceptible to wind erosion. Hudson (1971) believes that the most vulnerable regions are those with a mean annual rainfall of 250-300 mm, where the prevailing winds are from one direction, and where fairly large level land masses lack sufficient vegetation cover (Figure 2.1). Yet in humid and semi-humid regions, wind erosion does occur where the land has been exposed, especially by ploughing, as well as in the coastal zones and along river banks (Zachar 1982). In the humid regions it is the removal of vegetation, coupled with the drainage of lands, which is primarily responsible for accelerated wind erosion. Chepil (1957) states that wherever (i) soil is loose, finely divided and dry, (ii) soil surface is smooth and bare, and (iii) the wind is strong, wind erosion may be expected. Bennett (1939, 192) had previously stated that "throughout the world, land without a protective cover is subject to some degree of alteration".

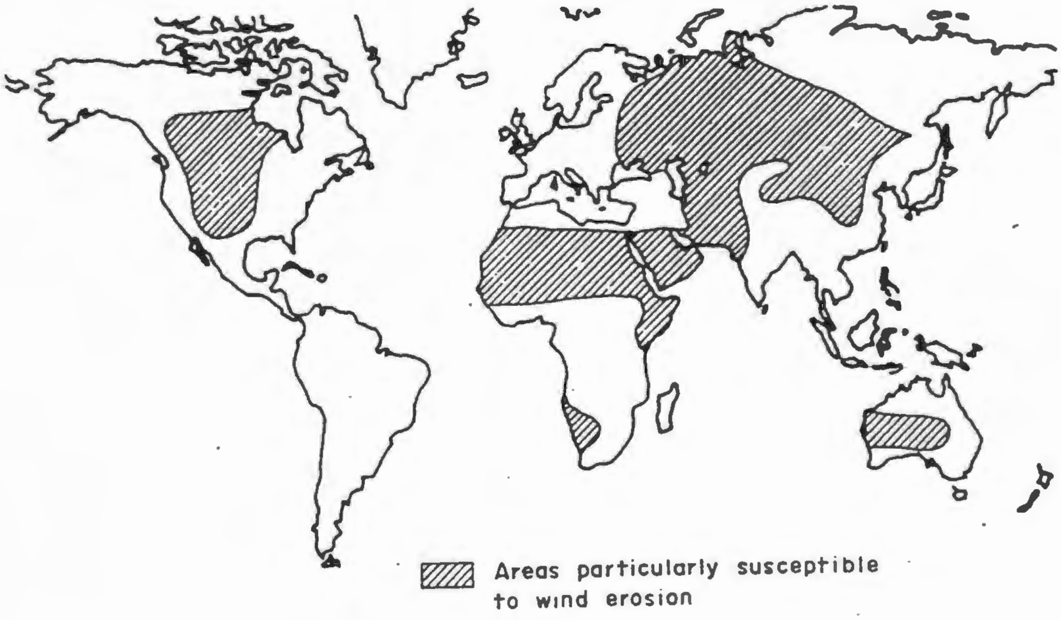


Figure 2.1 Map showing the distribution of areas susceptible to wind erosion (taken from Hudson 1971).

At the turn of the century there were a number of geomorphological studies of wind as an erosive agent. The focus of these studies was on the competence and capacity of wind to transport fine material and of the abrasive power of wind (e.g Udden 1894, Gilbert 1895, Keyes 1910 and Bryan 1923, as cited in Wilson and Cooke 1980). The work of R. A. Bagnold in the 1930's contributed a much greater understanding of the wind erosion system. His research examined the relationship between wind and sand transport in terms of the aerodynamics which were amenable to direct measurement. He conducted extensive experiments in the Libyan Desert and in the laboratory with the use of a wind tunnel. His findings were published in an oft quoted treatise, *The Physics of Blown Sand and Desert Dunes,* (Bagnold 1941)

Bagnold's research provided the basis for the work done at the Kansas State University Wind Erosion Research Station where the focus was on the control of wind erosion on cultivated lands. Chepil and Woodruff (1963) attempted to identify and quantify the factors affecting the rates and location of wind erosion and to develop a means of predicting soil loss on the basis of a climatic index. This research continues today with the aims of refining the prediction equation, improving the means of controlling wind erosion and in defining tolerable levels of soil loss.

The main focus of research on the nature and control of wind erosion has been on cultivated lands. In the dry regions of the United States, the use of practices such as stubble-mulch-tillage and minimum- or no-tillage have been shown to be effective protective measures, along with the use of strip cropping and wind breaks. These practices are, however, not appropriate in the semi-arid and arid rangelands, which are not cultivated as such. In these areas wind erosion is part of the problem of increasing desertification and land degradation. Here the maintenance of adequate ground cover, which is essential for the control of wind erosion, is related to land use pressures and grazing management.

Damage caused by wind erosion can be extensive. It is often a subtle process, the effects of which may only become apparent after many years. In the long term, the effects of wind erosion have been shown to include a loss of soil fertility which results in a lower return per hectare and necessitates increased use of fertilizers. Accompanying this is a potential loss of seeds, damage to seedlings and sensitive crop plants. Exposed surfaces may be subject to abrasion or the deposition of wind transported material. Blowing dust and sand also give rise to problems of atmospheric pollution. There are thus four main areas of concern in relation to the damages caused by wind erosion: (i) damage to soils, (ii) damage to crops and (iii) atmospheric pollution and (iv) deposition of eroded material. Discussion of each follows.

2.1 SOIL DAMAGE

A six day blow in Lincolnshire, England during March 1968 is reported to have affected 9 000 ha, giving rise to damage valued at £ 1 million (Wilson and Cooke, 1980). During the 1975-76 wind erosion season in the southern Great Plain states of the United States, over 3 million ha were damaged (Kimberlin *et al* 1977). Lands that are considered to be 'damaged' are those which lose soil at the rate of 33.6 t ha^{-1} yr^{-1} (Kimberlin *et al* 1977) or more. Pimentel (1976) estimates that in the U.S., agricultural lands are eroded at a rate of 30 t ha^{-1} yr^{-1}, which is 8 times faster than the rate at which topsoil is formed. The loss of soil to a depth of 2,5 cm is roughly equivalent to the loss of 112 to 374 t ha^{-1}. It is at this level that wind erosion damage is readily observed with the eye. Although erosion rates of this magnitude are rare, during the dust storms of the 1930's, soil loss was such that entire ploughed layers were blown away from many farm fields in the Great Plains. In western Canada some field have been reported to have lost 60 cm of soil in a single year (Troeh *et al* 1980).

Soil damage results from the sorting action of the wind, whereby finer particles are removed leaving behind the coarser soil grains (Troeh *et al* 1980, Lyles 1975, Kimberlin *et al* 1977). Over time, soil texture becomes coarser, and this in turn reduces soil fertility and water holding capacity. Eventually a gravel pavement forms as the more fertile elements are caught up in a system of shifting dunes. Associated with the changes in soil texture is the loss of plant nutrients and organic matter which reduces soil productivity. It is, however, difficult to measure the nature of these changes and to relate them to soil productivity and changes in yield.

2.1.1 Quantification of soil loss and productivity changes

As a result of the complexity of factors that contribute to soil productivity and to the difficulty of isolating the effects of a single process such as wind erosion, little attempt has been made to quantify the effect of wind erosion on intrinsic soil properties. Colloidal clay and organic matter are the essential components of inherent soil fertility. The early effects of wind erosion result in the removal of the finer particulate matter and thus the basis of soil fertility. It is thus the coarse-textured soil with few fines that suffer the greatest drops in fertility. Soil fertility, however, can also drop in soils that do not experience a change in texture.

The factors which affect soil productivity include crop varieties and rotations, planting dates, type and dates of tillage, rainfall amount and distribution, soil nutrients, fertilizer rates, slope, rooting depth, soil texture and erosion. It is thus obvious that productivity is related to climatic factors, management practices as well as natural hazards, and erosion is only one factor, the effects of which are, in turn, complex.

There have been reports (Lyles 1975) that wind erosion in the Great Plains caused a reduction in wheat yields of 0.045 t ha^{-1} yr^{-1} over a period of thirty years. If a linear relationship is assumed, this is equivalent to 0.0015 t ha^{-1} yr^{-1} (Lyles 1975). In the Great Plain states, the average annual wheat yield (measured from

1928-1972) is 0.15 t^{-1} ha^{-1}. Thus the loss of 0.0015 t by wind erosion is equivalent to about 1% of the average yield. This value, however, is misleading, as the coefficient of variation for long term wheat yields ranges from 69% in Texas to 37% in Saskatchewan, Canada. It is clearly apparent that it is impossible to isolate a single factor such as wind erosion to explain the degree of variation in crop yields.

As a result of the complexity, attempts to quantify the effects of wind erosion on soil productivity have been aimed at converting annual soil loss expressed as centimetres removed, to estimates of corresponding reductions in crop yield (Lyles 1975, 1977). This was done using the wind erosion equation (discussed in section 3.3.2) for parts of Kansas and Iowa. The area of Kansas studied consisted of 1,2 million acres made up of 6% sandy soils (WEG-1), 27% loamy sands (WEG-2) and 67% sandy loams (WEG-3). According to calculations of the wind erosion equation using residue management, potential soil losses would be 3.25, 0.46, 0.26 cm yr^{-1}, respectively. This gives an approximate reduction in wheat yield of 0.02, 0.0075, 0.0043 t ha^{-1} yr^{-1} for WEG-1,-2 and -3 respectively. Similarly, sorghum losses would be 0.034, 0.012, 0.0068 t ha^{-1} yr^{-1}. At 1972 prices, this is equivalent to a yearly loss of $1 255 000. Many assumptions have, however been used in achieving these figures, and as such they should only be viewed as an example which illustrates the extent to which it is feasible to estimate the economic losses caused by wind erosion.

2.2 CROP DAMAGE

Damage to crops occurs predominantly because of the abrasive action of the particles transported by wind (Kimberlin *et al* 1977). Crop damage may occur even when the actual soil losses are below the level that is considered damaging to the soil. Armbrust (1972) observed that changes in metabolic rate can occur before there is any visible evidence of damage to plants. Damage can also result in a loss of seedlings (requiring reseeding), decreases in yields, delayed harvest or even the complete loss of the crop (Downes *et al* 1977) Fryrear (1971) suggests that up to 80% of dryland in the Southern Great Plains has to be replanted each year. The Soil Conservation Service reported that for the 1975-1976 season, 809 000 ha were damaged to such an extent that yields were lowered below the level where it was considered economical to harvest (SCS, 1976).

Downes *et al* (1977) conducted a study to determine the survival of six vegetable crops (cabbages, carrots, onions, cowpeas, cucumbers and peppers) under conditions of varying wind velocity, soil particle flux densities, exposure duration and seedling age. The different factors were combined to express a single storm intensity value, the total kinetic effect (TKe). Their findings show that with increased TKe, early growth was considerably decreased. Following the initial growth rate reduction, growth became normal for cabbages, carrots, onions and peppers, possibly due to the result of decreased stands which resulted in a decrease in interplant competition. For the cowpeas and cucumbers plant growth and yield ultimately increased with increased TKe, with no reduction in stand. However, even root crops such as carrots and onions suffered from reduced growth rates and yield. Plant growth rates remained lower than normal for up to three weeks following a storm of high kinetic energy.

It can thus be seen that wind can affect the metabolic processes of plants and their growth rates. Evapotranspiration rates and the effectiveness of moisture usage are also affected by wind. The level of damage can be such that yields are reduced to the point where it is uneconomical to harvest. There is no available information on the effects of wind erosion on natural vegetation.

2.3 ATMOSPHERIC POLLUTION

Dust storms contribute more particulate matter to the atmosphere than all other sources combined (Kimberlin *et al* 1977). 310 tonnes of dust particles have been measured in 1 km^3 of air in a dust storm (Chepil and Woodruff 1957). Goudie (1984) describes dust storms as an insidious form of soil erosion. He states that in a dust storm of average intensity, a cube of air (3m by 3m by 3m) can hold 28 g of dust. If this figure is extended, a dust storm measuring 500 km by 600 km across, could be transporting 100 000 000 t of soil.

Wind erosion can thus give rise to health and safety hazards, the closing of business and public facilities, costs of clean up and restoration and the reduction of property values or loss of income. The Council on Environmental Quality (CEQ 1975) lists 33 cities in 14 states in the U.S.A. where air quality standards cannot be met as a result of uncontrollable air pollution sources such as dust storms or dust blown from farm fields or dirt roads.

2.4 DEPOSITION OF ERODED MATERIAL

Suspended dust can be transported for long distances and deposited as a thin film over everything, which although not causing any particular physical damage can be very demoralizing for the people who constantly battle to remove it. It can also be a costly process to keep equipment and living areas clean under these conditions.

The deposition of saltating material, on the other hand, can cause considerable damage. Farm fences and crops can be buried, drainage and irrigation ditches can be blocked, highways and engineering works can be covered and leveled land can be made hummocky by drifting sand. During a strong blow in March, 1968 in Lincolnshire, 3 - 4000 tonnes of soil from a 80 ha farm in the Holten-le-moor area, are reported to have been blown a kilometre into the drains. In Lindsey, nearby, it cost £ 4000 to clear drifted soil from farm fields and a further £ 6000 to clear infilled drains (Curtis *et al* 1976).

2.5 WIND EROSION IN SOUTH AFRICA

Literature on wind erosion and its effects is concentrated primarily on conditions in the United States, although conditions in the U.S.S.R. and Great Britain have also received some attention. In South Africa, on the other hand, wind erosion has received little attention, except for broad observations which suggest that the problem is considered to be serious. A world survey on soil erosion was conducted in the late 1930's by Jacks and Whyte. In it they stated that a national catastrophe due to soil erosion was more imminent in South Africa than in any other country they had visited (Jacks and White 1939).

In 1945 a report was written about the state of soil erosion and land use in South Africa by the Chief of the Soil Conservation Service of the United States Department of Agriculture, Dr. Hugh Bennett. He emphasized the cumulative effects of wind erosion and estimated that productivity on all kinds of farm lands had dropped by 25% as a result of erosion by wind. In parts of the Karoo, erosion was so severe that carrying capacity had been reduced to 10% of its former level (Bennett 1945, 16).

In 1944 a study of the land utilization and soil erosion of the Swartland and Sandveld in the western lowveld of the Cape Province was conducted by Professor W.T. Talbot of the University of Cape Town. He noted that in the Sandveld, soil deterioration resulted from two processes: recurrent removal of fine soil particles, and the deposition of sterile drift sand from nearby erodible surfaces. During the summer of 1938, the effects of wind erosion were obvious on 12 419 ha of arable land in the Sandveld and on 770 ha in the Cape Flats (Talbot 1947, 73).

Based on observations and using an analogy from figures calculated in the United States of America, J.C. Ross (1963) of the South African Department of Agricultural Technical Services, calculated that soil loss for the country as a whole was around 304.7 million t yr^{-1}. A value which is equivalent of a layer of soil 15 cm deep spread out over 107 062 ha. This value was determined for total soil loss, derived from both wind and water erosion.

More recently a report on the estuaries of the Cape Province states that, "Wind erosion of ploughed lands is a major problem in the Highveld Catchment of the Orange where dust storms are common" (Heydorn and Tinley 1980, 63). The South African Weather Bureau (1975) considers wind to be the primary erosion agent in the Karoo. In the Upper Karoo dust storms are a common phenomenon (Roux and Opperman 1986). On a smaller scale, dust devils or whirlwinds are a common feature throughout the Karoo. Drifting sand deposits are reported to be a serious problem in the cultivated areas north of the Orange River. Namaqualand is subject to severe deflation as seen in the severely areas north of the Orange River. Namaqualand is subject to severe deflation as seen in the severely eroded plains of which Knersvlakte is one example (Roux and Opperman 1986). The north-western coastal area of the Cape Province is subject to shifting sands, dune formation and the deposition of aeolian material in the adjacent interior.

The evidence suggests that wind erosion has been a problem in South Africa throughout this century. As remarked in the Proceedings of the Eighth National Congress of the Soil Science Society of Southern Africa, the problem has not received the attention it deserves (Scotney 1980). In the past, attention to the problems of wind erosion in South Africa has been focused on the control of coastal drift sands and dunefields, and in the Highveld on improved methods of cultivation. What is needed, however, is a background assessment of the basic climatic, biotic and physical features which make certain areas more susceptible to wind erosion. This project seeks to address this problem by providing the necessary initial assessment of actual and potential wind erosion in the Cape Province, south of the Orange River.

This chapter has reviewed the problems caused by wind erosion and their significance in different parts of the world and now the following chapter discusses the mechanisms whereby erosion occurs. The physical parameters which give rise to wind erosion are described. The means by which wind erosion can be controlled through management, as well as vegetative and mechanical measures are also discussed.

CHAPTER THREE

WIND EROSION PROCESSES AND THE CONTROL OF WIND EROSION

Two factors are significant for the movement of surface material by wind; erosivity and erodibility (Morgan 1986, Troeh *et al* 1980, Wilson and Cooke 1980). Erosivity refers to the characteristics of the wind and its ability to erode and transport material. Erodibility is determined by the nature of the surface and the soil characteristics which affect the extent to which it can be eroded and transported by the wind. Thus in the simplest terms, wind erosion is a function of wind erosivity on the one hand and surface erodibility on the other.

3.1 EROSIVITY

Erosivity is dependent on wind velocity, the frequency, duration and direction of flow, as well as the degree of turbulence.

The kinetic energy ($Jm^{-2}s^{-1}$) of wind can be calculated from:

$$KE = \frac{\delta_a v^2}{2g}$$

where v is the wind velocity in m s^{-1} and δ_a is the specific weight of air defined in terms of temperature (T) in ^{0}C and barometric pressure (P) in kPa according to the equation:

$$\delta_a = \frac{1.293}{1 + 0.00367\ T} \cdot \frac{P}{101.3}$$

Energy for windstorms can then be determined by summing the energies for the different wind speeds recorded and weighted according to their duration. This is, however, a fairly complex procedure and in practice more use is made of the wind erosivity index developed by Skidmore and Woodruff (1968). The wind erosivity for wind blowing in vector *j* is found:

$$EW_j = \sum_{i=1}^{n} \overline{V}t^3_{ij} \; f_{ij}$$

where EW_j is the wind erosivity value for vector *j*, Vt is the mean velocity of wind in the *i*th speed group for vector *j* above a threshold velocity of 19 km h^{-1} and f_i is the duration of the wind for the vector *j* in the *i*th speed group.

It appears that for a wind speed high enough to initiate movement, the flow is always turbulent. Bagnold (1941), Bisal and Nielson (1962) and Lyles and Krauss (1971) all note that surface particles vibrate with increasing intensity as wind velocity approaches the threshold velocity at which particle motion is initiated. The initial entrainment of soil particles by wind is affected by two factors, the shear velocity of wind and the bombardment of the soil by grains already in motion. There are thus two threshold velocities required to initiate grain movement, the static or fluid threshold which applies directly to the action of the wind and the dynamic or impact threshold which accounts for the effect of the bombarding particles (Bagnold 1937). The impact threshold velocity is about 20% less than that of the fluid threshold velocity (Morgan 1986). The values of these thresholds vary with the grain size of the material.

3.1.1 PARTICLE MOVEMENT

Once a particle has been dislodged it may be transported by suspension, saltation or surface creep. Particles transported in saltation are generally less than 50 um in diameter, but they may be as large as 100 um (Lyles 1977). They can be transported over long distance, in the order of hundreds of kilometres (Zachar 1982), and to very high altitudes. Dust clouds have been observed to extend up to 5 km (Chepil and Woodruff 1963). Between 3 and 40 % of the weight of soil can be transported in suspension (Chepil and Woodruff 1963).

Saltation is the most important form of soil movement as it accounts for 50 to 80 % of transport (Chepil and Woodruff 1963). Particles with a diameter of 100 to 500 um can be moved, in a series of jumps, up to several kilometres (Zachar 1982). The impact of small grains may then initiate the movement of larger, denser particles causing the spread of erosion in a leeward direction. Movement of still larger particles, with a diameter of 500 to 1000 um occurs in the form of surface creep, in which particles too large to leave the surface are rolled or pushed by other saltating particles, for distances up to several metres. Bagnold (1941) determined that surface creep accounts for 7 to 25 % of transport.

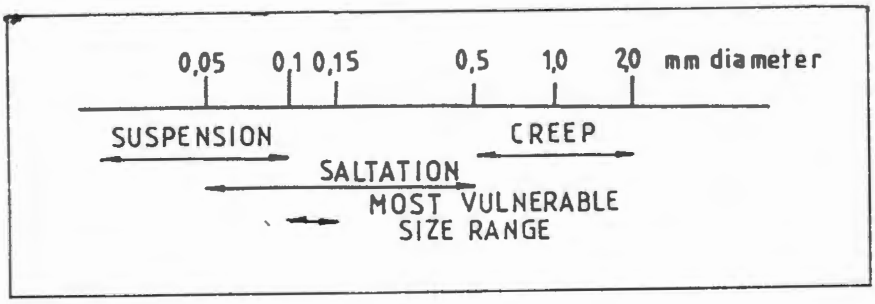


Figure 3.1 The forms of particle movement according to particle size (taken from Hudson 1971)

The height distribution to which particles are blown is shown in Table 3.1.

Height above soil surface (cm)	Amount of soil matter (%)
0 - 5	57.0
5 - 10	18.5
10 - 15	8.5
19 - 96	16.0

TABLE 3.1 Above ground height of soil particles transported by wind (taken from Holy 1980, p. 131).

3.1.2 *Critical velocity for the initiation of movement*

The determination of the critical velocity at which movement is initiated depends on a number of factors: wind velocity: atmospheric pressure, coefficients of friction, cohesion and resistance, aerodynamic roughness, particle diameter and specific weight, and the slope of the surface. Some of the data on critical wind velocity are summarized in Table 3.2 and it is clear from this table that particle diameter significantly affects the wind velocity at which wind erosion occurs.

	grain diameter (mm)					
velocity(ms^{-1})	0.01	0.1	0.25	1.0	1.5	2.0
movement initiated	3.65	3.83	4.57	6.62	7.65	8.57
particle saltation	3.62	5.41	6.60	10.71	13.41	16.25

TABLE 3.2 Velocities at which (a) movement is initiated and (b) saltation begins for a range of particle diameters (taken from Zachar 1982, p. 353).

3.2 ERODIBILITY

It is clearly evident that the extent to which the wind is able to dislodge and transport particles is determined by the erodibility of the surface. For individual soil particles, erodibility depends on their diameter, density and shape. For whole surfaces, it is the nature and stability of soil aggregates, as well as grain size characteristics (soil texture), that is important. These are in turn affected by the moisture content of the soil, the presence of organic or mineral cementing agents or the existence of a surface crust.

It has been shown that a soil of uniform grain size has the least resistance to wind erosion (Zachar 1982). This is related to the packing density and interparticle bond strength, which are affected by the particle size distribution within a soil (Smalley 1970). In a soil comprised of a range of grain sizes, it is the 0,1 mm to 0,15 mm particles (fine sand) that are removed first (Chepil 1945), the second most erodible category being grains in the 0,05 to 0,1 mm (very fine sand) and 0,15 to 0,5 mm (medium sand) diameter size groups, followed by a third category comprised of grains with diameters between 0,5 and 1,0 mm (coarse sand). It is thus the soil particle sizes classified as sand that are the most readily transported by wind. Figure 5.6 illustrates the soil textural classes in the Karoo and it can readily be seen from the map that much of the area along the coast is classified as very sandy and is thus highly erodible. The remaining areas are sandy to loamy and are thus less erodible, but as clay percentages are fairly low these soils would also be susceptible to wind erosion.

Resistance to wind erosion increases rapidly when particles or aggregates larger than 1 mm are dominant. If erosion gives rise to surface armouring in which more than 60 % of the surface material is of this size, then the soil is almost totally resistant to wind erosion, even at velocities of 12,5 m s^{-1} (Morgan 1986, Shiyatyy 1965 as cited in Zachar 1982).

3.2.1 *The effect of soil aggregates*

A soil that contains non-erodible elements, ie peds or aggregates too large to be transported by wind, is less susceptible to erosion. The peds increase the surface roughness and thereby absorb part of the total wind drag so that less force is exerted on the erodible elements (Lyles 1977). Fryrear (1984) found that rates of soil loss could be reduced by 89 % if 60 % of the soil surface was covered by nonerodible, artificial peds. There has been considerable effort made to quantify soil erodibility, Table 3.3 shows two indices which have been derived for soil erodibility of dry stable aggregates larger than 0.84 mm. The first index is based on research conducted in western Siberia and northern Kazakhstan for a wide range of windspeeds (Dolgilevich *et al* 1973 as cited in Morgan 1986). For a wind velocity of 23 m s^{-1} erodibility values ranged from 0,06 for a heavy clay solonetz to 2,14 for a loamy chernozem, 8,0 for a sandy chernozem and 21,2 for a sandy dark chestnut soil. Results of research by Chepil (1960) in Kansas have been extrapolated to give an index in t ha^{-1} y^{-1}. The values range from 84 to 126 for non-calcareous silty clay loams, silt loams and loams, 190 for sandy loams, clays and silty clays, 300 for loamy sand and 356 to 694 for sands (Morgan 1986).

It can be seen from Table 3.3 that computed values for erodibility differ considerably. Although the different methods by which these values were determined account for some of the difference, it would appear that knowledge of the conditions in a specific area is required to determine erodibility.

% dry stable aggregates > 0.84 mm	erodibility a* ($t\ ha^{-1}y^{-1}$)	erodibility b' ($t\ ha^{-1}y^{-1}$)
< 20	< 0,5	< 4
20 - 50	0,5 - 1,5	4 - 84
50 - 70	1,5 - 5	84 - 166
70 - 80	5 - 15	166 - 220
> 80	> 15	> 220

* After Dolgilevich *et al* (1973), for windspeeds of 20-25 $m\ s^{-1}$.

' After Chepil (1960) for Garden City, Kansas.

TABLE 3.3 Assessments of soil erodibility by wind (taken from Zachar 1982)

The resistance of soils to wind can also be expressed in terms of cohesion. Shiyatyy *et al* (1972) derived the following index of soil resistance (R):

$$R = 100 - C,$$

where C is a measure of the actual cohesion based on clay and sand fractions of the soil, defined by:

$$C = 34{,}7 + 0{,}9X_1 - 0{,}3X_2 - 0{,}4X_3$$

where X_1, X_2 and X_3 denote the proportions of soil in the different textural classes, <0,001 mm, 0,05-0,25 mm and >0,25 mm respectively.

The stability of soil aggregates is affected by the dispersive forces of rain drops, the abrasive force of wind, the direct force of wind, wetting-drying and freeze-thaw cycles, and mechanical breakdown by tillage. The ability of peds to resist mechanical breakdown depends on the content of carbonates, organic matter and soil texture. Once erosion has been initiated, further breakdown of aggregates is expected due to the abrasive action of the wind transported material itself (Chepil and Woodruff 1962).

3.2.2 *The effect of ridges*

Fryrear (1984) conducted a study to determine the effects of ridges and aggregates in controlling wind erosion. He covered nonerodible ridges of 0, 63, 127 and 254 mm in height, with 10 mm of erodible soil. Using a wind tunnel he found that by ridging the soil, rates of soil loss were reduced by 85 - 89 % for the 127 and 254 mm ridges. This is of particular significance for the management of ploughed fields, although it also contributes to an understanding of the importance of surface roughness inreducing wind erosivity.

3.2.3 *The effect of avalanching*

Wind erosion tends to spread in the down wind direction. Chepil (1957) refers to the downwind increase in the quantity of material transported as 'avalanching'. He gives three main reasons as to why avalanching occurs; firstly, there is a progressive increase in the number of grain impacts which results in the the entrainment of more material; secondly, the higher number of impacts increases the rate of abrasion which increases the supply of erodible material; thirdly, particles tend to be trapped in depressions so that surface roughness is gradually reduced and therefore shear velocity and rate of transport are increased. The saturated flow (q_s), or the maximum amount of material that can be transported, for a given wind velocity is found to be independent of soil type, however Chepil (1959) notes that the distance from the point of initiation of erosion to q_s varies with soil erodibility. For soils with the greatest erodibility the distance is 65 m while for the least erodible soils it increases to 1900 m. These distances remain relatively constant regardless of wind velocity.

The efffect of avalanching is significant in that, without intervention, wind erosion spreads in the down wind direction. The implications are such that once erosion has been initiated, a self-perpetuating cycle is started and further soil erosion by wind and water is inevitable. It thus appears that once erosion is active, direct means of controlling it are required in order to break the cycle. This can be readily seen in much of the Karoo as bare pathes increase in size with time unless they are actively controlled (Rubidge *pers. comm.*).

3.2.4 *The effect of soil moisture*

Soil moisture, along with soil texture plays an important role in reducing erodibility. Water acts to bind the soil grains together. Chepil (1956) found that soil erodibility decreases as the square of the moisture increases, to the point where the amount of moisture held is at a level roughly equal to that of the wilting point. This is at a suction equivalent to 15 atmospheres pressure. Belly (1964) also showed that threshold shear velocity increases rapidly as moisture content increases. Bisal and Hsieh (1966) found that a wind of 5,36 m s^{-1} was required to initiate movement on a fine sandy loam and loam with 3,5 % moisture content, and a clay with 11 % moisture content. The effects of soil moisture combined with soil texture in increasing the velocities at which wind erosion is initiated is illustrated in Figure 3.2.

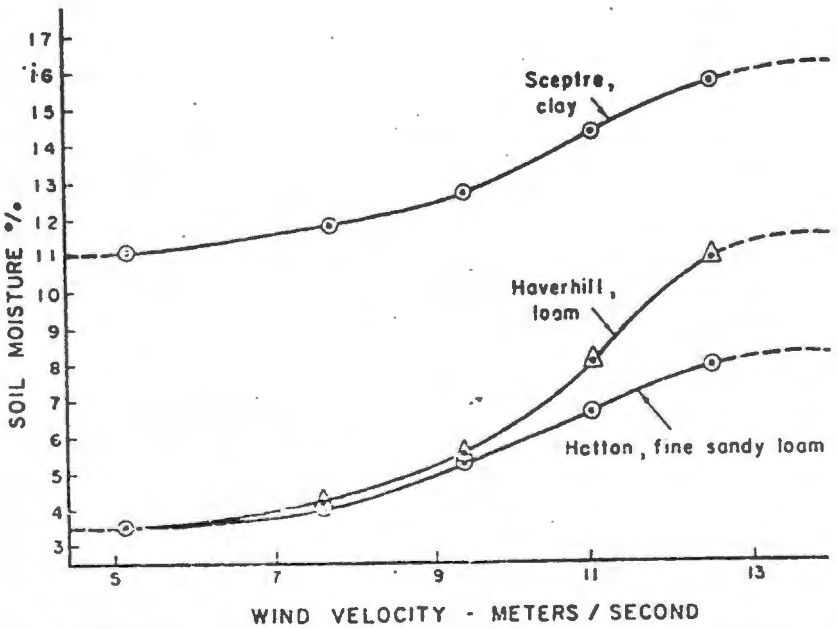


Figure 3.2 Influence of percentage soil moisture on the initiation of soil movement for three different soils (taken from Bisal and Hsieh 1966).

Azizov (1977) conducted a study to determine the influence of moisture content on the wind erosion of loamy sand soils. He found that for moisture contents of less than 4 %, the effect of moisture on critical flow speed is insignificant. For moisture contents greater than 4 %, it is significant and the calculation of critical flow velocities is dependent on the moisture content of the upper soil layers. If the maximum wind speed of a region, U_{cr}, and the speed at which movement is initiated for a dry soil in the same region, U_{ci}, is known, then the moisture content below which wind erosion is inhibited is calculated according to the following equation (Azizov 1977):

$$W = 10{,}36 \cdot \ln\left[\frac{U_{cr}}{U_{ci}}\right] + 3$$

Moisture is also important as the impact of rain causes the surface soil to be dispersed which upon drying forms a thin crust. Medium textured soils with a high percentage of silt are most likely to form a crust and as a result are more resistant to wind erosion than sandy soils lacking the finer particles (Chepil and Woodruff 1962). Wind erosion, however, increases if the soil crust is lost or disturbed.

At a large scale the relationship between moisture and erosion is complex as it involves a consideration of both water and wind. It is described by (Kirkby 1980) as follows. Under natural conditions, the transition from desert to forest is associated with an increase in rainfall. The effects on erosion are illustrated in Figure 3.3.

It must be noted that water contributes to erosivity as well as erodibility. In an arid situation where wind is the predominant erosive agent, moisture acts to bind soil particles thereby reducing soil erodibility. In a wetter environment, however, water is the dominant erosive agent. The following discussion is based on one hypothesis as to the way in which erosion is related to water, wind and vegetation. It must be noted that in a semi-arid environment such as the Karoo, wind may not be the predominant erosive agent, although it will be dominant at times.

Higher rainfall leads to increased runoff and more vegetation. At the desert end of the spectrum higher rainfall leads to surface runoff and increasing erosion. Wind erosion, however, is dominant in both a relative and absolute sense as water erosion is low in very arid areas (Kirkby 1980). Once rainfall levels are such that they can support semi-arid vegetation then the protective cover it offers has a greater effect in controlling erosion than does the increased runoff in causing erosion. Therefore, net erosion decreases as rainfall increases. It is important to note, however, that an area like the Karoo is subject to both wind and water erosion. The two work together to increase the extent to which an area is affected by soil loss. Once forest vegetation is reached, however, the additional vegetation cannot offer further protection and higher rainfall results in increased erosion.

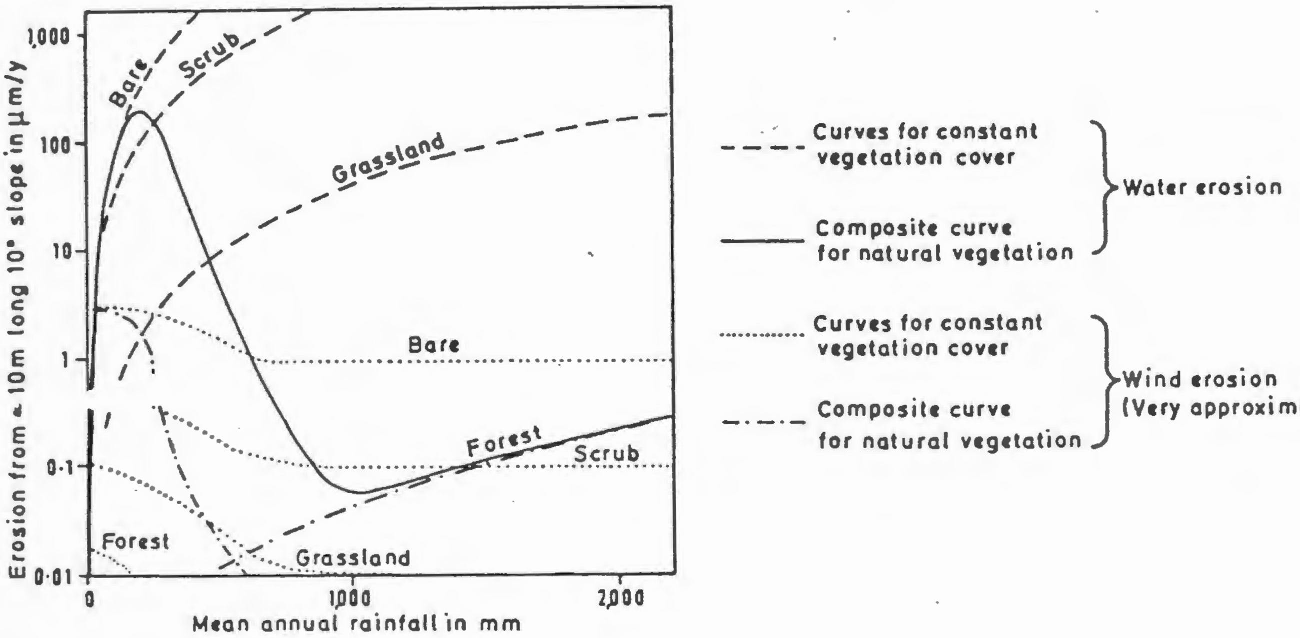


FIGURE 3.3 Estimated rates of soil erosion by wind and water as a function of rainfall and vegetation cover (taken from Kirkby 1980, p 4).

This approach is not accepted by all researchers. The relative importance of wind and water as geomorphological agents in deserts is controversial. Wind erosion is an ongoing process whereas water erosion is less frequent but of greater magnitude, and as such may play a greater role in shaping the land surface.

3.2.5 *The effect of cementing agents*

The breakdown of organic material by micro-organisms produces a variety of cementing agents. Chepil (1955) found that additions to the soil of 1 and 6 % organic matter during the initial stages of decomposition gave rise to enhanced ped production and decreased erodibility. Over a period of four years, however, ped production declined and erodibility increased. He concluded that continuous addition of organic matter is required in order to improve soil cohesion. It is thus important to prevent the erosion of the topsoil as it contains most of the organic matter.

The addition of calcium carbonate has been shown by Chepil (1954) to weaken soil structure and therefore increase erodibility, with the exception of sandy soils where soil structure does not strongly develop in the first place. In this case the silt-sized calcium carbonate acts as a weak cementing agent.

3.2.6 *The effect of plant cover*

Plant cover plays an important role in reducing soil erodibility. "Managing living and dead vegetative cover is the most effective and practical method for controlling wind erosion" (Lyles and Allison 1981, 405). The effectiveness of vegetation in controlling wind erosion depends on the quantity, type and orientation with regard to prevailing wind directions. The effects of plant cover can be calculated by determining the frictional drag coefficient (Cd) according to the equation:

$$Cd = \frac{2V*^2}{\bar{v}^2}$$

where $\bar{v}$ is the mean wind velocity measured at height z, and z = 1,6 times the average roughness element height. Values range form 0,1 in light winds to 0,01 in strong winds, for a wide range of crops (Morgan 1986). It is the conditions closest to the ground that are of greatest importance in reducing wind erosion. Drag

It can readily be seen from this discussion of the factors which affect the erosivity of the wind and the erodibility of the surface, that it a complex process. The complexity is further increased in the way that land management affects the various factors, or acts directly to control wind erosion.

For arid rangelands the only economical way of controlling soil erosion by wind is to ensure the maintenance of the protective shrub vegetation (Marshall 1970). Shrubs protect the soil surface in two ways. First, their presence as immovable roughness elements reduces the area available to erosion by an amount equal to the basal cover. Secondly, they act to reduce wind velocity. It is however, very difficult to quantify the effect of shrub vegetation as the distribution of natural vegetation may be clumped or random, and it is difficult to measure the mean drag coefficient of irregularily distributed shrubs. Using a wind tunnel Marshall (1970) determined the efficiency of roughness of various sizes and shapes (Table 3.4)

	Cylinders					Hemispheres
diameter/height ratio, d/H	0.5	1	2	3	5	2
silhouette area/projected area ratio, L/P	2.546	1.273	0.637	0.424	0.255	0.5
Efficiency, E = CL/P	1.823	0.858	0.306	0.155	0.113	0.186
Relative efficiency where E(d/H=5) = 1	16.13	7.59	2.71	1.37	1	1.65

Table 3.4 Efficiency of roughness elements of varying size and shape (taken from Marshall 1970).

From Table 3.4 it can be seen that the efficiency (E) of a roughness element in reducing wind velocity in terms of drag (C_f) per unit of projected area (P_a) is greatest for roughness elements of small diameter/height ratios. However, the critical roughness element density rises sharply with a decreasing d/H ratio, a compromise between efficiency of protection and moderate roughness density is reached with diameter/height ratios of 1 or 2. The situation is further complicated by the dietary preference of grazing stock which will differentially alter the diameter/height ratios of different shrubs according to their palatability. Nonetheless the data in Table 3.4 is usefull in determining a planting density if planting is required to re-establish a shrub community (Marshall 1970).

3.3 MECHANICAL AND VEGETATIVE CONTROL OF WIND EROSION

3.3.1 *Vegetative means of controlling wind erosion*

Cover crops are grown as a soil conservation method during the off-season or as a ground protection under trees. Wind tunnel studies in the U.S.A. have shown that winter rye sown at the recommended density can prevent blowing of the soil with windspeeds up to 21 m s^{-1} as measured at a height of 10 m (Knottnerus 1976 as cited in Morgan 1986). In areas where there are soil moisture shortages, this might not be the most effective conservation measure as the cover crop will reduce moisture availability for the main crop.

An alternative approach to soil conservation is found in strip cropping where row crops and protection-effective crops are grown in alternating strips perpendicular to the prevailing winds. In this fashion, erosion is limited to the row crops and the soil is then trapped downwind by the protection effective crop which is usually a leguminous or grass crop (Morgan 1986). It has also been found that by planting crops with a closer row spacing, wind erosion can be reduced. Skidmore *et al* (1966) determined that by adopting a closer row spacing in grain sorghum, wind erosion could be reduced by 29 to 55 %.

Mulching is the covering of the soil with crop residues in order to reduce wind velocity. It has the similar effect to the planting of cover crops, however, it does not have the same moisture requirements. Lyles and Allison (1976) determined the following relationship for the effect of the number of stalks per unit area and their size, on wind velocity:

$$\frac{V^*}{V_{*t}} = 1{,}638 + 17{,}044 \frac{N A_s}{A_t} - 0{,}177 \frac{L_y}{L_x} + (1{,}0236)^C - 1 \qquad (8{,}4)$$

where V^* is the drag velocity for a given open wind velocity, V_{*t} is the critical drag velocity for the soil, N/A_t is the number of stubble stalks per cm^{-2}, A_s is the average projected area of a single stalk facing the wind (cm^2), L_y is the distance between the stalks in a line perpendicular to the wind (cm), L_x is the distance between the stalks in a line in the same direction as the wind (cm) and C is percentage of dry soil aggregates larger than 1 cm in diameter.

Extensive research has been undertaken in the Orange Free State and western Transvaal to determine the effects of various ground protection and tillage practices on wind erosion. Using a wind tunnel, McPhee (undated) measured the effects of leaving a standing stubble of maize and wheat on soil loss. The results are summarised in Table 3.5.

Stubble (kg ha^{-1})	Soil loss (t ha^{-1} yr^{-1}) wheat	maize
0	220	220
500	85	210
1000	27	157
2000	1	67
4000	-	22

Table 3.5 The influence of wheat and maize standing stubble on wind erosion (taken from McPhee undated).

Van der Westhuizen (1985) found that soil loss under conservation tillage practices is 8 t ha^{-1} yr^{-1} as compared to a loss of 28 t ha^{-1} yr^{-1} under conventional cultivation.

It is important to note that most of these methods are directed to controlling wind erosion in cropped areas and they are not applicable to pasture lands such as the Karoo. In rangeland areas, adequate ground cover must be maintained through the implementation of appropriate management techniques.

3.3.2 **Shelterbelts**

Shelterbelts planted perpendicular to erosive winds are an effective means of reducing wind velocity. If they are spaced at regular intervals, they break up the length of open wind blow. The ideal density for a wind barrier is 40 to 50 % porosity as this gives the greatest overall reduction in windspeed over a distance 30 times the height of the barrier (Skidmore and Hagen 1977). Figure 3.4 shows the effect of windbreaks in terms of the percentage wind velocity downwind from a windbreak relative to the wind velocity without a windbreak.

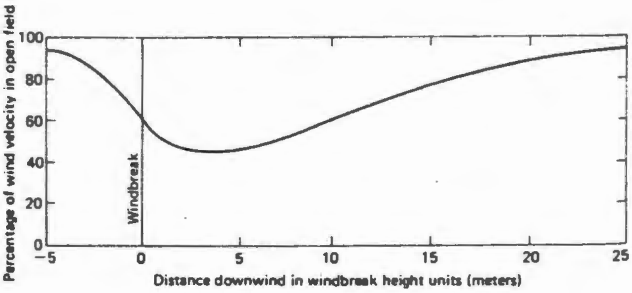


Figure 3.5 Wind velocities about 40 cm above ground level in the vicinity of a windbreak, as a percentage of what they would be in the absence of the windbreak. The curve represents an average value, as width, height and porosity of the windbreak, wind velocity and topographic features all affect the effectiveness of windbreaks (taken from Troeh et al 1980).

Windbreak spacing can be determined according to the equation developed by Woodruff and Zingg (1952):

$$L = 17H(V_t/V) \cos$$

where L is the distance between the shelterbelts (m), H is the height of the belt (m), V is actual wind velocity measured at a height of 15 m above the ground surface (m s^{-1}), V_t is the threshold velocity for particle movement, taken as 34 km h^{-1} and is the angle of deviation of the prevailing wind from a line perpendicular to the belt.

In practice, however, it has been found that effective protection in the field rarely reaches this theoretical level of 17H, and that a distance 10 to 12 times the height of the belt is more realistic (Sneesby 1953). For an area with a dominant erosive wind, the most effective protection is achieved by planting shelterbelts in parallel rows, perpendicular to the wind direction. If, however, the winds come from several directions, a grid or herringbone pattern may be necessary.

Shelterbelts should be planted from species that are rapid growing, tolerant to wind and light. Shelterbelts will also cause a decrease in evapotranspiration, higher soil temperatures in winter and lower temperatures in summer, there may also be an increase in weeds and pests (Morgan 1980, 1986).

Wind erosion control is aimed at reducing soil erodibility by improving ground cover or soil characteristics which affect its resistance to wind, and by reducing wind velocity and its erosivity. In areas of cultivated lands, wind erosion can be controlled by maintaining a vegetative cover in the off-season or in the gaps between row crops, and by modifying tillage practices to ensure a high proportion of soil aggregates. In rangelands, it is essential that one of the main goals of any grazing management be the maintenance of good ground cover. It is this later approach which is required for the Karoo region as with the exception of a few areas of fodder crops most of the land is used for grazing.

This chapter provides a summary of the factors which determine erosivity and erodibility. It is an understanding of these factors which forms the basis for predicting which areas are at risk with regard to wind erosion. As described in the following chapter, the models developed for predicting wind erosion have been based on attempts to quantify these factors.

CHAPTER FOUR

THE MEASUREMENT AND PREDICTION OF WIND EROSION

This chapter contains a discussion of the different approaches to measuring and predicting wind erosion. There have been numerous attempts to measure rates of soil loss by wind erosion in the field and in a wind tunnel. They have, however, been problematic and it is really only in a wind tunnel, where all the variables can be controlled, that rates of wind erosion have been measure accurately. It is not known for sure if these values can be extrapolated to the much broader scale and complexity of conditions in the field. To overcome these problems models are used to predict soil loss by wind erosion. A discussion of the various approaches to the measurement of wind erosion and the associated problems follows with a view to illustrating the variety of approaches and some of their weaknesses. It was against this background that the use of the two models: the Wind Erosion Equation and the analysis of limited climatic data, were considered to be most appropriate for this study.

4.1 THE MEASUREMENT OF WIND EROSION

There were several early attempts to measure rates of wind erosion. Cornish (1900) (as cited in Wilson and Cooke 1980) calculated the annual passage of sand 'in the desert' over a one centimetre square. His measurement of a value equivalent to a 10 m layer each year was determined by visually estimating the velocity of sand grains over the surface and the frequency with which erosion occurred. Measurements taken on the flats at the mouth of the Columbia River by O'Brien and

Rindlaub (1936) showed a relation between sediment discharge and wind velocity according to the empirical equation:

$$G = 0{,}036u_5^3 \quad (\text{when } u_5 > 20)$$

where G is the discharge (pounds per foot width per day), and u_5 is the wind velocity at five feet above the surface per day (in feet per second). The equation, however, is only valid for a mean grain size of 0,2 mm and is of little general use.

Bagnold (1941) attempted to derive a universally applicable relationship, based on empirical data, in which the rate of sand flow q, was related to wind shear velocity over an eroding surface U'_*:

$$q = C \int (d/D) \cdot p/g \cdot U'^3_*$$

where q is the weight of sand which moves along a lane of unit width past a fixed point in unit time, D is a standard grain diameter of 0,25 mm, d is the mean grain diameter of the sand in question, *p* is the density of air, g is the gravitational constant and C is an empirical constant. The value of C was found to vary with size distribution, such that it achieved the following values: 1,5 for a uniform sand; 1,8 for a naturally graded sand; and 2,8 for a sand with a wide range of grain sizes.

There are, however, a number of problems with this equation, as it fails to account for the transport of material by suspension. It further predicts sand flow for velocities below the threshold of movement, so that the threshold must be determined independently and the value of C is very difficult to determine (Wilson and Cooke 1980). Zingg (1953) determined a similar equation for given velocities using a wind tunnel:

$$q = C \, (d/D)^{3/4} \, p \, U'^3_*/g$$

in which the value of C is 0,83.

Kawamura (1951 as cited in Horikwa and Shen 1960)) developed an expression which takes into account the threshold shear velocity (U_{*t}) of the material involved:

$$q = (Cp/g)(U'_{*} - U_{*t})(U'_{*} + U_{*t})^2$$

This, however, is not easy to use in the field, as the values of C and U_{*t} have to be determined in a wind tunnel. From this description of attempts to measure wind erosion in the field, it can be seen that none have proven to be very successful.

4.1.1 SAND TRAPS

The equipment used to measure wind transport rates includes various types of sand traps developed to trap sand moving in a band of unit width. There are two main types of traps; horizontal and vertical. The horizontal type of trap consists of troughs set in the ground level with surface and parallel to the prevailing wind direction. The trap can be divided into a series of compartments so that grains bouncing or rolling along the surface will be separated according to the length of the 'hop'. Alternatively, several traps of different lengths can also be used. The horizontal trap has the advantage of not interfering with the wind flow, although a considerable length is required in order to collect a representative sample. Borsy (1972) found that in maize fields on sand dunes in Hungary during a storm of 2h 30 min, with a wind velocity of 8-10 m s^{-1}, the amount of sand collect in a 10 cm wind horizontal trap varied from 218 g for 1 cm length to 370 g for 50 cm length and 570 g for 1 m length. Vertical traps, on the other hand, consist of an opening or series of openings arranged vertically so as to trap all particles moving at different heights. These traps, however, are inefficient because of the way in which they interfere with airflow. The build up of 'back pressure' due to unsufficient or no exhaust causes a deflection of the airflow and presumably its load around the trap. This problem was largely overcome by Horikawa and Shen (1960), in adjusting the ratio between the sizes of the inlet, outlet and collecting basin and by improving the exhaust system (Morgan 1986). Neither form of trap, however, is without problems.

As a result of the problems encountered in the use of sand traps it was not considered meaningful to use them for the purposes of this study. They were also considered inappropriate as there was not enough time available for data collecitron. Ideally a minimum of 3 to 5 years duration is required to describe seasonal and annual soil erosion in order to eliminate the effects of an exceptional year. The scale of the study area also made it virtually impossible to give an accurate cover of the entire Cape Province with sand traps.

4.2 THE ASSESSMENT OF WIND EROSION USING AERIAL PHOTOGRAPHY AND SATELLITE IMAGERY

It has been found that features produced by wind erosion can be seen on aerial photographs and on satellite images. The most prominent features which are indicative of wind erosion are blowouts, smoothly rounded and irregularly shaped depressions; sand streaks, light-toned but poorly defined parallel streaks; and sand blotches, light-toned and poorly defined patches (Avery 1962). Any surface that is unprotected by vegetation and not continuously moist is susceptible to wind erosion. These surfaces, which are easily identified on aerial photographs, include ploughed fields, alluvial fans, beaches and floodplains.

Fryrear and Wiegand (1974) conducted a study in west Texas to determine the effectiveness of aerial photography in the detection and monitoring of wind erosion. Both colour and colour Infra-Red (IR) film was used and variations in optical density were examined in order to find the optimum level at which evidence for wind erosion could be detected. They discovered that eroded areas surrounded by grass, or blowouts, can be detected with an isodensitometer by rapid variations in film optical densities. Precise ground truthing is, however, essential as the optical density of roads and bare turnrows at the end of cultivated fields is very similar to that of blowouts. It was found that the colour IR film was more effective in registering the soil reflectance differences. In cases where the wind erosion from one field has resulted in the deposition of the surface soil in a noneroded downwind field, it is very difficult to distinguish the reflectance characteristics and this may result in an over estimation of the extent of wind erosion. Nonetheless aerial photography provides a good overview for the initial assessment of wind erosion and a basis for more detailed investigations on the ground.

Satellite imagery has also been used to interpret the wind erosion hazard of the Nebraska Sandhills by Seevers *et al* (1975). They discovered that blowouts were easily recognized on the ERTS-1 images in the MSS band 5. Using satellite imagery, they produced a map of the frequency of blowouts per township, as well as the areas of overgrazing, poor vegetation cover or burned areas. An advantage of satellite imagery is the availability of multiseasonal images which were found to be useful for the identification of areas with the greatest wind erosion potential. They found that satellite imagery was a helpful tool in locating the areas of wind erosion or those areas susceptible to wind erosion due to poor range conditions and low vegetation cover, and thereby indicating those areas where rangeland management had to be improved.

It is apparent that aerial photography and satellite imagery are appropriate for the initial assessment of wind erosion. Aerial photography at the necessary scale is available for much of the study area. As a result the interpretation of the photography was chosen as a means of providing a basis against which the results of the wind erosion models could be compared (Sections 4.3.2 and 4.3.5).

4.3 THE PREDICTION OF ACTUAL AND POTENTIAL WIND EROSION

4.3.1 Climate and soil factors for the prediction of wind erosion as determined in the U.S. and the U.S.S.R.

The most simple methods for predicting wind erosion are based on the relationship between climate and soil in giving rise to erosion:

$$E_v = KP$$

where E_v is wind erosion, K is a factor of climate and P is a factor of soil resistance. The climatic factor is a function of the kinetic energy and lifting force of the wind, as well as the effect of soil dryness.

Chepil et al (1962) determined that soil loss by wind erosion depended on wind velocity and soil moisture according to the equation:

$$q = f \frac{v^3}{w^2}$$

where q is soil removal by wind erosion, v is the wind velocity ($m\ s^{-1}$) measured 10 m above the ground surface and w is the effective soil moisture content calculated according to:

$$w = f \frac{P - E}{T^2}$$

where P is the annual precipitation (mm), E the annual evaporation (mm) and T the mean annual temperature

(°C). The climatic factor (C) is thus expressed by (Chepil et al 1962):

$$C = 100 \frac{v^3}{(P - E)^2}$$

Where C is a dimensionless value, v is the mean annual wind velocity ($m\ s^{-1}$) and P-E is Thornthwaite's annual moisture index. The climatic factor has also been calculated by Pasak (1978, as cited in Zachar 1982) for conditions in the USSR:

$$C = 100\ (6 + 0{,}52n)^3\ (I_z + 60)^{-2}$$

where n is the frequency of wind over a Beaufort Scale reading of 5 (expressed as a percentage of all winds in a year), and I_z the index of climatic humidity according to Koncek :

$$I_z = \frac{R}{2} + \Delta r - 10t - (30 + v^2)$$

where R is the total precipitation in the growth season, Δr the positive deviation of the total winter precipitation from the value of 105 mm and t the mean wind velocity ($m\ s^{-1}$) at 14 hours throughout the growth period. This method gives results identical to Thornthwaite's moisture index which was used by Chepil et al (1962). In the USSR, the hydrothermal coefficient HTK = R/ t 10 is used in the computation of the coefficient of climatic humidity, where R is the total precipitation for the period and t is the total temperature for the period in which the average temperature exceeds 10 °C.

4.3.1.1 Soil Erosion Regions of the USSR

In order to separate the macroregions of the USSR susceptible to different levels of wind erosion, Kosov et al (1976, as cited in Zachar 1982) used a simple method to separate the soils into two regional types. Type I constitute soils resistant to wind erosion occurring where velocities greater than 10 $m\ s^{-1}$ are according to the wind force; for the first type, the three categories of wind velocities were 6 to 9 m s^{-1}, 10 to 15 m s^{-1} and more than 15 m s^{-1}, and for the second group they were 10 to 15 m s^{-1} and greater than 15 m s^{-1}. By multiplying wind velocity by the percentage probability of its occurrence, values up to 510 were obtained for the first soil type and up to 209 for the second. On the basis of these parameters, the territory was divided into four categories with respect to susceptibility to wind erosion (Table 4.1).

intensity of erosion	wind force level
1. slight erosion	< 50
2. moderate erosion	50 - 100
3. severe erosion	100 - 200
4. very severe erosion	> 200

TABLE 4.1 The four wind erosion categories according to wind force level (taken from Zachar 1982).

The territory was then divided into five categories according to the moisture parameter HTK, according to the following groupings; I > 1,33; II 1,33 - 1,0; III 1,0 - 0,77; IV 0,77 - 0,33; and V < 0,33. The higher the values of HTK the greater the severity of wind erosion. The results for the USSR are shown in Table 4.2.

This model was included to illustrate an example of how the different regions of a country can be classified according to the intensity of wind erosion. It was not considered appropriate for this study, however, as greater detail of the differences in erosion within the Karoo and other regions of the Cape Province are of particular interest. The most common approach to the assessmnt of a wind erosion hazard is the Wind Erosion Equation which is discussed in the following sections.

Geographical zone	wind erosion parameter		
	v_s	HTK	grade of erosion
Tundra and forest tundra	428-510	> 1,33	4
Taiga	100-350	1,0-1,33	1 - 3
Forest steppe	<50-209	0,77-1,0	1 - 4
Steppe	110-377	0,33-1,0	2 - 4
Semidesert and desert	204-419	< 0,33	3 - 4

TABLE 4.2 Intensity of wind erosion in West Siberia, Kazakhstan and the central Asia regions of the USSR (taken from Zachar 1982).

4.3.2 *The Wind Erosion Equation*

Several attempts have been made to develop more complex means of calculating wind erosion which also account for factors such as soil structure, soil ridges, crop residues, cropping practice, and field width. The most widely used method is the Wind Erosion Equation developed by W.S. Chepil, N.P. Woodruff and F.H. Siddoway of the Agricultural Research Service of the U.S. Department of Agriculture. The equation is designed to serve a twofold purpose of determining (i) if a particular field is adequately protected from wind erosion, and (ii) the different field conditions of soil structure, roughness, vegetation cover, sheltering from wind barriers, or width and orientation of field required to reduce potential soil loss to tolerable levels under different climatic conditions (Woodruff and Siddoway 1965) The wind erosion equation is expressed as follows:

$$E = f(I', C', K', L', V)$$

where E is the annual loss of soil (t ha^{-1}), I' the soil erodibility factor, C' the climatic factor, K' the ridge roughness equivalent factor, L' the field width and V the vegetation factor.

This approach is similar to that of the Universal Soil Loss Equation (USLE) which expresses soil loss by water as a factor of:

$$A = R\,K\,L\,S\,C\,P$$

in which A is the soil loss per unit area, R is the fainfall erosivity factor, K is the soil erodibility factor, L is the slope length factor, C is the cropping management factor (vegetative cover) and P is the erosion control practice factor. The equation was developed for the prediction of average annual soil loss from a field slope with specific land use conditions.

4.3.2.1 I' - Soil Erodibility Factor

The soil erodibility is the potential annual soil loss in t ha^{-1} from a wide, unsheltered, isolated field with a bare, smooth, noncrusted surface. Values of I are based on wind tunnel studies and field measures in the area of Garden City, Kansas during 1954 to 1956, an excessively dry and windy period. The values of I are related to soil structure, such that I increases as the percentage of soil fractions greater than 0,84 mm in diameter decreases. It can be determined by standard dry sieving and the use of Table 4.3

percentages (tens)	percentages (units)									
	0	1	2	3	4	5	6	7	8	9
0	-	694	560	493	437	403	378	356	335	315
10	300	292	285	278	270	262	254	245	236	228
20	220	213	206	200	195	190	185	180	175	170
30	166	162	158	154	150	146	142	138	134	130
40	126	122	118	114	111	108	104	99	94	89
50	84	79	74	69	65	61	57	54	52	49
60	47	45	43	41	39	37	35	33	31	29
70	27	25	22	19	16	13	10	7	6	5
80	4	-	-	-	-	-	-	-	-	-

Reading the body of the table from right to left gives I values for 0%, 1%, 2%, 3% ... 11%, 12%, 13% ... 80% nonerodible peds.

TABLE 4.3 Soil Erodibility (I') values in $t\ ha^{-1}\ yr^{-1}$ for soils with various percentages of nonerodible peds (> 0,84 mm diameter) determined by standard dry sieving. (taken from Woodruff and Siddoway 1965).

The soil erodibility values are adjusted for knolly topography, that is for areas where slope is greater than 1,5 % and slope lengths are less than 150 m. This is due to the fact that the wind is more erosive over the top of the knolls. Chepil *et al* (1964) determined that knolly land is generally more erodible than level land. Figure 4.1 illustrates the effect of knoll steepness on soil loss (I_s).

The literature (Chepil and Woodruff 1963) suggests that the presence of surface crusts is important in reducing soil erosion. Soil crusts are, however, readily disintegrated by abrasion, once wind erosion has been initiated and are therefore not important when average soil erodibility for the entire soil drifting period is considered. Soil erodibility is, therefore, taken to be the product of soil erodibility (I') and the knoll-steepness factor (I_s).

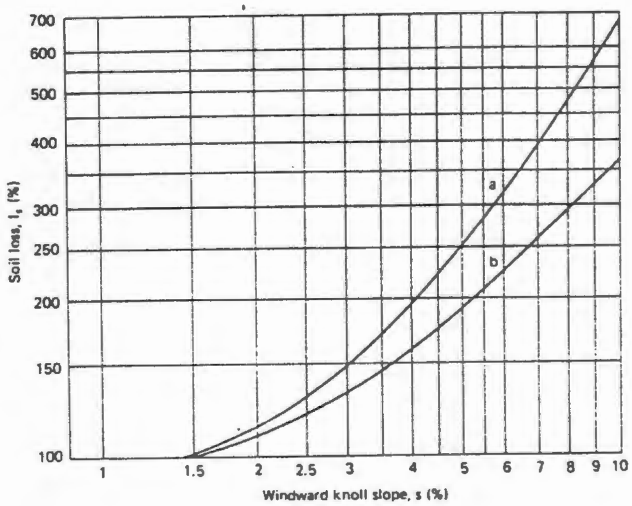


FIGURE 4.1 Potential soil loss I_s, from the crest of knolls (a) and from the upper third of the windward side (b) of slopes < 150 m long as percentages of I_s on level land (taken from Woodruff and Siddoway 1965).

4.3.2.2 K' - Soil-Ridge-Roughness Factor

Surface roughness results from three factors; aggregates on the soil surface which is accounted for by I', vegetative cover which is accounted for by V, and ridges on the soil surface (K'). These ridges result mainly from tillage and planting operations, or are a natural feature of the surface. Ridge roughness is defined as the height of ridges composed of nonerodible gravel 2,0 to 6,4 mm in cross section, having a height to spacing ratio of 1 : 4. The ridge roughness equivalent K_r can be calculated in the field according to:

$$K_r = \frac{\text{measured field ratio } (1 : x)}{\text{standard ratio } (1 : 4)} \text{ y } \begin{array}{c}\text{measured}\\ \text{ridge height}\end{array}$$

Calculated K_r values are then converted to the dimensionless soil-ridge-roughness factor (K') according to the relationship in Figure 4.2.

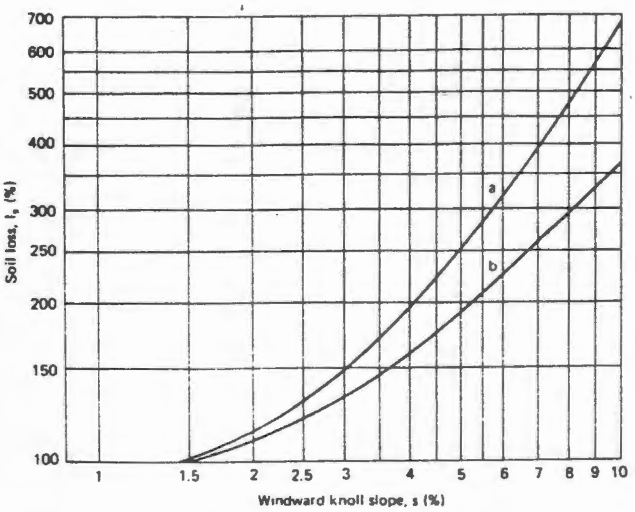


FIGURE 4.1 Potential soil loss I_s, from the crest of knolls (a) and from the upper third of the windward side (b) of slopes < 150 m long as percentages of I_s on level land (taken from Woodruff and Siddoway 1965).

4.3.2.2 K′ - Soil-Ridge-Roughness Factor

Surface roughness results from three factors; aggregates on the soil surface which is accounted for by I′, vegetative cover which is accounted for by V, and ridges on the soil surface (K′). These ridges result mainly from tillage and planting operations, or are a natural feature of the surface. Ridge roughness is defined as the height of ridges composed of nonerodible gravel 2,0 to 6,4 mm in cross section, having a height to spacing ratio of 1 : 4. The ridge roughness equivalent K_r can be calculated in the field according to:

$$K_r = \frac{\text{measured field ratio } (1 : x)}{\text{standard ratio } (1 : 4)} \quad \text{measured ridge height}$$

Calculated K_r values are then converted to the dimensionless soil-ridge-roughness factor (K′) according to the relationship in Figure 4.2.

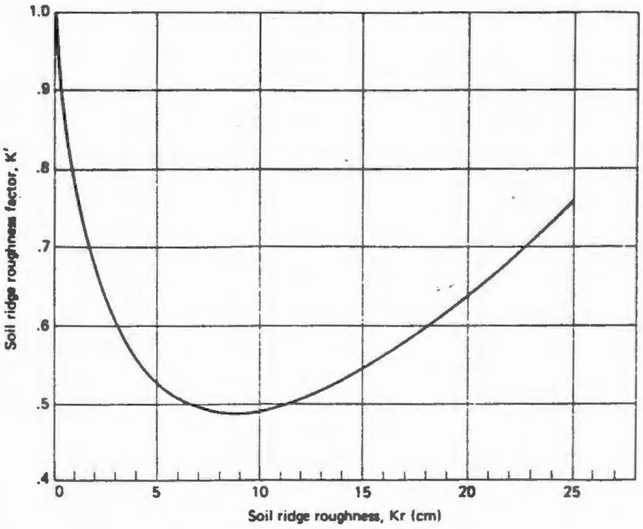


FIGURE 4.2 Relationship of equivalent soil ridge roughness in centimetres, K_r, to the soil ridge roughness factor K' (taken from Woodruff and Siddoway 1965).

4.3.2.3 C' - the Climatic Factor (see also section 4.3.1)

The power of the wind to detach material is related to the square of the velocity, and the transporting power is proportional to the fifth power of the velocity Bagnold (1941). The amount of erosion is, therefore, proportional to the cube of wind velocity. Soil moisture affects plant growth, and plant material in return reduces wind velocity close to the soil. Soil moisture also acts to bind soil particles together.

Chepil et al (1962) suggested that soil movement varied directly with the cube of wind velocity and inversely with the square of surface soil moisture as calculated with Thornthwaite's (1931) P-E index,

$$C = \frac{v^3}{(P-E)^2}$$

P-E is calculated according to the following equation:

$$P\text{-}E = 115 \sum_{i=1}^{12} [P/(T-10)]_i^{10/9}$$

where P is the monthly precipitation (in) and T the mean monthly temperature, °F.

The average value for the climatic factor for Garden City, Kansas was 2.9. As this was the site where the soil-erodibility data were collected, the climatic factor (C') for the rest of the country was expressed as a percentage of the value at Garden City.

$$C' = \frac{u^3}{(P\text{-}E)^2} \cdot \frac{100}{2.9}$$

or

$$C = 34 \frac{u^3}{(P\text{-}E)^2}$$

Chepil *et al* (1962) produced a map of the C' values of southern Canada and the United States (Figure 4.3)

4.3.2.4 L' - Field Width Factor

The width of a field (D) is the unsheltered distance across the field in the downwind direction. In order to determine the field width factor, the prevailing wind direction and the proportion of erosive forces from each wind direction must be known in order to assess the average downwind distance over which the erosive winds travel.

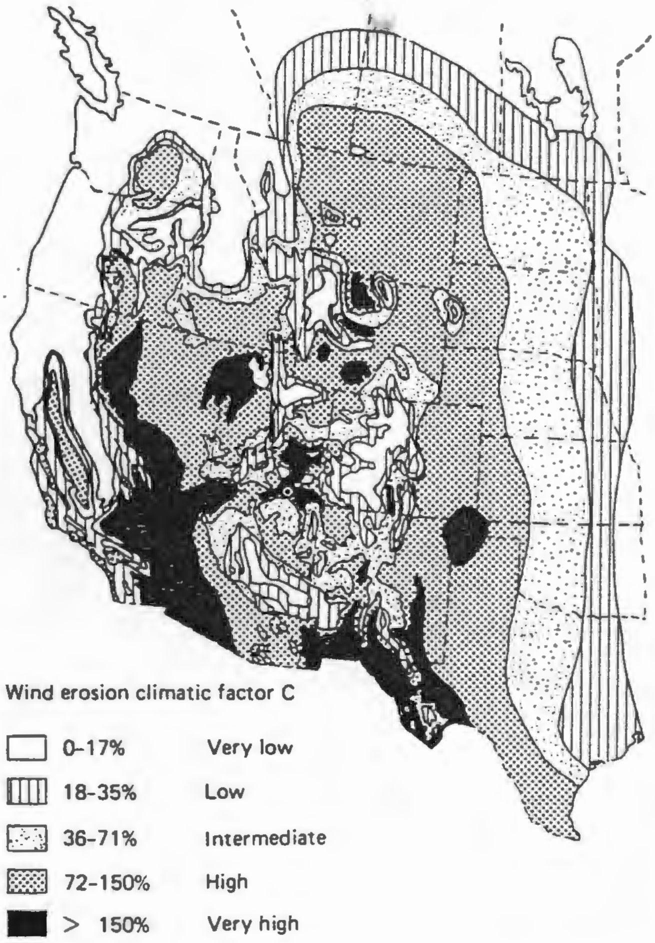


FIGURE 4.3 Wind erosion climatic factor C', as a percentage of the value at Garden City, Kansas (taken from Chepil *et al* 1962).

Skidmore and Woodruff (1968) developed a method for estimating an equivalent field width (D_{50}). The method is based on summing the erosive forces from all points of the compass. The preponderance of erosive forces, Rm, is determined by summing the product of the cube of the mean wind speed and the duration for all the wind speed groups, for each of the sixteen points of the compass. The forces are calculated in terms of those parallel to and those perpendicular to the prevailing direction:

$$R_m = \frac{\Sigma \text{ wind erosion forces parallel}}{\Sigma \text{ wind erosion forces perpendicular}}$$

where R_m = 1,0 there is no prevailing wind direction, whereas for R_m = 2,0 there is a prevailing wind direction and the erosion forces parallel to it are twice as great as those perpendicular to it. This data is then used to calculate the percentage of wind-erosion forces that travel distances that are specific multiples (K) of the geometric field width. A median condition (K_{50}) is one for which half the erosive forces travel farther and half not as far as the prevailing wind direction across the field (Troeh *et al* 1980).

Table 4.4 shows part of the table supplied by the Soil Conservation Service of the U.S. Department of Agriculture for the calculation of K_{50} from the preponderance of erosion forces (R_m) and the deviation (A) of the direction of the prevailing wind-erosion forces from perpendicular to the field.

Any distances in the field that are sheltered by wind barriers must be subtracted from the equivalent field width. The sheltered distance for field hedges, tree shelterbelts and similar barriers is taken to be ten times the height of the barrier (B). Thus the field width factor (L') is:

$$L' = D_{50} - 10B$$

The nomogram in Figure 4.4 is used to asses the effect of L' on erosion loss by incorporating it along with soil erodibility-soil-ridge-roughness-erosion estimates (E_2) and soil erodibility-soil-ridge-roughness-climatic erosion estimates (E_3) in the prediction equation.

	A (degrees)										
R_m	0	5	10	15	20	25	30	35	40	45	50
1,0	1,9	1,9	1,9	1,9	1,9	1,9	1,9	1,9	1,9	1,9	1,9
1,5	1,3	1,4	1,4	1,5	1,5	1,6	1,6	1,7	1,8	1,9	2,0
2,0	1,2	1,2	1,3	1,3	1,4	1,4	1,4	1,6	1,7	1,9	2,0
2,5	1,1	1,2	1,2	1,3	1,3	1,4	1,4	1,5	1,7	1,9	2,1
3,0	1,1	1,1	1,2	1,2	1,3	1,4	1,4	1,6	1,8	2,0	2,3
3,5	1,0	1,1	1,2	1,3	1,3	1,4	1,5	1,7	2,0	2,2	2,5
4,0	1,0	1,1	1,2	1,3	1,4	1,5	1,6	1,9	2,2	2,5	2,7

TABLE 4.4 Chart to determine the multiplier (K_{50}) used to calculate the median travel distance of erosive forces across a field from the degrees of deviation of prevailing wind direction from perpendicular to field or strip border or barrier (A) and the preponderance of erosion forces in the prevailing direction (R_m) (taken from the soil conservation service of the U.S. Department of Agriculture, as cited in Troeh *et al* 1980).

4.3.2.5 V - Vegetative Factor

The degree of protection offered by vegetation depends on the amount of dry matter it contains, its relative texture, its height and whether it is living or dead, standing or flattened.

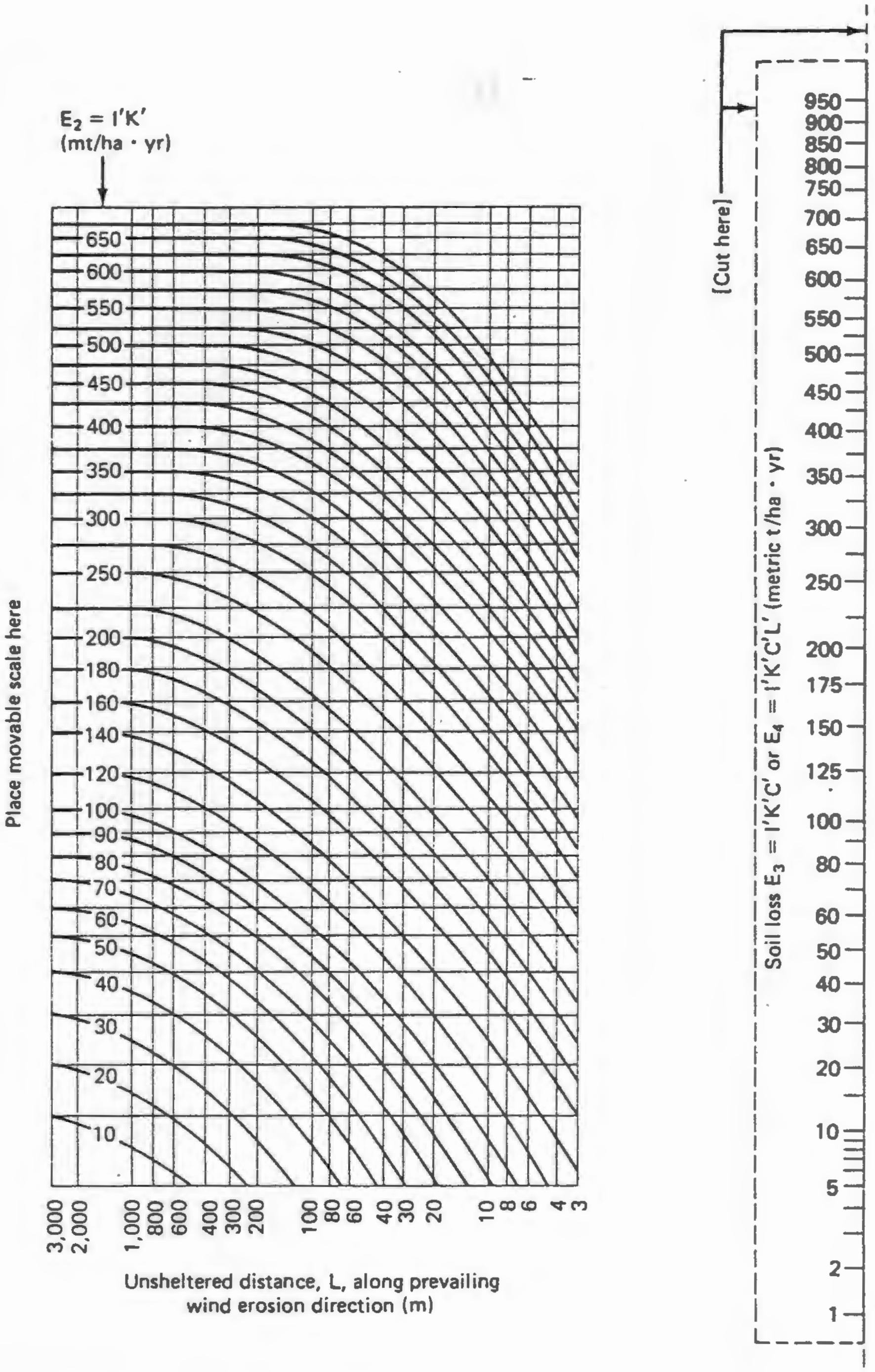


FIGURE 4.4 Nomogram to determine soil loss, E4 = f(I', K', C', L') from soil loss E2 = I'K' and E3 = I'K'C' and the unsheltered distance L' across the field. A copy of the movable scale is placed along the left side of the graph so that E3 on the scale is aligned with E2 on the graph. A line parallel to the curved lines is then followed to its intersection with the unsheltered distance line. The value of E4 is located by following a horizontal line from the intersection back to the movable scale (taken from Woodruff and Siddoway 1965).

The original research (Chepil and Woodruff 1963, Woodruff and Siddoway 1965) on the effect of vegetative cover was done using flattened wheat straw, and this provides the basis for the standards of V used in the erosion equation. For growing crops, or crop residues other than wheat straw the dry-matter amounts must be converted to the equivalent amounts of flattened wheat straw. Figure 4.5 shows the conversion factor for weights of living or dead small grain (R') in the seedling and tillering stages. Figure 4.6 illustrates the conversion of (a) flat, anchored, small grain stubble and straw and (b) of standing, or flat sorghum stubble and stover into the equivalent value of V.

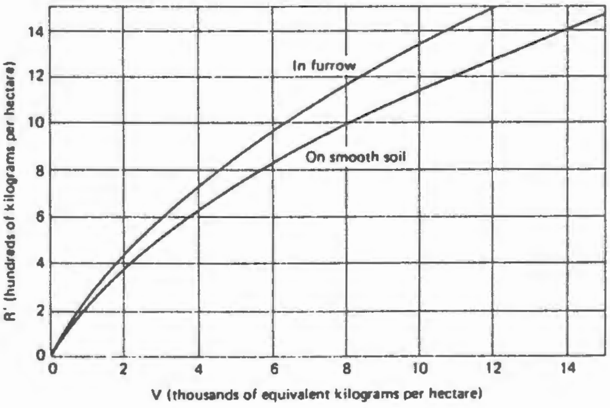
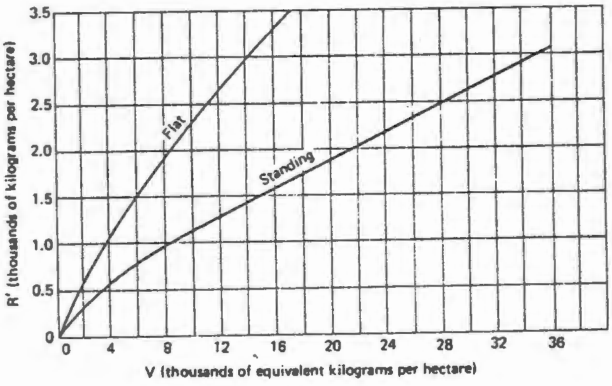
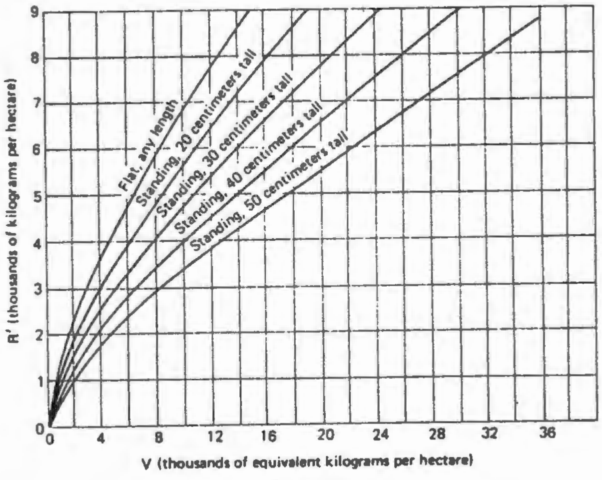


FIGURE 4.5 Curves to convert weights of living or dead small grain in seedling or tilling stages (R') into equivalent amounts of flattened wheat straw (V) (taken from Woodruff and Siddoway 1965).



(a) Small grain



(b) Sorghum

Figure 4.6 Curves to convert weights of small grain or sorghum stubble (R') into equivalent amounts of flattened wheat straw (V) (taken from Woodruff and Siddoway 1965).

Vegetation cover is best assessed by picking the living plant material or residue from a unit area, drying it and weighing it. The 'line-transect' method to estimate cover has been modified to produce weight of cover. Sloneker and Moldenhauer (1977, as cited in Troeh *et al* 1980) describe a method whereby a beaded string is used to determine cover. There are, however, many other approaches to measuring vegetattion cover. The following equations can then be used to convert the faction of soil covered into weight to cover:

Corn: $X = -5{,}917\log(1-Y)$

Small grain: $X = -17{,}398\log(1-Y)$

Soybeans: $X = -31{,}270\log(1-Y)$

where X is the residue in kg ha^{-1} and Y is the cover as a decimal fraction. Figure 4.7 can then be used to relate V to erosion.

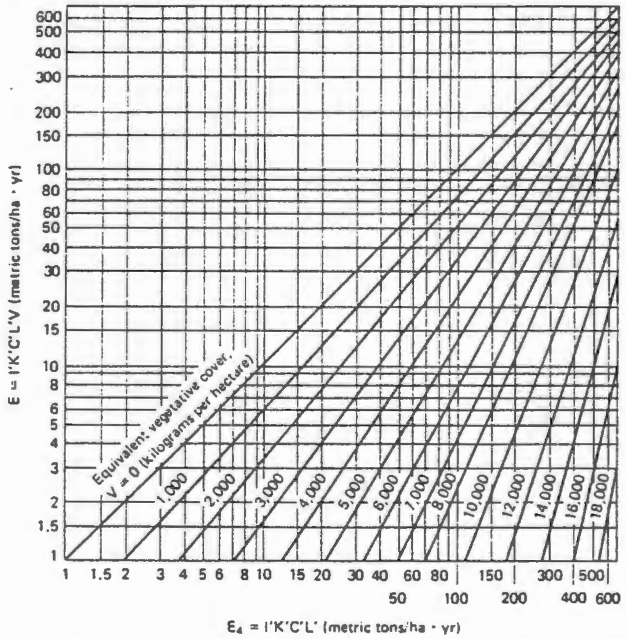


FIGURE 4.7 Graph to convert values of E_4 and V to predicted rates of wind erosion, E = f(I',K',C',L',V). The E value is determined by entering the table at the E_4 value on the bottom scale, following upward to the V value and then across to the E value (taken from Woodruff and Siddoway 1965).

The wind erosion equation can be used to estimate the potential average annual soil loss, E or solved in reverse to determine the condition of any of the factors needed to control erosion; I', K', L' or V.

4.3.3 *Applications of the Wind Erosion Equation*

Since the development of the wind erosion equation, it has been applied in other parts of the world and modified for different applications. Yaalon and Ganor (1966) used the climatic index to evaluate wind erodibility in Israel. They found that the boundaries of the climatic wind erosion index coincided with the arid and semi-arid climatic zones of Israel, and that it gave a good indication of the areas of potential deflation and deposition. Although additional data were required on the nature of the soils in order to quantify the levels of removal and accumulation.

Soil erosion by wind was recorded for several areas of South Yorkshire. Briggs and France (1982) used a form of the Wind Erosion Equation to determine actual and potential rates of soil loss in order to assist environmental and agricultural planning for the region. They found that detailed information on some of the parameters was lacking and they had to rely on assumptions and manipulations in order to obtain values for the necessary variables.

Their results showed that soils susceptible to erosion are widespread in the county. The climatic conditions are such that erosion is a real threat in the east, while the western areas have lower wind speeds and generally wetter soil conditions. They further found that, despite potential soil loss throughout the county, actual soil loss is negligible in all but a limited area, this being due largely to the existence of hedgerows and other barriers. The influence of natural vegetation in controlling wind erosion was shown to be of secondary importance except in the western area of blanket peats where there is a dense cover of heather and moorland grass which when disturbed gives rise to localized erosion. Erosion in this area is the result of both water and wind action. Sheet erosion removes vegetation cover exposing patches to wind erosion and a self perpetuating cycle is initiated. In the east where large areas are under intensive cereals or horticulture, it is the presence of hedgerows, coppices and buildings which play an important role in limiting erosion (Briggs and France 1982).

The Wind Erosion Equation has also been used in air pollution surveys (Wilson 1975). In order to evaluate the impact of wind eroded dust on concentrations of airborne particulates, it is necessary to develop an emission factor that gives a rate at which soil material enters the atmosphere. Attempts were made to generalize the Wind Erosion Equation for use on a regional basis and to convert values of gross erosion to estimates of suspended particle emissions. In order to do so, Wilson (1975) modified the variables in the Wind Erosion Equation so that they applied to the general conditions of the region in question, in this case southwestern New Mexico. He found that this could be done successfully to provide a generalised figure for gross erosion rates. As gross erosion is composed of movement by the means of creep, saltation and suspension, this figure had to be adjusted to refer to suspension only. The evidence suggests that suspension is between 1 and 5 % of gross erosion, and therefore Wilson used a value of 3 %.

He concluded that the wind erosion equation is of value in making an air pollution survey and in determining whether or not enforcement of air pollution regulations is needed in areas where natural factors are an important source of particulate matter. He suggests that the climatic indices should be recalculated on an annual basis in order to reflect contemporary conditions and the effects of dry periods.

4.3.4 *Modifications to the Wind Erosion Equation*

The climatic factor (C') was initially developed for annual conditions. Seasonal differences in wind speeds and moisture levels, however, indicate the need for a short-term climatic index (Woodruff and Armbrust 1968). In order to adapt the equation for the climatic factor, monthly wind velocities were used instead of annual figures. The annual precipitation-evaporation index was still used, however, as the monthly figures were found to be meaningless. Nonetheless a comparison of the annual and monthly climatic factors shows that wind velocity differences strongly influence the climatic factor (Figure 4.8) This is of particular significance in South Africa where there is a distinct differentiation between areas of summer and winter rainfall.

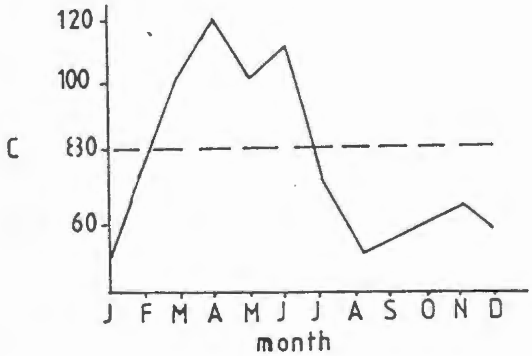


FIGURE 4.8 Variations in monthly climatic factors in relation to the annual climatic factor for Midland, Texas (taken from Woodruff and Armbrust 1968).

The calculation of the climatic factor has been further modified by Bondy *et al* (1980) and Lyles (1983). They developed a method whereby wind erosion was calculated for periods, based on erosive energy distribution. Erosive wind energy is defined by months as the sum of the cube of wind speeds between 8 and 20 m s^{-1}, in

1 m s^{-1} increments. Bondy *et al* (1980) advocate that the values of I', K', L' and V be determined for each crop-stage period and that the soil loss, E, determined for that period be multiplied by the percentage of annual erosive wind energy for that period to provide an estimate of the period erosion. Table 4.5 illustrates the procedure for a 2 year sequence of winter wheat-fallow near Garden City, Kansas.

Crop	Period (month/day)	K	SG[a] (kg/ha)	E (t/ha/y)	EWE[b]	E * EWE (t/ha/y)	E[c] (t/ha/y)
fallow	7/1-5/1	1,0	3360	0	0,74	0	0
	5/1-6/1	1,0	2800	0	0,12	0	
	6/1-7/1	1,0	2240	1,6	0,14	0,2	
	7/1-8/1	1,0	1680	8,0	0.07	0,6	
	8/1-9/1	1,0	1120	29,5	0.06	1,8	
winter	9/1-10/15	0,5	560	29,2	0,11	3,2	
wheat	10/15-11/15	0,5	840	18,6	0,06	1,1	
	11/15-4/15	0,75	1400	11,8	0,39	4,6	11,8
	4/15-7/1	0,75	2800	0	0,31	0	
Total					2,00	11,5	11,8
Average						5,8	5,9

(a) flat small grain residue equivalent
(b) erosive wind-energy, proportion during period
(c) potential average annual erosion using current procedure of selecting a 'critical' period as a basis of determining E

TABLE 4.5 Example solution of wind erosion equation using crop-stage periods and erosive wind -energy for a winter wheat-fallow rotation at Garden City, Kansas, I = 108 t/ha/y, C = 100 and L = 1,829 m (taken from Bondy *et al* 1980)

4.3.5 *The prediction of a wind erosion risk for areas of limited climatic data (Lynch and Edwards 1980)*

Lynch and Edwards (1980) note that in many arid and semi-arid areas there are only limited climatic data available, as in the case of the Cape Province. They have proposed a method of extrapolating the data, by way of regression analysis, reciprocal distance squared and pattern analysis, so that qualitative assessment of wind erosion can be made at any site.

They argue that the presentation of climatic data in the form of isolines on a map, as is the case for the wind erosion equation, is often inappropriate. It implies a degree of accuracy which is often not there. It is difficult and tedious to show seasonal or monthly figures, as a number of different maps are required and incorrect contours can results from a single erroneous figure. Depiction of data in this format does not readily lend itself to management guidelines as they are usually given on a broad area basis. To be able to assess the erosion risk, data for rainfall, evaporation and wind force are necessary.

4.3.5.1 Water Balance

A monthly moisture balance is determined using rainfall and evaporation figures, according to the method suggested by Lynch (1975). Months are classified according to soil moisture levels, such that the months of interest are those where rainfall plus the residual carry-over from the previous month are less than 20 % of the pan evaporation for that period. The value of 20 % is based on work by Bell (1962) who defined the effective carry-over rainfall needed to maintain plant growth as being greater than this proportion of pan evaporation. An aridity index is then calculated by expressing the number of occurrences of such months as a fraction of the number of complete years of record. A seasonal aridity index was then calculated by averaging the monthly values for each of the four seasons.

4.3.5.2 Wind Force

Wind observations from 0900 and 1500 on the Beaufort scale are used. For each season, the magnitude of wind forces was obtained by a method similar to that of Skidmore and Woodruff (1968):

$$F = \sum_{i=1}^{n} U_i^3 f_i$$

where F is the wind force, U_i is the mean wind speed within speed group *i* and f_i is the proportion of total observations that occur within speed group *i*. These seasonal magnitudes are regressed separately against the latitude and the longitude in order to determine if there is a pattern which could be used to extrapolate the wind force to the rainfall stations. Reciprocal distance squared was also considered as means of extrapolating the wind force data to the rainfall stations. This method gives a weighting inversely proportional to the square of the distance of a station from the unknown site and a weighting directly proportional to the length of record of the site:

$$F' = (\sum_{i=1}^{n} F_i W_i / D_i^2) \;/\; (\sum_{i=1}^{n} W_i / D_i^2)$$

where F' is the predicted wind force at a rainfall station, n is the number of wind stations in the study area, F_i is the known wind force at a station, W_i is the length of record of wind data and D_i is the distance between the wind station and the rainfall station. A wind index was derived by dividing the individual wind forces by the largest overall predicted wind force.

Pattern analysis using hierarchical agglomerative classification is used to define similar zones within the study area. The weather stations are grouped on the basis of their similarities using the flexible sorting method of Lance and Williams (1967) with a value of -0,25 for a.

The advantage of pattern analysis is that it allows for extrapolation by defining zones within which characteristics could be expected to be similar and between which there are real differences. The range of values within a zone indicate that there is a degree of variation within each zone and that a discrete description cannot be applied to a whole zone.

The use of zones rather than isolines allows for the integration of wind and aridity indices without any assumptions being made about the two. Lynch and Edwards (1980) conclude that the resulting map allows for an easy assessment of the risk of occurrence of arid conditions and of the occurrence of high winds at any sites and is thus a valuable tool for management. It was therefore decided to apply this model to the conditions in the Cape Province.

4.3.6 *A markov process model of wind erosion*

The rationale behind the development of a markov process model for the determination of soil movement and loss by wind, is that although most methods of studying wind erosion are deterministic, Nassar *et al* (1984), argue that it is a stochastic process. They see the movement of a soil particle by wind as a random event, and as such they suggest that it might be useful to model soil erosion for any storm by using the principles and techniques of stochastic theory. A similar approach has been taken to forecast rainfall, to predict flood and stream flow, as well as sediment yield in reservoirs. The use of a markov process model allows for the prediction, at any time, of (i) the average soil loss, (ii) the variance of soil loss, and (iii) the probability distribution of soil loss.

For the development of the model, the field or wind tunnel is partitioned into sections as expressed by:

$$\{ S_i, i = 1, 2, 3, \ldots, n\}$$

Soil movement can be visualized as making transitional steps from state S_1 to S_2 through saltation and surface creep. Soil movement by suspension is considered a loss at that state, as it is unlikely to be redeposited in the same field. The objective of the model is to derive a probability distribution for the amount of soil remaining in each state at time t given a certain initial condition. From this probability distribution, mean and variance of soil loss can be predicted at any time t. Three probabilities are of interest: (i) the probability that a mass of soil will move from state S_i to state S_j through saltation and surface creep in a given time interval, (ii) the probability that a mass of soil will be lost from state S_i as a result of suspension in wind or ground movement in the given time interval, and (iii) the probability that a unit mass of soil in state S_i at time t will remain in the same state during the time interval.

Nassar *et al* (1984) found that this model was readily applicable to wind tunnel data. In the field, however, it is more difficult due to the complexity of factors and variable conditions that affect the intensities of the model. Each field, must therefore be analyzed independently. In order to make the model more generally acceptable, more research is required to determine the relationship between the intensities of the model and the factors affecting erosion.

As illustrated in this chapter, there are a number of ways of measuring and predicting actual or potential wind erosion. Although none of these methods is without its weaknesses, they have been shown to be useful in some areas. It was considered to be of interest to test two of the models in South Africa so as to determine the relative success of each given the limitations with regard to the availability of weather records and the variability of the climate. The two models which are considered to be the most applicable are the original Wind Erosion Equation for annual and seasonal climatic data and Lynch and Edward's model for the analysis of limited climatic data. No attempt was made to measure actual rates of wind erosion due to the size of the size -of the study area, the short duration of the study and the unreliability of the results.

In order to adequately test the applicability of these two models an appropriate study site has to be determined. It was necessary to find an area large enough to cover a wide range of climatic conditions, an area that was known to suffer from wind erosion and one in which appropriate wind records are available. The Cape Province was found to meet these criteria. A description of the general characteristics of the region is found in the following chapter.

CHAPTER FIVE

THE STUDY AREA

This chapter contains a description of the Cape Province. The climate, soils, vegetation and agricultural activities are all discussed as they are important factors in determining the susceptibility of specific regions to wind erosion.

5.1 GEOGRAPHICAL LIMITATIONS

The Cape Province was chosen as a suitable area in which to undertake this study (Figure 5.1) because it meets the following criteria:

(i) Soil erosion is known to be a problem. Bennett (1945), Roux and Opperman (1986) and Roux (*pers. comm.*) have all made statements with regard to the severity of wind erosion in the Karoo. The coastal areas of the province have extensive dune areas further indicating the ability of wind to transport coastal soils.

(ii) The size of the Cape Province is such that it encompasses a wide range of rainfall and wind regimes, soil and vegetation types and agricultural activities.

(iii) Weather records are available for much of the area. They are, however, fairly sparse in the northern areas of the Province. As a result, the area north of the Orange River was not included in the study area as there was only adequate data for the town of Kimberely. Even in the remaining portion of the province there is a problem with the distribution of the weather stations which is such that the density is very uneven, relative to the areas in which the models were developed. The distribution was nonetheless considered adequate for the testing of the models.

The Cape Province covers a large area, 645 767 km^2 or 57,3 % of the national territory, incorporating a wide range of climatic conditions, land forms and agricultural practices, and as such it is considered to be an appropriate region in which to test these predictive wind erosion models.

5.2 PHYSIOGRAPHIC AREAS

There are two major physiographic areas within the province; the interior plateau with a mean altitude of 1 200 m and the marginal lands between the plateau and the coast, separated by the Great Escarpment. The plateau is composed of two subregions: (i) the Kalahari Basin, a sandy expanse in the north west and the peripheral highlands which is a level surface with wide open river valleys and the occasional dolerite ridge. (ii) The Cape fold belt makes up the core of the marginal lands, including the Great Karoo to the north and the more or less extensive coastal lowlands between the fold belt and the sea. The dominant features of this area are a series of parallel mountain ranges comprised of Table Mountain Group sedimentary rocks (TMG) rising over broad longitudinal valleys. North of the fold belt and south of the Great Escarpment is the Great Karoo, a wide shallow arid basin, drained by rivers whose headwaters rise in the Great Escarpment. The coastal foreland is a fairly level area except where it has been dissected by rivers, and where isolated TMG fragments or granitic bornhardts rise abruptly. Much of the coast line is overlain by deep even sand drifts.

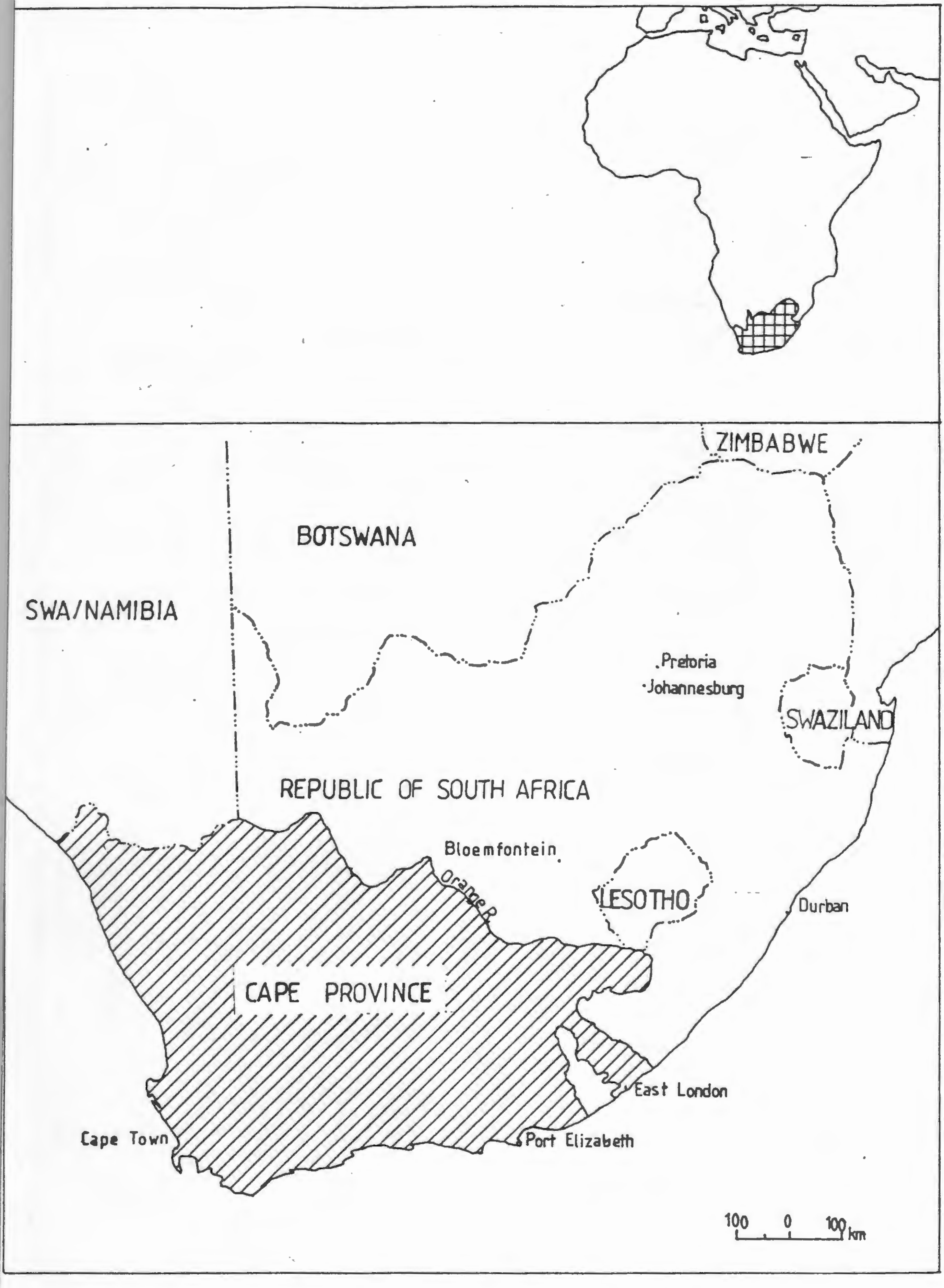


FIGURE 5.1 Location of the study area

5.3 CLIMATE

5.3.1 Atmospheric circulation and precipitation

In general South Africa is an arid country with a national average annual precipitation of 464 mm. This, however has little meaning as 65 % of the country receives less than 500 mm of rainfall annually, a level usually regarded as the minimum required for dry-land farming (South Africa 1983). The areal distribution of total annual precipitation is characterised by two features; a decrease in rainfall from east to west, and the strong influence of orographic features (Figure 5.2). Of particular importance for wind erosion is the way in which the country is divided into areas of winter and summer rainfall (Figure 5.3). Separating the two is a transitional zone in which rain occurs throughout the year.

Atmospheric circulation over South Africa is dominated by the semi-permanent subtropical belt of high pressure which is located 3^0 to 4^0 of latitude further north in the winter than in the summer. The sub-tropical pressure belt in not continuous, but composed of individual anticyclonic cells, one of which is located over the interior of the subcontinent. It is best developed during the winter and gives rise to the dry, sunny conditions of the interior during those months. In the summer when surface heating causes the anticyclone to weaken, inland transport of humid east coast air masses becomes possible, convective precipitation is also common in unstable conditions. Thus, the weakening or displacement of the continental anticyclone is a precondition for rain in the interior. It is also the changing position of the anticyclonic cell which gives rise to the seasonal distribution of rainfall in South Africa. This pattern is illustrated in Figure 5.3.

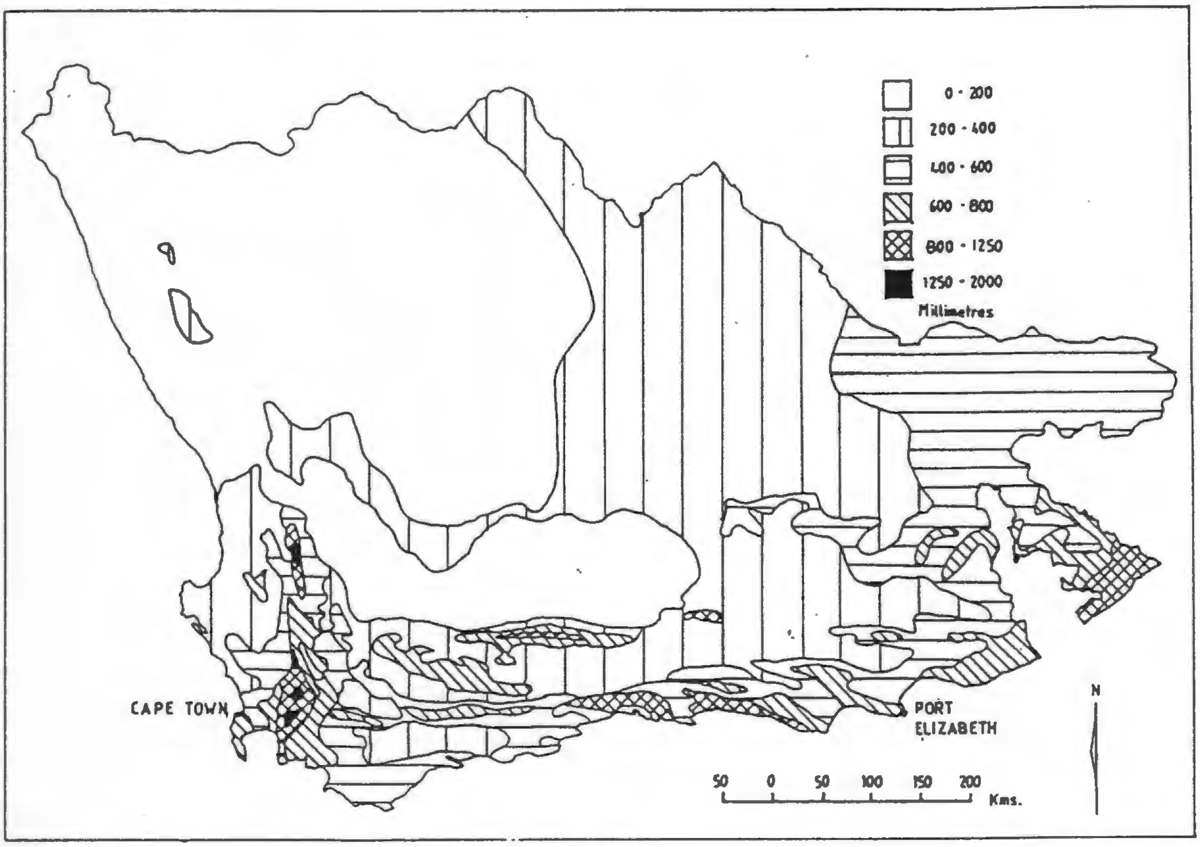


FIGURE 5.2 Mean Annual Precipitation (taken from South Africa 1983)

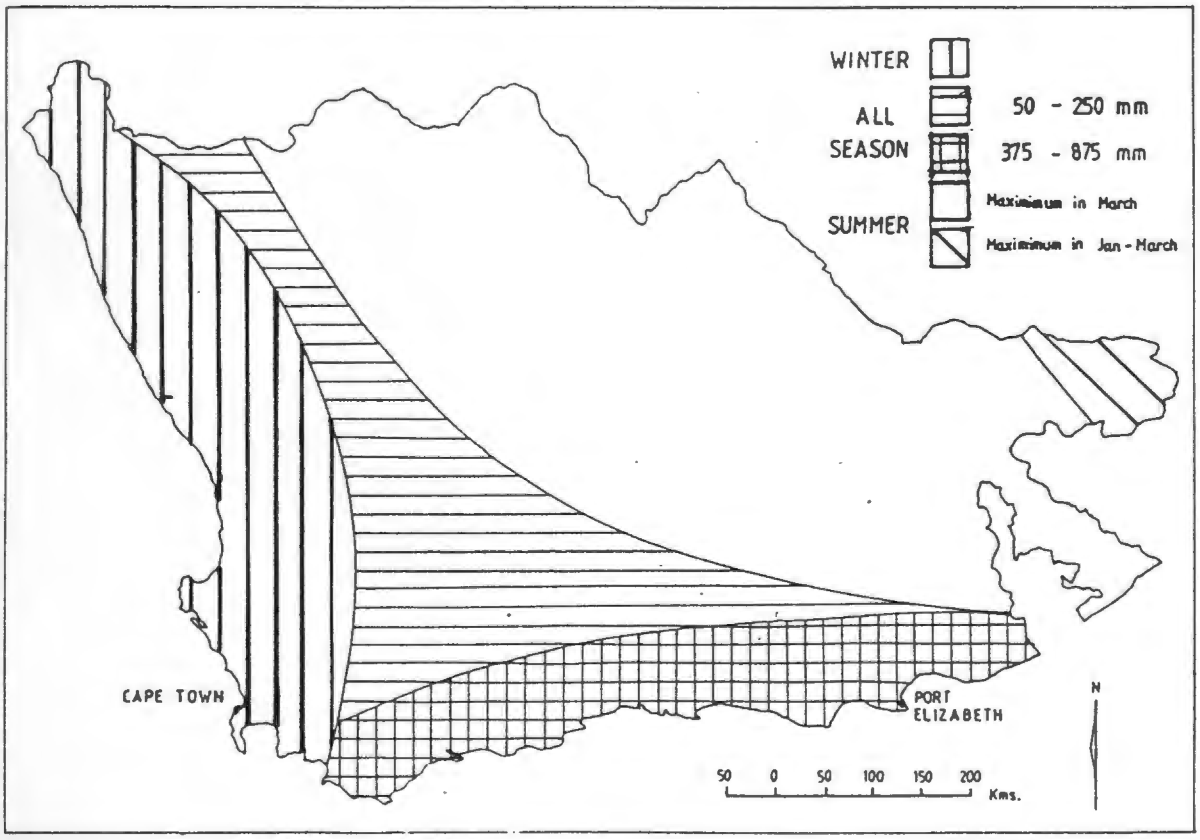


FIGURE 5.3 Seasonal rainfall distribution (taken from South Africa 1983)

The opposite condition exists in the south-western Cape, where the winter rain and dry summer is prevalent, controlled by the migration of the wind and pressure belts. During the summer, a ridge of high pressure extends across the south coast connecting the South Atlantic and southern Indian Ocean anticyclonic cells. This gives rise to hot, cloudless summers which are often very windy. In the winter, the high pressure belt shifts to the north and the south western Cape is under the influence of the moving cyclones and associated fronts. The cold fronts are followed by a flow of cool, humid subpolar air which brings showery, cold weather and often snow on the mountains.

5.3.2 Wind

Wind direction in the interior during the winter is controlled by the continental anticyclone, northerly in the central interior, north-westerly or westerly in the western and southern interior. Summer winds are more variable, although they tend to be southerly over the western interior. Along the coast the prevailing winds are always parallel to the coast line. During the winter the south-western coast is dominated by north-westerly winds and by south-easterly winds during the summer. Wind velocities are generally higher along the coasts, although the highest mean velocity of 27,7 $m\ s^{-1}$,with gusts of 44,6 $m\ s^{-1}$ was recorded at Beaufort West (South African Weather Bureau 1983). A comparison of the wind speeds at the main wind recording stations for the Cape Province show that although the highest hourly wind speeds are not significantly different across the province, Beaufort West which has exceptionally high winds. A consideration of wind gusts, on the other hand, show that they are generally higher inland than in the coastal regions (South African Weather Bureau 1975). Dust devils or whirlwinds are common in the interior on hot summer days.

5.3.3 Temperatures and evaporation

Surface temperatures in South Africa are remarkably uniform from north to south due to the increasing elevation in the interior plateau. The mean annual temperature of Cape Town is 17 °C whereas that of Pretoria is 17,5 °C. The hottest areas of the country are found in the eastern and northern Transvaal and in the north-western interior of the Cape. In the lower Orange River valley, temperatures frequently exceed 38 °C. Cold temperatures of -11,7 °C have been recorded at Sutherland in the Roggeveld mountains, where the mean annual temperature is only 12,4 °C. With regard to wind erosion, the importance of temperature is in its relation to evaporation, in that higher temperatures give rise to higher evaporative moisture loss which in turn increases aridity and susceptibility to erosion. The pattern of evaporative loss reflects the pattern of temperature across the province. Within the Cape Province the highest annual evaporation losses occur in the north west. They decrease progressively southward as influenced by changes in elevation (Figure 5.4).

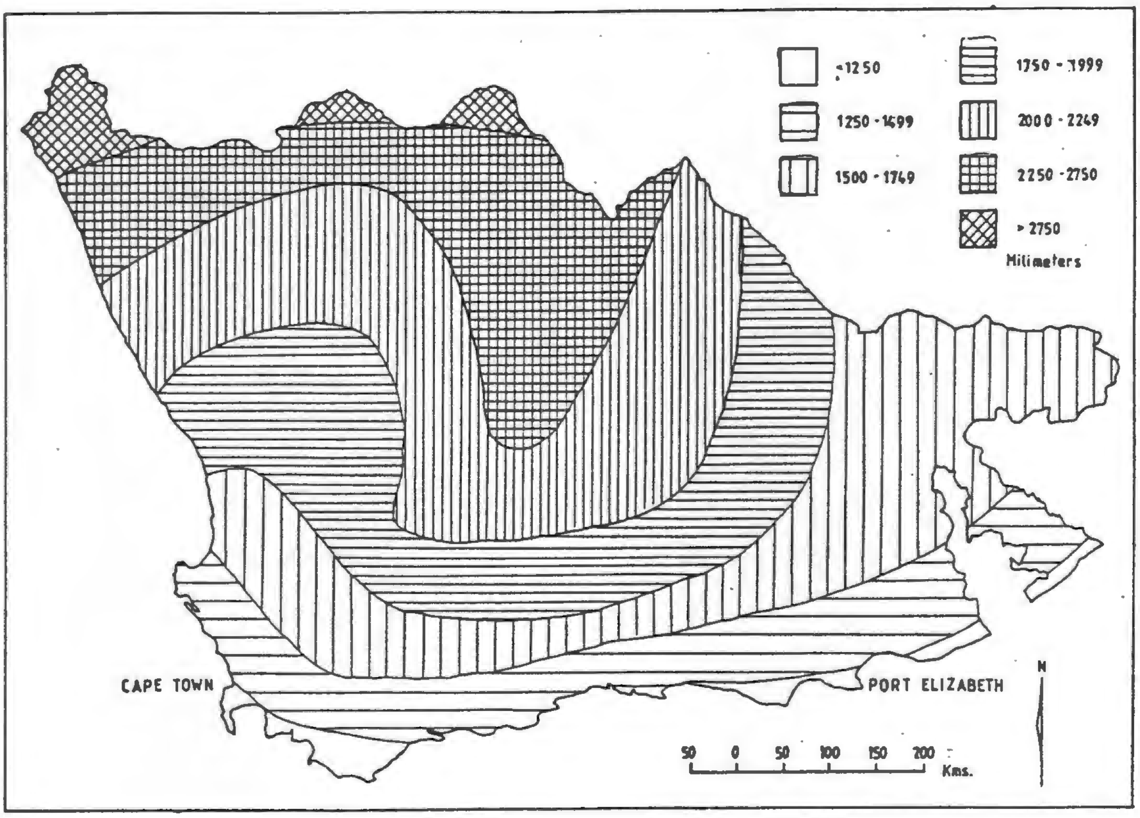
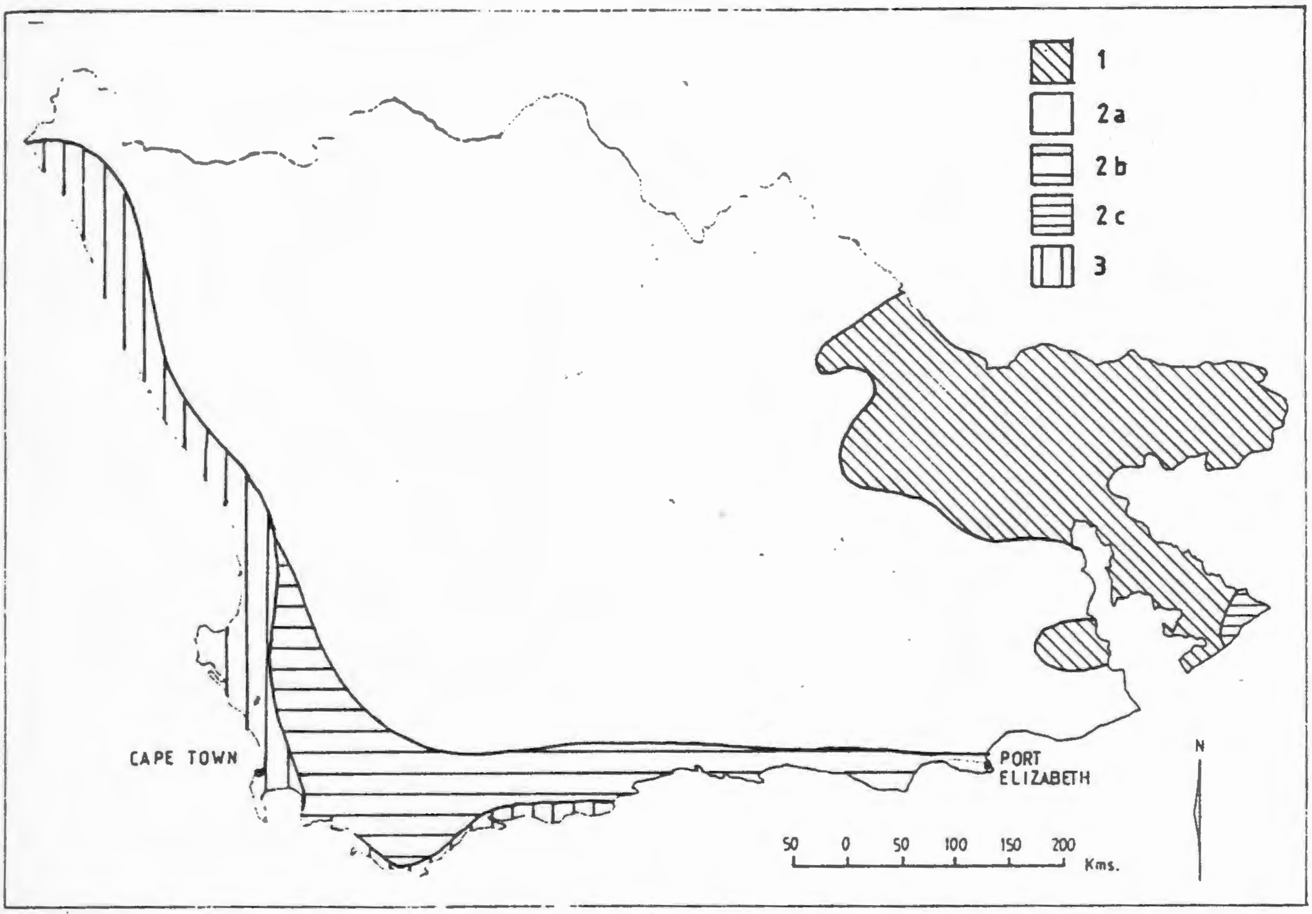


FIGURE 5.4 Annual evaporation losses from an open water surface (taken from South Africa 1983)

5.4 <u>SOIL</u>

Soil is a product of the natural environment. Differences in parent material, climate, vegetation, topography, time and the influence of man will all contribute to give rise to the complex assortment of soil types that exist. In the most general sense, South Africa can be divided into six major soil associations (South Africa 1983). Only three of these associations are found within the Cape Province; duplex and paraduplex soils, weakly developed soils on rock and sand soils (Figure 5.5).



1. Duplex and Paraduplex soils with varying amounts of rock and lithosols

2. Weakly developed soils on rock:
(a) Loams and clays with lime in upland and bottomland sites and much rocky land
(b) Loams and clays with lime common in bottomland sites but absent in upland sites and much rocky land
(c) Loams and clays with lime rare or absent and varying amounts of rock

3. Grey sand soil with varying amounts of rock and lithosols.

FIGURE 5.5 Soils of the Cape Province (taken from the South Africa 1983)

(i) Duplex and paraduplex soils are characterised by topsoils which differ markedly from subsoils with respect to texture, structure and consistency. In the duplex soils there is an abrupt transition between the topsoil and subsoil, whereas the transition is more gradual for the paraduplex soils. These soils cannot be considered ideal arable soils, and as they are highly susceptible to misuse, severe soil erosion by water is common, which may subsequently render the area more susceptible to wind erosion.

(ii) Weakly developed soils on rock occur where the soil profile consists of a topsoil overlying rock or weathered rock. These soils are thus shallow and their genesis is ascribed to low rainfall, steep topography, resistant rock or youthful landscapes. Such soils are not very arable due to their shallowness and aridity, however they are used for winter wheat in the western Cape due to the winter rainfall.

(iii) Sandy soils occur extensively along the South African coast, derived mainly from beach deposits. They are generally highly infertile and subject to wind erosion, as is apparent in the extensive areas of coastal dunes which are distributed across the entire Cape coastline. The red sandy soils of the central interior are aeolian in origin. Dunes are common in the shifting sands of the Kalahari.

Recently a more detailed examination of the soils of the Karoo was conducted (Ellis and Lambrechts 1986).

Soils were grouped into seventeen map units according to: morphological, physical and chemical properties, distribution, natural fertility status and genesis. As reported in Chapter 3, texture is of particular importance in determining the ability of the soil to hold water and to withstand erosion. Figure 5.6 shows the distribution of topsoil texture classes of the Karoo Region.

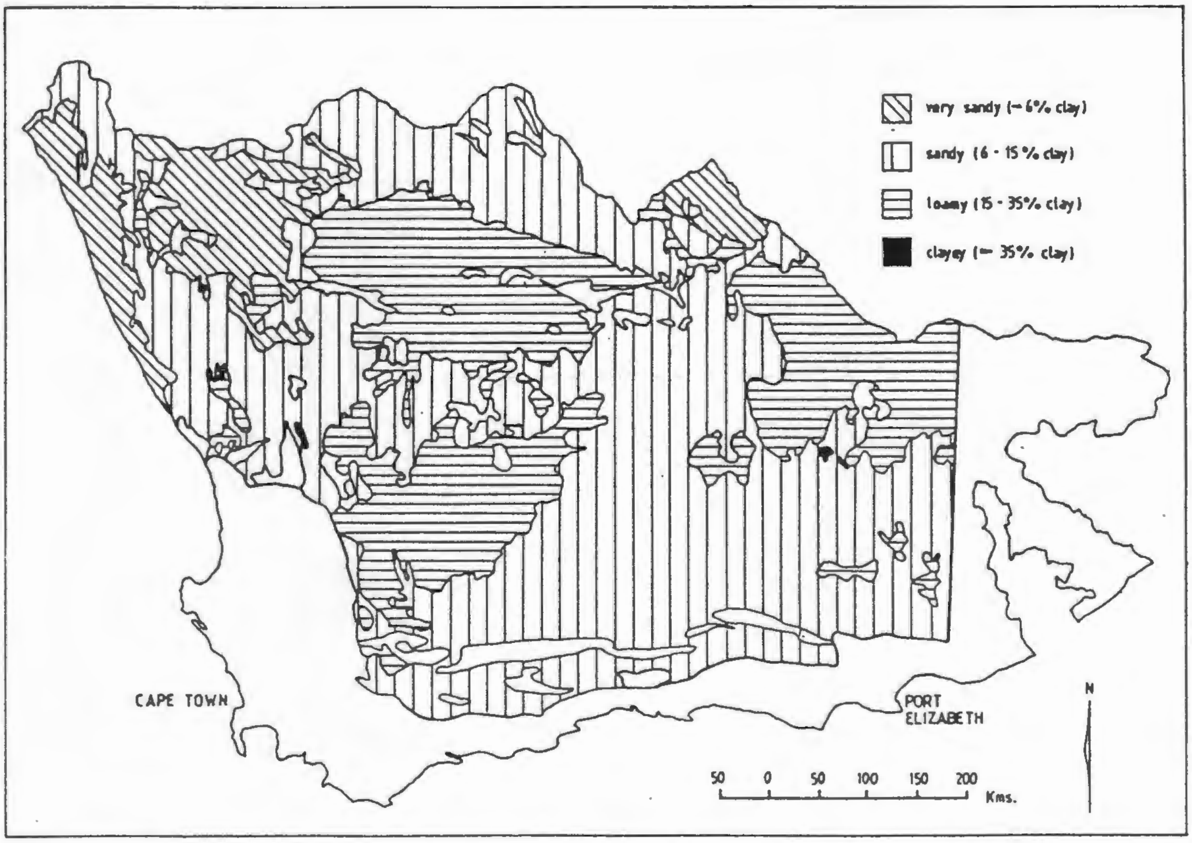


FIGURE 5.6 Textural Classes of Topsoil in the Karoo (taken from Ellis and Lambrechts, 1986)

As noted in Section 3.2, it is the soil particles classified as sand (diameter between 0,05 mm and 2 mm) which are most susceptible to wind erosion. Clay acts as a binding agent, since clay particles absorb moisture and cations which facilitate the formation of soil aggregates, thereby reducing erodibility.

The clay content of soils in the Karoo is comparatively low and thus the Karoo soils would not be prone to aggregate formation. These soils are therefore all susceptible to wind erosion. The loamy soils are the least erodible, the sandy soils are more erodible and the very sandy soils are highly erodible.

5.5 NATURAL VEGETATION

Five primary natural vegetation units are recognised; desert and semi-desert, 'Mediterranean' plants and shrubs, bushveld or savanna, temperate grassland and forest (Figure 5.7) (South Africa 1983, Huntley 1984).

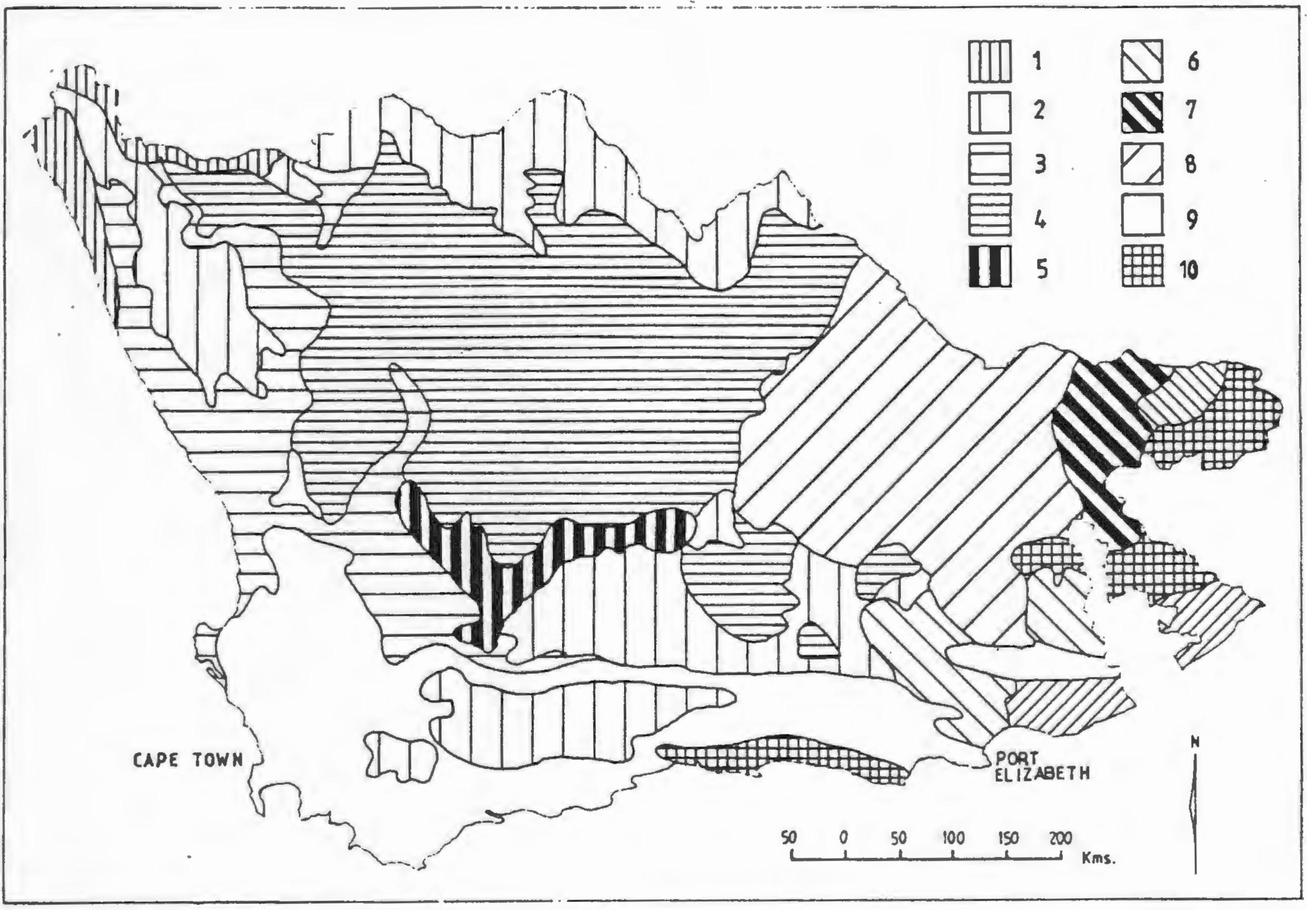
(i) True desert vegetation occurs in a narrow strip along the west coast. Annual rainfall is between 50 and 125 mm, vegetation is characterised by widely spaced low shrubs and succulents; and annuals are common after good rains. Most of the western interior is covered by Karoo or semi-desert vegetation, characterised by dwarf and low open shrublands dominated by fine-leaved and succulent perennial shrubs. These shrubs are often interspersed with low succulents and grasses (increasing towards the east).

(ii) Mediterranean vegetation or Fynbos occurs on the nutrient poor soils of the winter rainfall region of the south western Cape. Fynbos comprises evergreen sclerophyllous heathlands and shrublands in which fine-leaved low shrubs and tufted grass-like plants are common. It is characterised by three main families, Ericaceae, Proteaceae and Restionaceae, and although many other species are present, grasses and trees are scarce.

(iii) The Cape Province, like the rest of South Africa, contains very little natural forest. The largest forest area, 180 by 16 km, is found in the all-season rainfall area between George and Humansdorp on the southern coast. It is characterised by tall, evergreen hardwood trees, low shrubs and tree-ferns.

(iv) The Kalahari thornveld in the western interior is an open type of savanna, comprised of a sparse grassland with scattered shrubs and trees. The most extensive areas of savanna are found in the Lowveld and do not fall within the study area.

(v) Temperate grasslands occupy most of the eastern interior of the Cape. The area between the escarpment and the east coast is an area of tall grasses (0,6 to 1,0 m). For elevations greater than 1 200 m to the top of the escarpment, the true temperate grasslands are found. These grasses make up the best natural pasture, however, due to poor management practices they have been replaced by less nutritious species over large areas. Poor management of the grasslands surrounding the Karoo has resulted in the encroachment of karoo bushes and an increased erosion potential as the bushes provide less effective ground cover.



Arid and Semi-arid

1. Namib desert
2. Bushy Karoo shrubland
3. Succulent Karoo shrubland
4. Dwarf Karoo shrubland
5. Montane grassy Karoo shrubland
6. Evergreen and semi-evergreen bushland

Savanna and Grassland

7. Highveld grassland
8. Transitional Karoo-Highveld grassland

Mediterranean

9. Fynbos

Miscellaneous

10. Undifferentiated afromontane vegetation

FIGURE 5.7 Major vegetation units of the Cape Province (taken from Meadows, 1985)

5.6 AGRICULTURAL REGIONS

Ross (1963) describes the seven main agricultural regions of South Africa, three of which fall into the study area; the Winter Rainfall Region, the Karoo Region and the Eastern Cape Region.

The Winter Rainfall region of the Cape Province is situated in the south west and extends from the Orange River in the north west along the coast to the Gamtoos River in the south east. Agriculturally it is a diversified region in which the mean annual rainfall varies from 250 to 500 mm, except for the north west and "Little Karoo" where it is much lower. The Winter Rainfall Region is the country's principal region for winter cereal (predominantly wheat), deciduous fruit and wine production. The wheat is grown as a system of mixed farming in rotation with lucerne, clover or lupins, and together with livestock such as dairy cattle, pigs, poultry, mutton and wool. The principal crops in the fruit and wine area are grapes, apples, pears, apricots, peaches and prunes, together with small amounts of livestock and wheat. In the "Little Karoo", much of the area is devoted to crop production under irrigation and livestock is of secondary importance. The agricultural regions of the winter rainfall area area not particularly prone to wind erosion as there is adequate ground cover throughout the year to prevent aeolian transport of soil material. In this region, it is predominantly the areas where vegetation is disturbed or destroyed that makes them liable to erosion.

The Karoo Region occupies roughly half of the Cape Province, bounded by the Winter Rainfall Region to the west and south, by the Orange River to the north and the Eastern Cape Region to the east. Rainfall varies from a low of 100 mm in the west up to a high of 450 mm in the east. The area is dominated by livestock production, dependent on grazing the natural vegetation, with merino sheep for the production of wool the most numerous. The other products of the region include mutton, karakul pelts, mohair, beef and dairy on the eastern edge. Irrigation potential is limited, yet important for the production of supplementary feed crops.

Much of the Karoo suffers from poor ground cover due to inappropriate grazing management. This makes the area highly susceptible to wind erosion. It is thus essential to determine the appropriate carrying capacities for the different approaches to management which will ensure adequate ground cover as well as economical yields.

The Eastern Cape Region is bounded on the west by the Gamtoos River and the Karoo Region and the Natal and Orange Free State Regions in the north. The western edge has a rainfall of less than 500 mm per annum, but it increases to between 750 and 1250 mm for much of the region. The marginal areas are primarily suited to livestock farming, however the remainder of the region is well suited to mixed farming with a strong emphasis on beef and dairy cattle and merino sheep, as well as fodder crops, maize, wheat, potatoes, tobacco, fruit and vegetables. The frost-free coastal belt is used for the production of pineapples and chicory as well as some citrus fruits.

It can thus be seen that the Cape Province covers a large area with a variety of climatic conditions, soil types and land use activities. It is against this background that an attempt has been made to produce a map of the wind erosion hazard according the Wind Erosion Equation and Lynch and Edward's model for the analysis of limited climatic data.

From this description of the Cape Province it is clear that the nature of most of the area is such that wind erosion is likely to occur in the event of disturbance of surface cover. The exceptions are the areas which have adequate rainfall throughout the year to maintain good ground cover, such as the mountainous and forested areas.

The soils of much of the Cape Province are sandy and as such will be readily eroded if exposed. The aridity over much of the area, especially in the north-west and the inappropriate grazing management has given rise to a depauperate vegetation cover and as a result, soil loss by wind.

CHAPTER SIX

METHODOLOGY

The aims of this research project have been identified as follows: to produce a map of the wind erosion hazard in the Cape Province, and to evaluate the effectiveness of two different methods for predicting areas of potential wind erosion. In order to achieve these aims four main tasks were undertaken:

1. The calculation of Chepil and Woodruff's Wind Erosion Equation for both annual and monthly climatic data.
2. The calculation of Lynch and Edwards' model for the analysis of limited climatic data.
3. An examination of the extent to which wind erosion is apparent on the aerial photography of the Cape Province.
4. The use of a postal survey to determine the perceptions of agricultural extension officers and farmers of the wind erosion hazard.

6.1 THE WIND EROSION EQUATION

6.1.1 Calculation of the climatic factor

The approach taken in the application of the Wind Erosion Equation is similar to that of Yaalon and Ganor (1966) in Israel. They were concerned primarily with the climatic factor as an indication of wind erosion and not with the nature of the vegetation, or soil or the layout of farm fields.

Weather records were obtained from the regional office of the Department of Agriculture at Elsenberg. The climatic factor was calculated for 76 agricultural weather stations in the Cape Province, using monthly mean temperature, monthly rainfall and wind run figures. Only the weather stations with a minimum of four years of continuous record of rainfall, temperature and wind were included. Hourly wind records are not available for most weather stations in the province, therefore wind run had to be used instead. Wind run is a cumulative figure (in metres) of wind force over a monthly period. These values were then converted to the equivalent of a monthly average wind speed in metres per second by dividing the wind run figure by the number of seconds in each month.

Due to the known regional, seasonal variations in rainfall in South Africa (section 3.3.2.3), five variations of the climatic factor were calculated to determine the effect of seasonal differences in moisture availability and windforce; (i) an annual figure was calculated using average annual temperatures, overall annual rainfall $(P-E)_a$ and average wind speeds (U_a), for each year of record and then an overall figure was determined by averaging the yearly figures,

$$C = 34 \frac{U_a^3}{(P-E)_a^2}$$

(ii) a winter figure was calculated by dividing the average winter wind speed (U_w) by the winter P-E figure $(P-E)_w$, and then averaging the yearly figures,

$$C = 34 \frac{U_w^3}{(P-E)_w^2}$$

(iii) a summer figure was determined by dividing the average summer wind speed (U_s) by the summer P-E figure $(P-E)_s$,

$$C = 34 \frac{U_s^3}{(P-E)_s^2}$$

(iv) annual-monthly figures were determined by dividing the average monthly wind speed (U_m) by the annual P-E figure, for each month of the year,

$$C = 34 \frac{U_m^3}{(P-E)_a^2}$$

(v) seasonal-monthly figures were determined by dividing the average monthly wind speed by the appropriate seasonal P-E figure.

$$C = 34 \frac{U_m^3}{(P-E)_w^2 \text{ or } (P-E)_s^2}$$

The calculations were computed using the spreadsheet package Lotus 1-2-3 ver 2 (Lotus Development Corporation) as this produces an easy means of replicating steps and examining different values at various stages of the calculation, rather than just obtaining the final value. Lotus 1-2-3 was also used to graph the different values for selected weather stations in the different seasonal rainfall zones, in order to determine the nature of the differences between the regions.

Contour maps of the first three variations of the equation, the annual, winter and summer values were produced using the Saclant Graphics Package on the Sperry-1100 mainframe (Diederiks 1979). The Saclant Graphics Package (SGP) plots a perspective picture of a single-valued surface defined over a rectangular grid. Grid interpolation is achieved through a process whereby the initial assignment of values to the grid points is followed by iterative improvements until the surface has been adequately 'smoothed'. Grid points are initially assigned the values of the datapoints nearest them, or the average of the two nearest points. The remaining grid points receive the value of their datapoint neighbours, these points are referred to as non-datapoints. The smoothing procedure is a two part process in which the first step involves the adjustment of the non-datapoints and the second the improvement of the datapoints. Each non-datapoint is adjusted by means of a combination of linear and third degree polynomial interpolations through its two immediate neighbours to the left, right, above and below. After all the non-datapoints have been adjusted, the datapoints are improved by trying to 'shift' them closer to their original position. The contour lines consist of a number of straight-lines segments whose end points have been determined by the linear interpolation between grid points. Contour smoothing can be achieved by: (i) dividing each grid division into two or (ii) by replacing each segment of a contourline with between 2 and 10 subsegments.

6.1.2 Soil erodibility and other factors

As was previously stated, the aim of this research was to produce a regional map of the wind erosion hazard for the Cape Province. As a result the scale at which the research was conducted was inappropriate to allow for the consideration of the local effects of field width, and surface roughness. The main driving forces behind the susceptibility of an area to soil erosion by wind are seen to be climate and soil texture. No specific data on soil erodibility are available for South Africa. It was seen, in any case, in section 2.2.1 that soil erodibility indices are highly variable and therefore not likely to be very accurate. A general consideration of the soil mapping and classification for South Africa was thus considered an appropriate means for estimating the wind erosion hazard for an area as large as the Cape Province, although it is understood that detailed studies would be required to determine actual rates of soil loss for smaller areas. The map produced by Ellis and Lambrechts (Figure 5.6) of the topsoil textural classes for the Karoo, the maps and discussion of Talbot (1947) in the Swartland and Sandveld, and a general soil map of the country (Figure 5.5) were used.

No attempt was made to quantify soil erodibility absolutely as the necessary soil data were not available at a significant level of detail. A qualitative assessment was made, however, using the textural soil map of the Karoo (Figure 5.6).

Figure 5.6 identifies 4 textural classes. Clayey soils cover very little of the study area and are resistant to wind erosion. The remaining 3 classes were separated in a relative sense, as follows: loamy soils were considered to be fairly erodible, sandy soils to be erodible and very sandy soils to be highly erodible. In this manner, soil was considered in a general sense as a background against which the values of the climatic factor were more closely related to an overall consideration of soil loss by wind.

6.2 THE ANALYSIS OF LIMITED CLIMATIC DATA

The conditions in the Cape Province are similar to those of New South Wales, Australia, where Lynch and Edwards (1980) developed a model for the analysis of limited climatic data, for regions in which there is a lack of comprehensive, reliable long term climatic records. The area of Australia where the model was developed is located in New South Wales west of a line joining Moree (29^0 30'S, $149^0$54' E) and Albury ($36^0$05'S, $146^0$57'E). A total of 98 weather stations are located in the area, 34 of which have wind data. This is in fact an area smaller than the area under consideration in this study and it has more climatic data. It was thus considered appropriate to attempt to apply this model to the conditions in the Cape Province. It was also of interest to compare the results from this approach to those produced by the Wind Erosion Equation.

A total of 76 rainfall weather stations was used together with 15 wind stations. Unfortunately, hourly wind records are limited to the airports and the main agricultural weather stations. The 0800 and 1400 wind speed readings were used and classified according to the Beaufort Scale, so as to be in the same form as the data used in the original model. The aridity index and wind force index were calculated according to the method described in section 3.3.5. The seasonal values of wind and aridity were then regressed separately against latitude and longitude and against latitude and longitude together, to determine if there was a geographical pattern of wind force and aridity.

Agglomerative hierarchical cluster analysis of the data was then performed, according to the procedure contained in the statistical package BMDP. The computer program used by Lynch and Edwards was not available, so an attempt was made to find an appropriate algorithm and adapt it to the specific nature of this project. The BMDP program used, calculates the correlation between two cases according to Euclidean distance. Clustering is then calculated according to single linkage between variables. An alternative approach was also undertaken with the use of computer program which calculates the squared correlation between two nominal variables by taking the optimal scores and replacing these scores by their ranks and using the ranks in an ordinary product moment correlation calculation. In this approach the resulting similarity matrix was then grouped according a method of hierarchical clustering which minimizes the average distance or maximizes the average correlation between the merged groups. This method is derived from the 'group average' method described by Lance and Williams (1967), which is referred to by Lynch and Edwards (1980). The results of this method were, however, unsatisfactory as the groupings were very large and showed virtually no correlation with the initial data. It was therefore decided to use the results from the BMDP analysis although they were not ideal either.

The various clusters from the BMDP analysis were then identified on the map so as to indicate the different regions for the wind erosion hazard.

6.3 AIR PHOTO INTERPRETATION

In order to verify the results produced by the application of the two different models it was decided to examine the aerial photography of the Cape Province. The intention in doing so was to determine the extent to which erosion is apparent from the air and to see how the distribution of erosion correlates with the erosion hazard as predicted by each of the models.

The photography was examined for signs of actual erosion by means of erosional scaring and for potential erosion as indicated by the presence of erosion control methods such as windbreaks.

Aerial photography of the Cape Province is available at a scale of 1:40 000 and 1:50 000. Other scales are available for limited areas, although they were not considered for this project. The photography dates from 1973 to the present (Table 5.1); it was not possible to obtain photography of the whole area taken in any one year. In the case of the sections that have been reflown more recently, the older material is no longer readily accessible.

A structured sampling approach was adopted in order to cover the entire area so that any patterns or trends would be apparent. For each job number, stereo pairs from every third flight line were examined using a Sokkisha stereoscope. It was not considered necessary to examine every stereo pair due to the 60 % overlap between consecutive photos along a flight line and the 20 % overlap between flight lines. The actual number of stereo pairs examined for each flight line differed due to the differences in the lengths of the flight line, however, sufficient stereo pairs were examined to ensure complete coverage of the flight line.

Year of Photography	Region
1973	Willowmore - Uniondale MIddleberg - Queenstown
1974	Outdshoorn - George
1976	Springbok, Calvinia, Vanrynsdorp
1977	Malmesbury, Sutherland, Brandvlei, Williston
1978	Vanwyksvlei, Uithenhage, Fraserberg, Victoria West
1979	Beaufort West
1980	Garies - Loriesfontein Richmond
1981	Britstown, Steytlerville Da Aar - Colesberg
1986	Citrusdal, Humansdorp
1987	Ceres - Laingsburg Worcester, Montague

TABLE 6.1 Dates of the available aerial photography at a scale of 1:40 000 or 1:50 000 for the Cape Province, south of the Orange River

The photographs were then classified against a scale for 0 to 4 in terms of the severity of wind erosion and potential wind erosion according to:

0 - no sign of erosion or erosion control methods

1 - very slight evidence of erosion, or the presence of windbreaks

2 - sand blotches visible, or blowouts present, areas of bare ground indicate actual or potential wind erosion

3 - extensive sand blotches or sand streaks, and bare areas, soil colour may be mottled due to uneven surface and moisture conditions, possibly related to erosion, stabilized sand dunes

4 - active dune fields, or very extensive scars as a result of erosion

The values observed for each of the stereo pairs were then averaged for each of the grid squares on the map. These results are shown in Figure 7.10. This figure illustrates the severity of actual and potential wind erosion as apparent on aerial photography.

6.4 POSTAL SURVEY (APPENDICES A AND B)

A second approach taken against which to verify the results from the two models, was a postal survey to ascertain people's perceptions of the wind erosion hazard in the area in which they live. An attempt was made to locate the agricultural extension officers throughout the Province. Contact with the staff at Elsenberg and the Department of Agriculture offices in Cape Town indicated that no such list was available. A list was. however, readily available from Grootfontein for the extension officers of the Karoo region. Each of the 16 extension officers (Appendix C) was sent a questionnaire and was asked to pass on additional questionnaires to 5 farmers in his district. The questionnaires (Appendices A and B) were short and simple, focusing on the farmers perception of the severity of wind erosion in their area and on a number of secondary factors which are indicative of wind erosion, i.e. the occurrence of dust storms or damage to farm buildings or equipment through abrasion. Farmers and extension officers were asked to rate the severity of the wind erosion problem on a 5 point scale: no problem, slight problem, problem, serious problem, very serious problem.

The results from the postal survey were mapped according to region and the indicated severity of wind erosion. Comments on the seasonality of wind erosion were used in comparing the results produced by the seasonal variations of the wind erosion equation.

The results from the above methods and the problems encountered in their implementation are discussed in the following chapter.

CHAPTER SEVEN

RESULTS

The previous chapter contains a description of the steps taken to achieve the aims of this research project as stated in Chapter 1. This chapter examines the results produces in the implementation of the methodology. It is clear from these results that there are problems in the application of a procedure developed in a different place even though the conditions appear to be similar.

Each of the steps in the methodology: the calculation of the Wind Erosion Equation, the analysis of limited climatic data, the aerial photography and the questionnaire are discussed separately. The way in which they come together to indicate the overall wind erosion hazard is dealt with in Chapter 9.

7.1 THE WIND EROSION EQUATION

The climatic factor was calculated for 76 agricultural weather stations. Contour maps were produced to show the results for the annual, winter and summer climatic figures (Figures 7.1, 7.2 and 7.3). An examination of Figure 7.1 shows that the climatic factor throughout the Cape Province is low relative to values obtained in the U.S.A (figure 4.3). There are higher values occurring along the west coast and especially in the north west, yet even these where wind erosion is known to be a problem are very low. This trend is as expected considering the distribution of rainfall and evaporation over the province (Figures 5.2 and 5.4). The most arid areas of the province are those of the northwest which makes the area highly susceptible to wind erosion, as vegetation cover is very sparse.

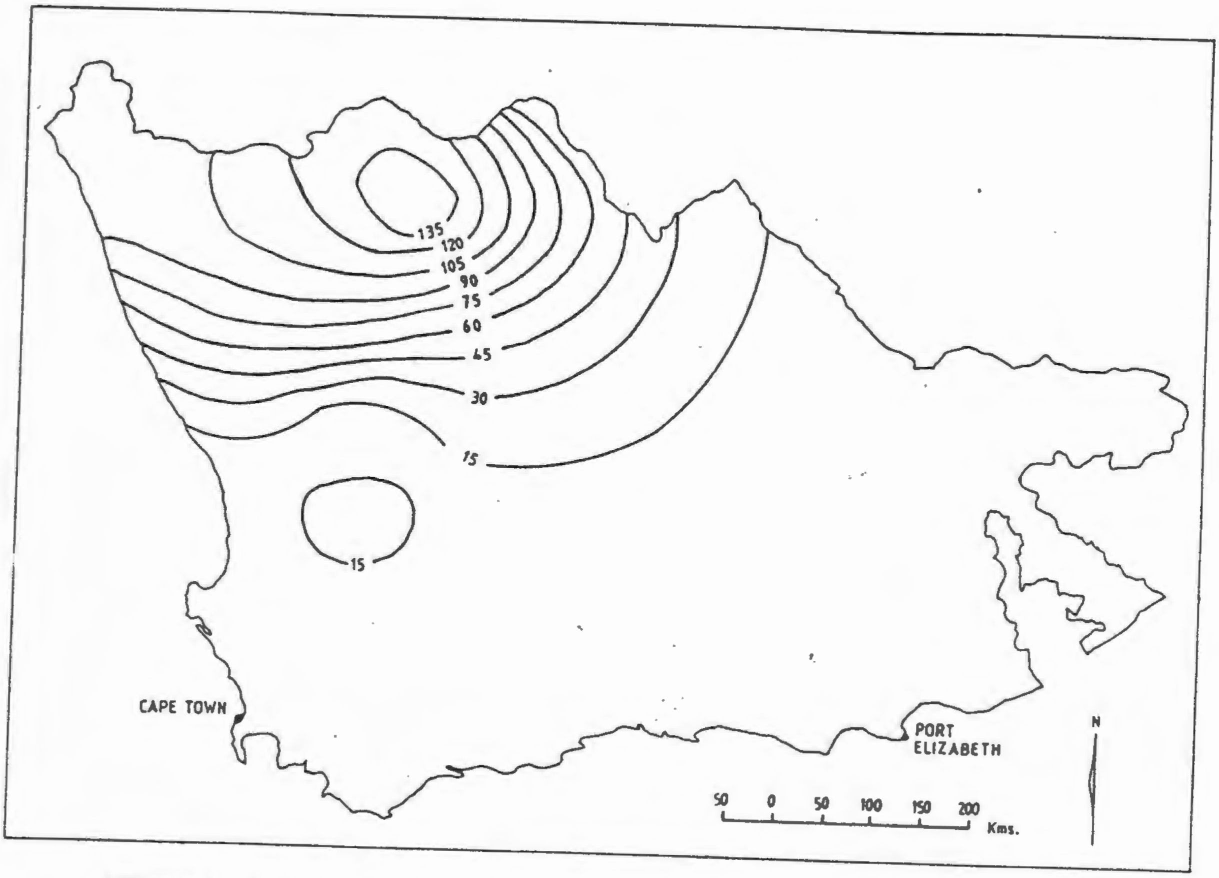


FIGURE 7.1 The Climatic Factor, calculated on an annual basis.

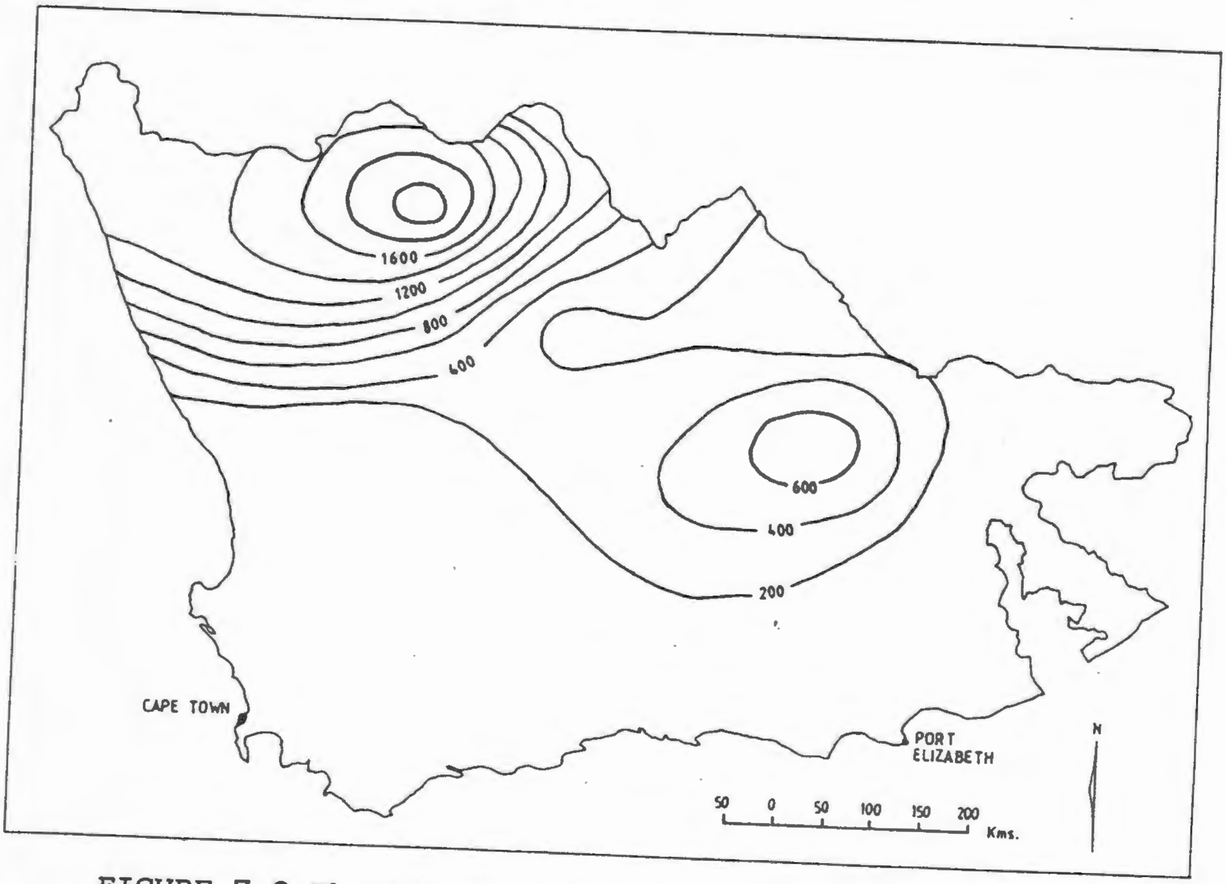


FIGURE 7.2 The Climatic Factor, calculated for the winter months.

If the seasonal climatic factor maps are considered together with the soil and vegetation maps of the province (Figures 5.4 and 5.7) it is apparent that the areas with the highest values of the climatic factor are also most susceptible to wind erosion with regard to soil type and vegetation cover. Figure 5.6 shows the soils of the north western Cape to be sandy or very sandy and as such they are highly susceptible to wind erosion. These soils were initially derived from aeolian deposition and as such they will be readily transported again by wind if the protective vegetation cover is disturbed. The vegetation cover in this area of the province is very sparse due to the aridity and as such is unlikely to offer much protection against the wind. It is clear that all three factors, climate, soil and vegetation, point to the greatest erosion potential occurring in the north west section of the province

Figures indicating monthly variations in the climatic factor were also calculated on an annual and seasonal basis to determine how representative are the values reflected in the maps. Graphs have been produced showing the monthly variations for weather stations from the different seasonal rainfall zones in the province (Figures 7.4, 7.5 and 7.6). Figure 7.4 is a graph of the conditions in the winter rainfall region using the example of Boontjieskraal (34°12'S 19°12'E). From this graph the seasonal differences are clearly apparent. The lines for both the winter and annual climatic factor severely underestimate the wind erosion potential during the summer, whereas the summer climatic factor is an exaggeration of the winter conditions. The curve produced by dividing monthly wind figures by the annual P-E figure also fails to show the difference for the summer conditions. It is clear that the curve produced by dividing the monthly wind figures by the seasonal P-E factor gives the closest representation of actual conditions. For the

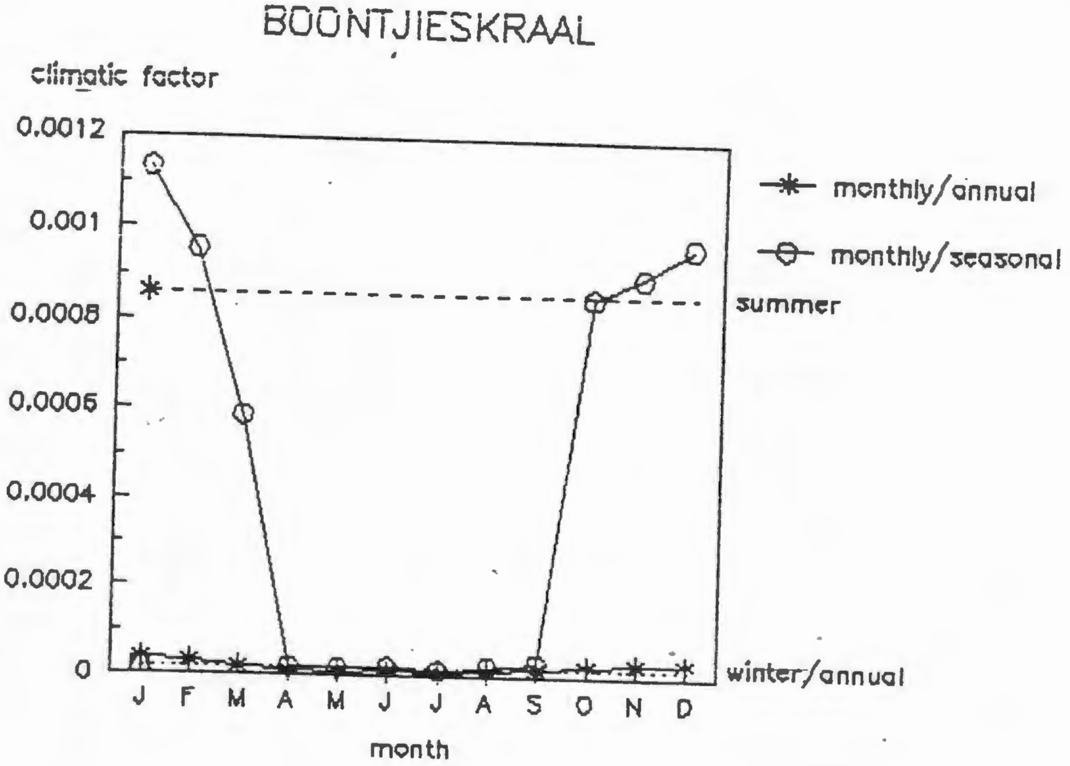


FIGURE 7.4 Graph showing the variations in the calculation of the monthly climatic factor for Boontjieskraal.

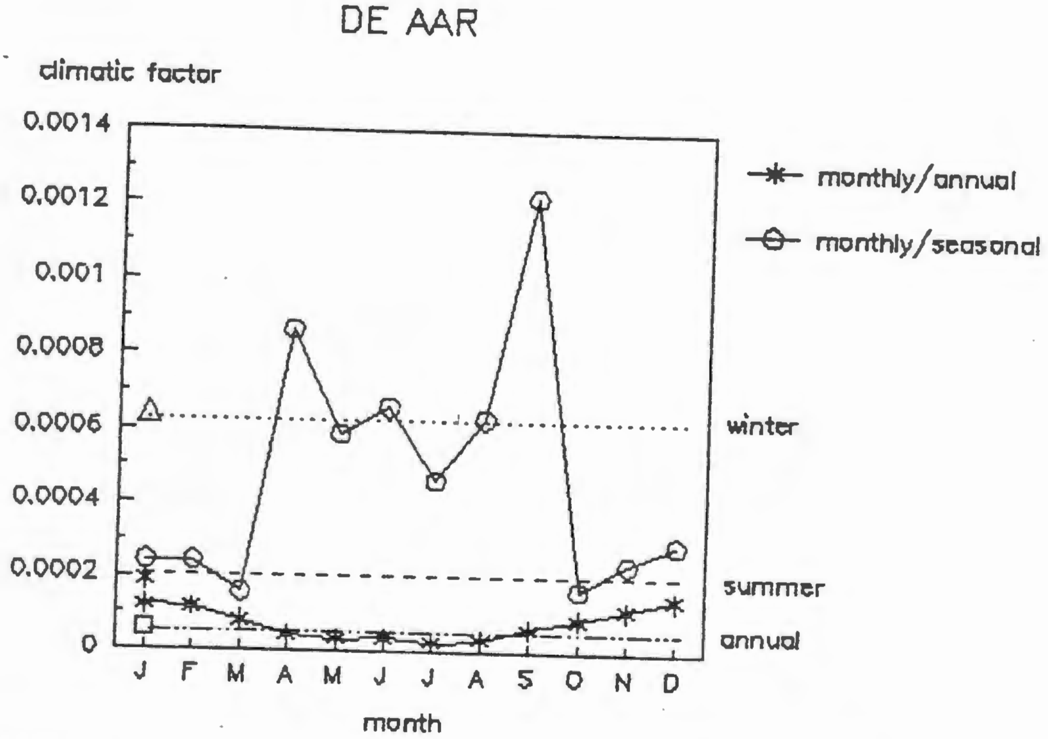


FIGURE 7.5 Graph showing the variations in the calculation of the monthly climatic factor for De Aar.

summer rainfall region as illustrated by conditions at De Aar (30°39'S 24°01'E), the opposite condition exists. The winter climatic figure exaggerates erosion potential during the summer months while the summer figure underestimates erosion during the winter months. The annual climatic figure appears to underestimate conditions throughout the year. As was the case for the previous graph, the best representation of actual conditions is found in the curve reflecting monthly wind figures divided by seasonal P-E. For the all year rainfall region, represented by Kakamas (28°46'S 20°37'E) both the winter and summer climatic figures appear to be representative of actual conditions. The annual climatic figure as well as the monthly curve divided by the annual P-E appear to be very low relative to the other covers and fail to show the true extent of the wind erosion hazard.

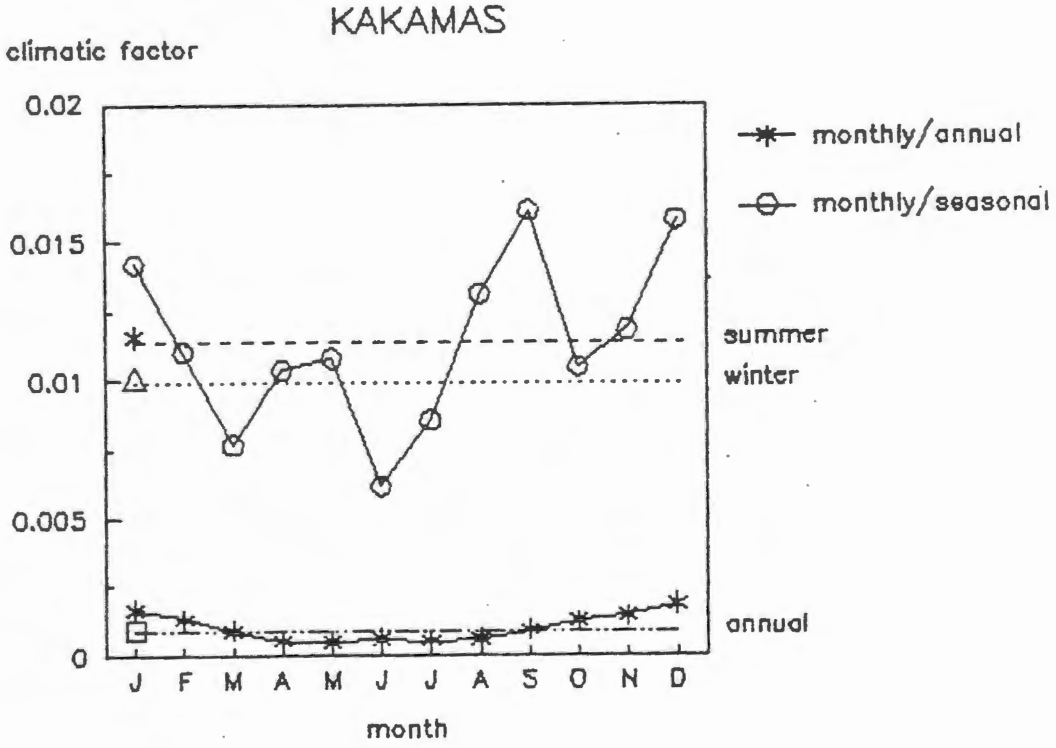


FIGURE 7.6 Graph showing the variations in the calculation of the monthly climatic factor for Kakamas

A summary of the climatic values for each of the weather stations is contained in Appendix C.

No specific calculation of soil erodibility was possible due to a lack of data. Nonetheless a consideration of the maps of the seasonal climatic factor (Figures 7.2 and 7.3) with the soil texture map (Figure 5.6) gives a more detailed picture of the wind erosion hazard. Where the areas of very sandy soil correspond to areas with a high climatic factor, the wind erosion will be highest. It was not possible to illustrate this on a map as there is insufficient detail of the soil textural classes for much of the area under consideration. It is clear, however, that the very sandy areas are those most susceptible to wind erosion as they coincide with the highest values of C.

No attempt was made to consider the effect of vegetation, as no detailed information is readily available on vegetation cover in the different parts of the province. it is likely, however, that the additional information gained through a consideration of vegetation will only provide a further refinement of detail. The distribution of natural vegetation cover is closely related to climate and soils. Agricultural areas are a separate consideration as management aims and practices will directly affect potential erosion rates.

7.2 THE ANALYSIS OF LIMITED CLIMATIC DATA

The seasonal aridity and wind indices were calculated for each of the weather stations (Appendix D). These values were then subject to cluster analysis and regression.

7.2.1 The aridity index

Cluster analysis performed on the aridity index, according to the procedure in the statistical package BMDP, gives 11 distinct groupings. None of these groupings correspond to geographical zones that can be represented clearly on a map (Figure 7.7). In an attempt to explain why the clusters do not correspond to a any logical geographical distribution, regression analysis was performed between the seasonal values of the aridity index, latitude, longitude and latitude and longitude. The correlation coefficients, as shown in Table 7.1, indicate that there is little correlation between location and the aridity index and as such no

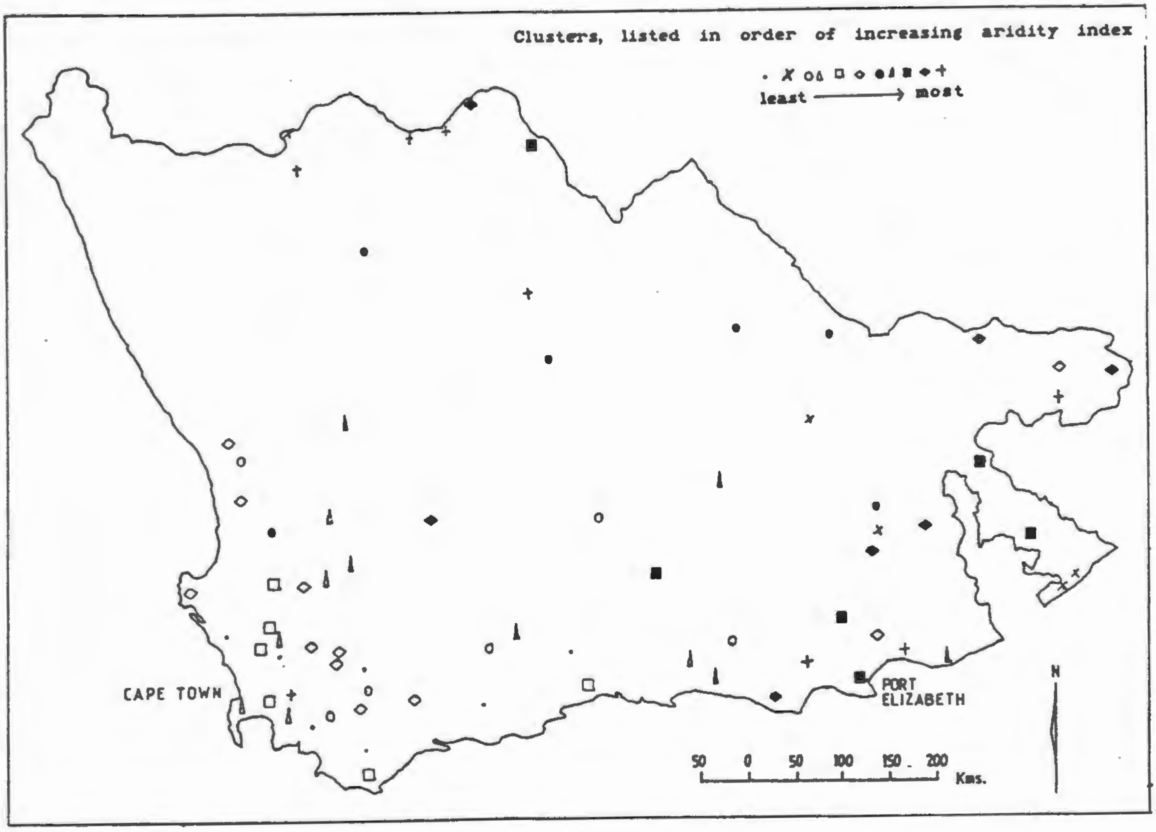


FIGURE 7.7 Clustering of the aridity index

Seasonal aridity index	Latitude	Longitude	latitude * longitude
Summer	-0.407	0.348	0.787
Autumn	-0.316	0.202	0.631
Winter	-0.447	0.479	0.572
Spring	-0.380	0.462	0.522

Table 7.1 Correlation coefficients between latitude, longitude, latitude * longitude and aridity index

An examination of the aridity index figures for the winter and summer shows that they reflect the seasonal rainfall pattern of the province. The weather stations within the winter rainfall region show very low aridity values for the winter months and considerably higher figures for the summer when it is drier. The opposite is the case for the stations that fall within the summer rainfall region. These seasonal differences are, however, not clearly apparent in the clustering of the data.

7.2.2 The wind index

Cluster analysis performed on the wind index gives 6 groupings (Figure 7.8). As in the case of the aridity index, these groupings cannot easily be distinguished on a map. Regression analysis of wind force against latitude, longitude, and latitude and longitude show correlation coefficients to be low and therefore, wind force cannot be expected to follow a distinct geographical trend.

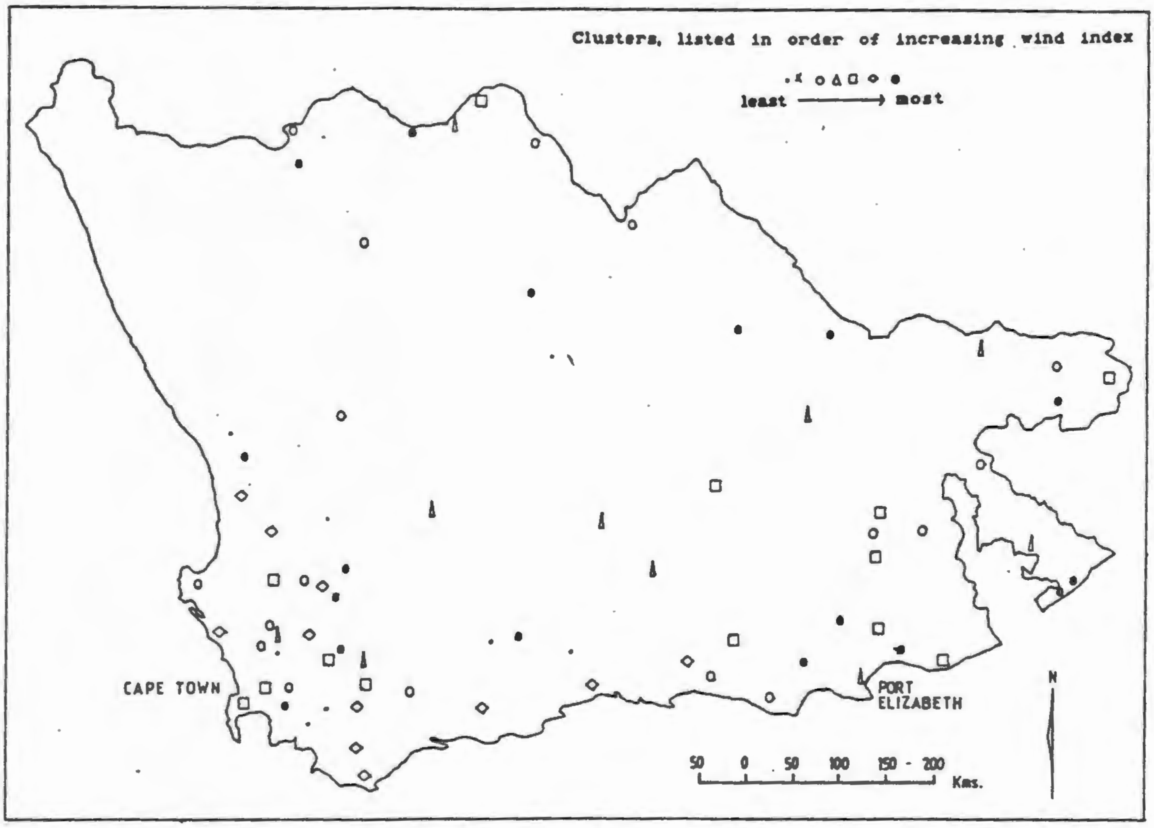


FIGURE 7.8 Clustering of the wind index

Seasonal wind force	Latitude	Longitude	latitude * longitude
Summer	-0.579	-0.147	-0.267
Autumn	-0.563	-0.346	-0.674
Winter	-0.354	-0.155	-0.309
Spring	-0.397	-0.160	-0.581

Table 7.2 Correlation coefficients between latitude, longitude, latitude * longitude and wind force.

7.2.3 The aridity and wind indices

The stations were also classified according to both wind and aridity indices. The classification produced 6 groupings which can be seen in Figure 7.9. As in the case of the previous two indices no distinct geographical trends are readily apparent. It does appear, however, that the stations within the Western Cape are predominantly within the first two clusters which represent the lowest erosion index. The erosion index increases to the north and stations within the highest grouping are found on the banks of the Orange River and on the eastern coast. There is, however, no distinct zonation as was the case in the development and initial application of the model in Australia. Possible reasons for this failure of the model in South Africa will be discussed in the following chapter.

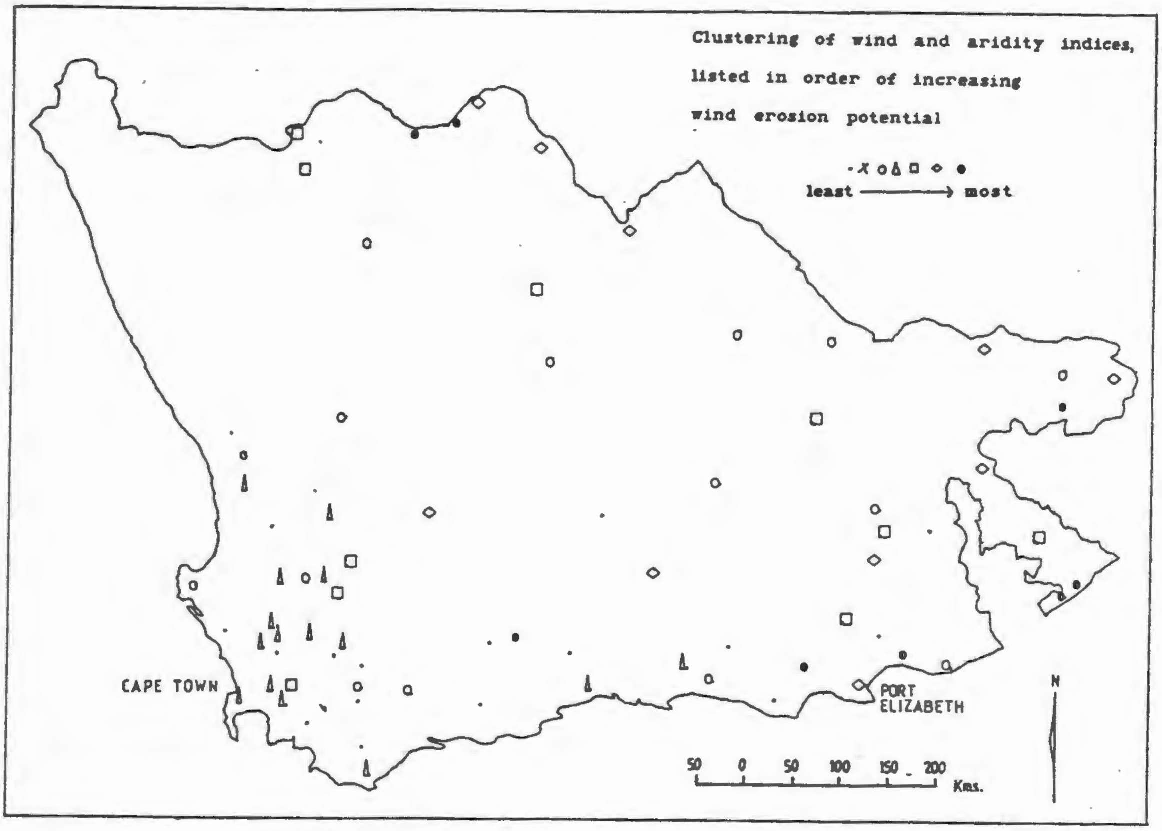


FIGURE 7.9 Clustering of both the aridity and wind indices

7.3 AERIAL PHOTOGRAPHY

Figure 7.10 shows the distribution of wind erosion as indicated by aerial photography. It can be clearly seen that the coasts are areas with a high wind erosion potential. This is due to a natural situation, and not necessarily a reflection of accelerated erosion. The highest wind speeds are found along the coast and there is an abundance of sandy material. As a result coastal dunes are found along much of the coast line. On the other hand, the areas of high wind erosion in the centre of the province reflect poor land management which has resulted in a loss of ground cover and subsequent wind erosion which in turn prohibits the re-establishment of an adequate ground cover.

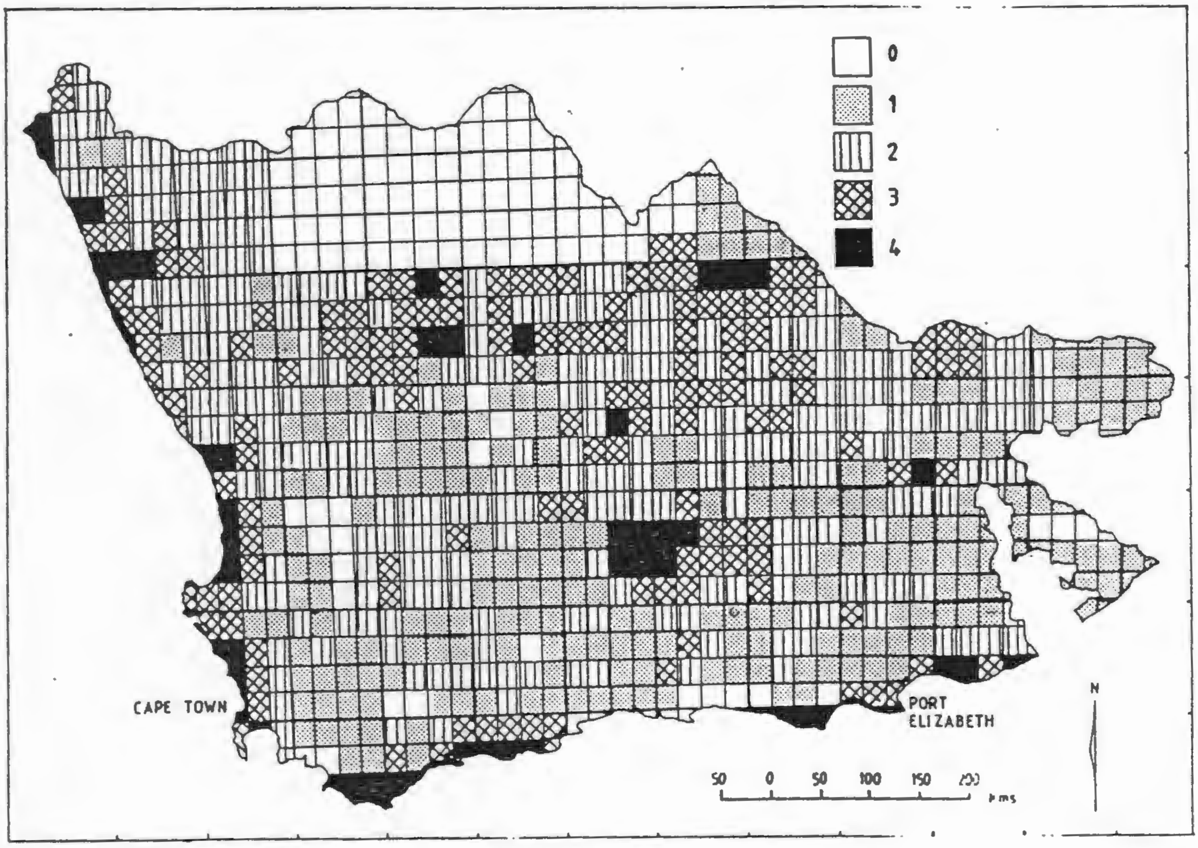


FIGURE 7.10 Wind erosion as observed on the aerial photography

7.4 THE POSTAL SURVEY

There was a relatively good return of the questionnaires. Of the 16 questionnaires sent to agricultural extension officers, 12 were returned, and of the 80 questionnaires passed on to farmers, 46 were returned. The impressions of the extension officers with regard to the severity of the wind erosion hazard are shown in Figure 7.11. In general the farmers considered the wind erosion problem to be less severe than the extension officers (Table 7.3). There is considerable variation between the attitudes of farmers in a single district, this is however partially a reflection of the size of the area and the range of environmental conditions in one district.

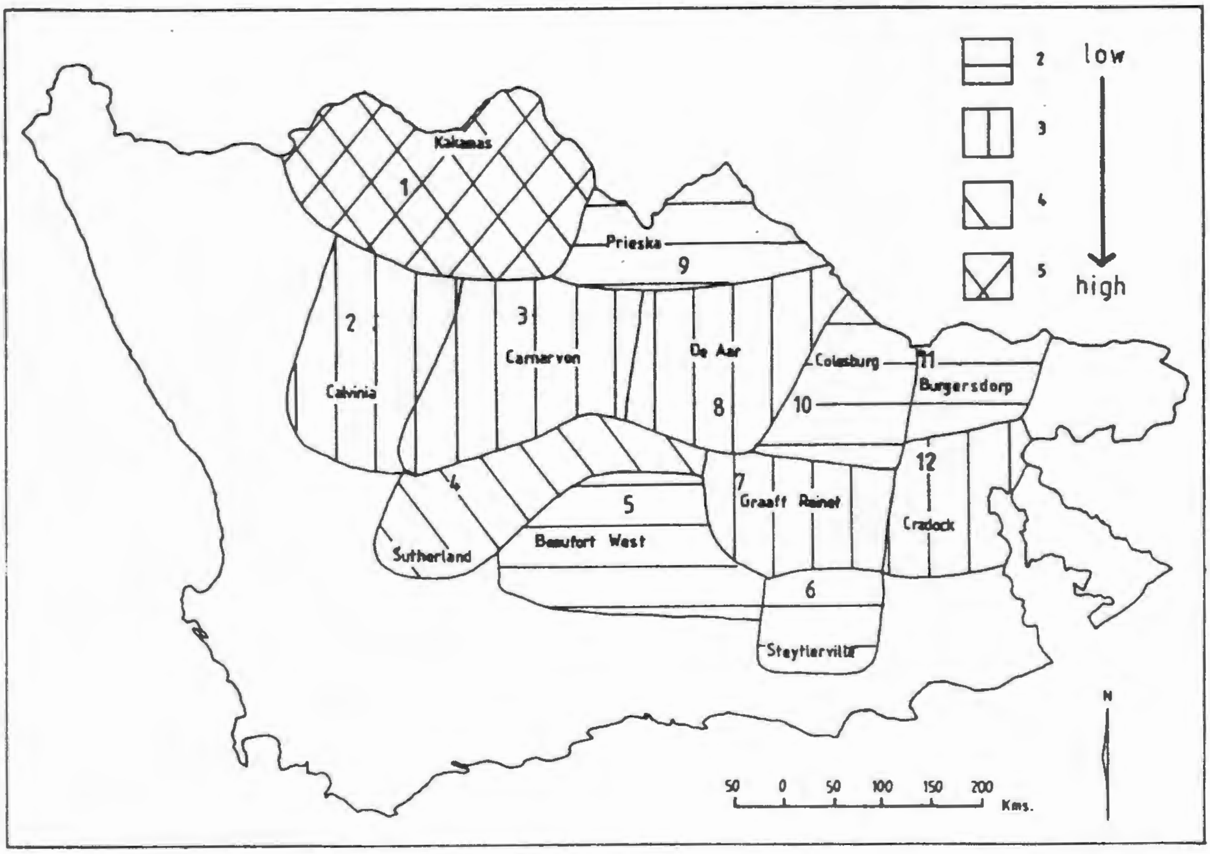


FIGURE 7.11 The impressions of the Agricultural Extension officers with regard to the severity wind erosion problem. The numbers for the district correspond with those referred to in Table 7.3.

It appears that dust devils or whirlwinds are common throughout the province especially in the spring and summer. It is also clear that many farms have extensive bare patches which are highly susceptible to erosion. Farmers in the Kakamas, Hofmeyer and Beaufort West districts also mention having had damage to buildings and equipment by wind abrasion.

District	Farmer's perceptions of the wind erosion problem
1	1, 4, 1, 2, 3
2	2, 3, 1, 2, 1
3[a]	2, 1, 2, 2, 2
4	3, 2, 2, 2
5	2, 2, 3
6	2, 2, 1, 3
7	2, 3, 2
8	3, 3, 2, 3, 2
9	2
10	2, 3, 2
11	2, 2, 2
12	3, 1, 3, 3

(a) District 3 covers both the summer and winter rainfall region and wind erosion is said to be more of a problem in the summer rainfall section.

(b) Erosion was recorded on a scale of 1 to 5 where 1 - no problem, 2 - slight problem, 3 - problem, 4 - serious problem, and 5 - very serious problem

TABLE 7.3 Farmers perceptions of the wind erosion problem according to the districts shown on Figure 7.11.

The way in which these various results come together to produce an overall picture of the wind erosion hazard of the Cape Province will be discussed in the following chapter.

CHAPTER EIGHT

DISCUSSION

It is clear from the previous chapter that the two models produce different assessments of the wind erosion hazard. Since problems were encountered in attempting to apply each of the models, it does not appear that direct application of a model developed elsewhere is possible without modification in regard to localized conditions. It would appear that a more detailed assessment of conditions in the place of development and the place of application are required in order to modify the models accordingly. Factors that are significant to the differences that arise are the seasonality of wind and rainfall regimes, the distribution of data points, veld management and the nature of the data records.

8.1 THE WIND EROSION EQUATION

One of the main problems with the WEE is that the values obtained for the climatic factor are up to 6 orders of magnitude lower than values determined in the United States. Vause (*pers comm*) who is conducting research on wind erosion in the Orange Free State for the Department of Agriculture, encountered a similar problem when attempting to calculate the climatic factor. Values for C obtained in the United States range from 15 to 200 % and even exceed 500 % in some of the desert areas (Lyles 1983). Values produced in the calculation of C are expressed as a percentage of the conditions in Garden City, Kansas. In the Cape Province the values are in the order of 0.000001 to 0.021462 %. This is even lower than values determined by Briggs and France (1982) in Nottinghamshire and East

Anglia. They calculated values of 0.0084 for Sheffield and 0.1792 for Finningley.

It is not clear why the values for South Africa are so low. It may well be that it is the loss of detail in the calculation of annual figures which partially accounts for the low values, as the highest values were produced in the calculation of the seasonal and monthly figures. Given the nature of the rainfall distribution in the province these seasonally-derived values are likely to be more representative.

In an attempt to determine why the differences between the calculated factors for the Cape and for the U.S.A. are so great, the climatic factor was computed for summary data obtained for Phoenix, Arizona and for Upington, Cape (Muller 1982). The data and the value of C are contained in Table 8.1. It can be seen that in this calculation the climatic factor obtained for Upington (0.23%) is marginally higher than that obtained for Phoenix (0.17%). The average monthly windspeed and P-E value in Upington are marginally higher than that of Phoenix, thus accounting for the difference. These differences are, however, insignificant. What is of concern, however is that the calculation of the climatic factor for Phoenix is also considerably lower than that shown on the map of the climatic factor in the U.S.A., C = 72-150 % (Figure 4.3). As the calculation was performed as documented, it is not clear why this discrepancy has arisen.

What is of interest is the difference in values obtained for Upington using the data obtained by the Department of Agriculture at Elsenberg and those contained in Muller (1982). The differences are shown in Table 8.2. The t test was calculated to determine whether they belong to the same population. It was found that for the precipitation and temperature figures there is no significant difference at a 99%

confidence interval, however there is a strong difference for the windspeed. The wind speeds contained in the Department of Agriculture data are considerably lower. The data in this study have been converted to m s^{-1} from wind run and it appears that this is not an accurate reflection of average windspeeds. It thus appears, that as a result, the windspeed has been underestimated throughout the calculations. Wind run is a cumulative monthly figure and as such it does not indicate the strength and duration of individual wind events, which are important considerations with regard to wind erosion. The available weather records are thus inappropriate for the calculation of the climatic factor. Nonetheless the windspeed figures used throughout this model are all based on wind run and as such it is of interest to examine the values <u>relative</u> to each other throughout the province. On this basis it is assumed that the values of the climatic factor can only be used qualitatively, indicating an increased wind erosion potential in the northern portions of the province.

Upington

	TEMP	RAIN	WIND	P-E	Monthly C
JAN	27.8	25	2.5	1.4139	0.00022
FEB	25.7	40	2.5	2.5292	0.00022
MAR	24	37	2.2	2.4407	0.00015
APR	19.7	27	1.7	1.9794	0.00007
MAY	14.9	11	1.7	0.8754	0.00007
JUNE	11.7	3	1.7	0.2379	0.00007
JULY	10.6	5	2.2	0.4419	0.00015
AUG	13.4	4	2.2	0.3033	0.00015
SEPT	17.4	3	2.5	0.1876	0.00022
OCT	21	11	2.2	0.6989	0.00015
NOV	24.2	16	2.8	0.9566	0.00032
DEC	26.1	22	2.8	1.2874	0.00032
YEAR			2.2	1535.5	

C = 0.00015

Phoenix

TEMP	RAIN	WIND	P-E	Monthly C
10.4	19	2	1.9641	0.00011
12.5	22	2	2.0943	0.00011
15.8	17	3	1.3688	0.00038
20.4	8	3	0.5008	0.00038
25	3	3	1.4564	0.00038
29.8	2	3	0.0811	0.00038
32.9	20	3	0.9661	0.00038
31.7	28	3	1.4462	0.00038
29.1	19	3	1.0063	0.00011
22.3	12	2	0.7377	0.00011
15.1	12	2	0.9564	0.00011
11.4	22	2	2.2028	0.00011
		2	1549.1	

C = 0.00011

TABLE 8.1 Summary climatic data for Upington, Cape and Phoenix, Arizona and the calculation of P-E and the climatic factor (C).

	TEMP-A	TEMP-B	RAIN-A	RAIN-B	WIND-A	WIND-B
JAN	27.8	26	25	22.1	2.5	1.4
FEB	25.7	24.6	40	28.6	2.5	1.2
MAR	24	22.5	37	33.3	2.2	1
APR	19.7	18.7	27	15.3	1.7	0.9
MAY	14.9	14.8	11	11.8	1.7	0.8
JUNE	11.7	13.1	3	3.8	1.7	0.9
JULY	10.6	11.2	5	2.1	2.2	1
AUG	13.4	12.8	4	8.3	2.2	1
SEPT	17.4	17.8	3	5.7	2.5	1.3
OCT	21	19.4	11	9	2.2	1.6
NOV	24.2	22.6	16	22.1	2.8	1.6
DEC	26.1	25	22	14.3	2.8	1.7
MEAN	19.7	19	17	14.7	2.3	1.2
ST. DEV	5.8	5	12.6	9.5	0.4	0.3
t	0.29		0.48		7.22	

TABLE 8.2 Differences in the climatic data for Upington. (a) data obtained in Muller (1982) and (b) data obtained from the Department of Agriculture. Values obtained in the calcu lation of the t test are shown (t critical = 2.508).

With regard to the figures shown on the contour maps, they are a reflection of the relative wind erosion hazard on an annual and seasonal basis. Due to problems with values that were too low for the contour program to pick up differences between weather stations, the values had to be increased by 5 orders of magnitude. As a result it is the relative nature of the maps that is of interest, rather than the actual figures, except to note the extent to which the seasonal values are higher than the annual figures.

The inclusion of the soil and vegetation maps in order to produce a broader assessment of the wind erosion hazard would not alter the picture portrayed in section 5.1. The fact that the soils of much of the province are sandy to very sandy acts to increase the likelihood of erosion. Vegetation cover is sparse due to the aridity and the effects of overgrazing which also contributes to the susceptibility to wind erosion. It thus seems that a consideration of the climatic factor along provides an initial basis for the potential wind erosion hazard, however a broader view is required for a more detailed assessment. A consideration of wind erosion on a smaller scale requires a detailed examinations of soils and the vegetation factor as cropped areas would differ from areas under natural vegetation in their susceptibility to wind erosion. The nature of the natural vegetation and the extent of the protective cover that it offers would also have to be assessed as, in the Karoo region, it is highly dependent on management. It is only through a more detailed approach that individual land owners could design specific soil conservation strategies.

A comparison of the results of the WEE with those from the aerial photography illustrates that a considerable variation exists. This is, however, not entirely unexpected as the wind erosion equation as calculated in this project is based primarily on a consideration of climatic factors. On the other hand, in the aerial photography, climate is a secondary factor and it is conditions as they exist on the ground that are observed. A trend of increasing wind erosion to the north west can be determined on the photography, although much of the photography from a large section bordering the Orange River is unavailable at the appropriate scale. It is also apparent from the photography that, for the inland areas, management and land use have the greatest impact on erosion. This can be seen in the difference in erosion patterns in similar areas separated by a farm boundary. It is not directly clear from the photography whether the erosional scarring is due to wind or water. It was, however, assumed that areas of little or poor vegetative cover are subject to wind erosion anyway, even if the main driving force is water erosion. Rubidge (*pers comm*), a Karoo farmer from the Richmond district, states that once an area is exposed, it will be subject to erosion by both water and wind. It is not always possible to determine which is the dominant factor as it varies seasonally.

The importance of management with regard to erosion is supported by comments made by farmers on the questionnaire. A farmer in the Graaff Reinet district states that "wind does not cause erosion, but is a result of poor grazing practices over the past 300 years". Another farmer in the Cradock district adds that "there is a direct correlation between wind erosion and veld conservation. Well preserved veld is far less susceptible to wind erosion". This would suggest that, although natural features determine whether an area is susceptible to wind erosion, it is the way in which the land is managed which determines whether erosion actually occurs. This is a limitation in the use of the Wind Erosion Equation model, as only the climatic and physical factors are considered. This problem would however, be overcome in the calculation of wind erosion on a local scale where field width and ridge roughness and a more detailed assessment of soil and vegetation, would be included in the calculation. Nonetheless on a broader scale, the model does indicate the sensitive areas in which management must be aware of the wind erosion hazard, as such it provides a useful approach for a preliminary assessment of wind erosion.

A problem encountered in the application of both of the models was the paucity of climatic data especially in the Karoo region. The South Western Cape has a very detailed cover by agricultural weather stations, as does the Southern and Eastern Cape although to a lesser degree. In the central and northern Karoo and Namaqualand, however, farms are very large and many areas have no weather stations or a very broken record with many gaps. As such the data base is inadequate to give an accurate description of actual climatic conditions. This is a serious limitation as one of the characteristics of a semi-arid or arid region is a rainfall distribution that is highly variable in time and space. As a result, extrapolation of data can be very misleading. The distribution of data points is also problematic in that there is a high density of weather stations in the southern Cape which tends to bias the analysis. The degree of extrapolation in the north and the variability of conditions over short distances is lost.

8.2 THE ANALYSIS OF LIMITED CLIMATIC DATA

Lynch and Edward's model was designed to overcome the problem of a limited data base. Semi-arid areas throughout the world are characterised by a sparse population distribution and as a result they have a limited climatic data base. Ironically, they are also the areas with the greatest wind erosion potential due to the aridity and poor vegetation cover. It is thus important to be able to assess the wind erosion hazard. The attempt to adapt this model to South African conditions was however unsatisfactory.

Maps of the rainfall distribution and evaporation show a distinct trend of increasing aridity to the north west. This trend is however poorly represented in the model, when applied in South Africa. Although the north western weather stations do appear in the groupings representing the highest wind erosion, there is no gradual zonation in which wind erosion is shown to increase towards the north. There is, however, a great deal of disparity between weather stations which are very close together. This is probably in part due to the fact that topography and orientation are not taken into consideration in the model. This is a problem in South Africa as much of the rainfall in the coastal zone is orographic. It is thus the location of the weather station with regard to the mountains which determines the moisture balance. The complex nature of the terrain in the South Western Cape makes it difficult, therefore, to place the weather stations into different zones.

Another factor which appears to have affected the effectiveness of the model is the seasonality of the rainfall pattern. This is illustrated to some degree in the regression analysis, through the differences in the correlation coefficients for the various seasons. In the clustering of the data, however, it appears that it is the overall moisture balance and wind force which is considered and seasonal differences are not noted. In other words, a weather station which has for example an aridity index of 0.37 in the summer and of 0.0 for the remaining seasons, and a station with an aridity of 0.37 in the winter with the remaining stations 0.0, will appear in the same cluster. In this manner the seasonal differences between the various weather stations are lost. Although this is a true reflection of the overall wind erosion index, the resulting maps of the different clusters is not an accurate reflections of the wind erosion index due to the seasonal rainfall distribution. It would thus be more appropriate to consider seasonal maps.

Moisture conditions are variable from year to year, a factor which is not taken into consideration in either of the models except for the requirement that a minimum of five years of record are necessary. The Karoo region is subject to frequent periods of drought (Venter *et al* 1986). Drought is defined to be a period in which the 12-month rainfall total is below 60 % of the average annual rainfall. Although the use of the term drought tends to be overused it is clear that the Karoo is subject to highly variable rainfall and that extended dry periods are common. It has been shown by a number of authors (Tyson and Dyer 1975, Tyson 1981, Louw 1980) that there is an apparent 15-20 year rainfall cycle with extended wet and dry periods of 9-10 years duration. It is thus part of the natural rainfall cycle of the region for there to be extended dry periods. The use of the term drought implies that it is considered to be an abnormal situation which requires special assistance for farmers. The effect of this on the veld is that stressed areas are even more stressed during these periods and wind erosion becomes a more serious problem. During drier periods, vegetation cover decreases and soil moisture levels are lower so that the wind erosion potential increases. This is illustrated by the questionnaires in that a number of farmers rated the wind erosion hazard differently for periods of drought and commented that dust devils were more common during the drought.

The cyclical nature of the rainfall pattern has implications for the application of both of the models to the conditions of the Cape Province. In both models the wind erosion figures are reached by averaging conditions over the number of years of record and in doing so the differences between the wet and dry periods are lost. There is also a problem which arises out of the fact that not all of the stations have the same length of record. Those weather stations whose record covers only a dry period, which has been the case for much of the 80's, will show a higher wind erosion hazard than those stations whose record extends further back and also includes a wet period. It thus appears that a detailed understanding of the climatic patterns, in time and space, and how they differ with regard to the area in which the model was developed are necessary in order to adapt the model for the local conditions. It would be better to have all the photography taken in the same period in order to eliminate the effects of climatic variability on evidence of erosion.

8.3 AERIAL PHOTOGRAPHY

The aerial photography provides a good means of determining which areas of the province are affected by severe erosion. The distribution of erosion as indicated by the aerial photography is different to those of the other models. The importance of wind as a geomorphological agent along the coastline is clearly evident. Although not necessarily indicative of actual erosion, it does illustrate that potential wind erosion is high in these areas, which the climatic models failed to pick up. On the other hand, the photography supports the models as it is clear that the north western portions of the province suffer from erosion. There are, however, other areas in the centre of the province which are highly eroded. In these areas, management appears to be more important than climate and natural features in giving rise to erosion. This has implications for the usefulness of the models as it does not appear that climate is the sole factor behind erosion, although it is important for determining the susceptibility of an area to erosion.

It is recommended, therefore, that a more detailed assessment of erosion using aerial photography should be conducted in order to highlight the problem areas. This should then be combined with a consideration of the climatic conditions, physical features and management as the most appropriate means of examining erosion on a local scale. A detailed mapping of erosion can provide the necessary information required to establish effective soil conservation measures.

8.4 POSTAL SURVEY

It is difficult to assess the usefulness of the questionnaire in light of the fact that the models are problematic. This research has highlighted the importance of management as a factor giving rise to erosion. The picture presented by the results of the survey is very broad. It does support the general trend of increased wind erosion in the north. The questionnaire, however, was not detailed enough with regard to the layout of the farm, its topography, rainfall and soil characteristics and management approaches and objectives. It would help in the assessment of the perceptions of farmers of soil erosion, if their attitudes towards conservation farming were known. An individual's perceptions will also be greatly affected by their expectations, a factor which was not incorporated in the questionnaire.

Nonetheless the results of the questionnaire are of interest in that they show that wind erosion is generally rated as a slight problem or problem. It also illustrates the complexity of the problem in that, although virtually all the farmers report seeing dust devils, not all equate this with a wind erosion problem. It would be of interest to conduct a detailed assessment of erosion in a small area and to examine people's attitudes to and perceptions of the problem against that background.

CHAPTER NINE

CONCLUSIONS

In conclusion it must be said that from the methods used in this study it is not possible to produce a clear map of the wind erosion hazard in the Cape Province. It is of interest to note that although neither of the models indicate that there is a severe wind erosion hazard in the Cape Province, observations and reports indicate otherwise. The author would go as far as to suggest that virtually the entire province, with the possible exception of the all year rainfall zone and the forested areas, is susceptible to wind erosion.

This conclusion is based on observations made while driving through various parts of the province and from comments made by various individuals throughout the course of this research. For example, the susceptibility of the Cape Flats area to the east of Cape Town has been clearly illustrated by the problems of blowing sand during the extensive road construction that has been ongoing for the past few years. The complaints of the residents of Khayelitsha and of communities on the western side of Cape Town will also attest to the problems of wind erosion. This, however, need not be an ongoing problem, as once construction has been completed and vegetation has been established, much of the blowing sand should be controlled. A close examination of many parts of the Karoo, on the other hand will reveal ripple marks on exposed areas, the accumulation of sand and debris at the base of bushes and where sand blasting is severe the loss of bark on the downwind side of some bushes. This is evidence that wind erosion has been a long term problem.

That the problem goes unnoticed by people in many areas including the Karoo is not surprising due to the insidious nature in which the effects of wind erosion accumulate. Nonetheless it is surprising that the models fail to adequately reflect actual conditions. It is for this reason that the author concludes that in the Karoo and inland areas of Namaqualand, management is the primary factor responsible for wind erosion.

Acocks (1953, 5-6), in his oft quoted treatise on the Veld types of South Africa discusses the effect of improper management. He regards continuous selective grazing as having had three main impacts in the Karoo. Firstly, it has changed the species composition of the veld so that good grazing species have been replaced by less useful ones. Secondly soil cover has been reduced giving rise to a loss of water through run-off, sheet erosion and <u>wind erosion</u>. The net result is a silting of rivers and a scouring of channels which has increased donga formation.

It thus appears that the effects of improper management have long been an issue of concern and that even in the 1950's it was apparent that management was a significant factor in giving rise to erosion and veld degradation.

South Africa is an arid country. Most of the Cape Province falls into either a summer or winter rainfall zone and as a result different parts of the province are particularly arid at different times during the year. It is during the dry season that the wind erosion hazard is most severe. South Africa also experiences a cyclical rainfall pattern of 18-20 years duration. It is during the 9-10 year dry period that the wind erosion hazard is greatest. Climatic data are notoriously poorly behaved in their statistical properties (Venter *et al* 1986). As a result they should be regarded with caution and not used for predictive purposes. Nonetheless as veld conditions cannot be changed immediately it seems important that management guidelines be based on maintaining an adequate ground cover during the drier years so as to avoid excessive erosion during these periods.

It is suggested that further research is required with regard to grazing management in the Karoo. It is essential that one of the goals of management be veld conservation in order to improve and retain the productivity of the Karoo. It is only by doing so, that the threat of increasing desertification of which wind erosion is only a part, can be brought under control.

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APPENDICES

APPENDIX A

Dear Sir,

I am investigating the wind erosion problem in the Cape Province. The aim of my research is to produce a map illustrating the risk of wind erosion according to climatic factors, soil conditions and land use.

In order to test the methods I have used I need to compare my data with people's perceptions of the extent and seriousness of wind erosion. Could you please take the time to answer the enclosed questionnaire and return it to me in the self addressed, stamped envelope enclosed.

I would also appreciate it if you could pass on the enclosed questionnaires and envelopes to 5 farmers from different parts of your district as I am interested in hearing the different opinions of farmers as well as those of the extension officers. I would appreciate it if you could reply as soon as possible as it is neccessary for me to have the information by August 31.

Thanking you in advance,

Geagte heer,

Ek is besig om die probleem van winderosie in die Kaap-provinsie te ondersoek. Die einddoel van my navorsingsprojek is om 'n kaart wat die risiko van winderosie na aanleiding van klimatiese faktore, grondkondisies en landgebruik illustreer, saam te stel.

Ten einde die metodes wat ek gebruik het te toets is dit nodig om my data met andere se persepsies van die omvang en ernstigheid van winderosie te vergelyk. Sal u asseblief die tyd neem om die ingeslote vraelys te beantwoord en dit in die selfgeadresseerde gefrankeerde koevert aan my terug te stuur.

Ek sal dit ook waardeer indien u die ingeslote vraelyste en koeverte aan 5 boere van verskillende dele van u distrik kan oorhandig/aanstuur want ek stel daarin belang om die verskeie menings van boere sowel as uitbreidingsbeamptes te verkry. Ek sal dit op prys stel as u so spoedig moontlik kan antwoord want die inligting word teen 31 Augustus benodig.

By voorbaat baie dankie,

****

QUESTIONNAIRE

Please circle the appropriate response or write in the requested information

1. Do you consider wind erosion to be a problem in your area?

no problem	slight problem	problem	serious	very serious

2. a. Are there patches of bare soil on the farms in the area?

yes / no

b. [If yes], please comment on their size and number.

----

3. a. Do you ever see dust devils or sand storms in your area?

yes / no

b. [If yes], Please indicate at what time of year they are more common.

winter spring summer autumn

4. Is there any evidence of damage from wind abrasion on farm buildings, signs or equipment in the area?

yes / no

5. What is the size of the area that you cover and where is it located (give latitude and longitude, or name(s) of nearest town(s))?

----

6. How long have you been doing extension work in the area?

years

7. What is the main farming activity in the area?

APPENDIX B

Dear Sir,

I am investigating the wind erosion problem in the Cape Province. The aim of my research is to produce a map illustrating the risk of wind erosion according to climatic factors, soil conditions and land use.

In order to test the methods I have used, I need to compare my data with people's perceptions of the extent and seriousness of wind erosion.

Could you please take the time to complete the enclosed questionnaire and then return it to me as soon as possible in the stamped envelope provided?

Thanking you in advance,

Geagte heer,

Ek is besig om die probleem van winderosie in die Kaap-provinsie to ondersoek. Die einddoel van my navorsingsprojek is om 'n kaart wat die risiko von winderosie na aanleiding van klimatiese faktore, grondkondisies en landgebruik illustreer, saam te stel.

Ten einde die metodes wat ek gebruik het te toets is dit nodig om my data met andere se persepsies van die omvang en ernstigheid van winderosie te vergelyk.

Sal u asseblief die tyd neem om die ingeslote vraelys te beantwoord en dit in die selfgeadresseerde gefrankeerde koevert aan my terug te stuur.

By voorbaat baie dankie,

****

QUESTIONNAIRE

Please circle the approporiate response or write in the requested information.

1. Do you consider wind erosion to be a problem on your farm?

no problem	slight problem	problem	serious	very serious

2. a. Are there patches of bare soil on your farm?

yes / no

b. [If yes] Please comment on their size and number.

----

3. a. Do you ever see dust devils or sand storms on your farm?

yes / no

b. [If yes] Please indicate at what time of year they are more common.

winter spring summer autumn

4. Is there any evidence of damage from wind abrasion on farm buildings, signs or equipment?

yes / no

6. What kind of farming do you do?

----

7. How long have you been farming in the area?

years

8. Where is your farm located?

****

APPENDIX C

Die Landbouvoorligter
Posbus 66
Beaufort-Wes, 6970

Die Landbouvoorligter
Posbus 201
Burgersdorp,5520

Die Landbouvoorligter
Posbus 65
Calvinia, 8190

Die Landbouvoorligter
Posbus 122
Carnarvon,7060

Die Landbouvoorligter
Posbus 5
Colesberg,5980

Die Landbouvoorligter
Posbus 131
Cradock,5880

Die Landbouvoorligter
Posbus 84
De Aar,7000

Die Landbouvoorligter
Posbus 116
Fraserburg, 6960

Die Landbouvoorligter
Posbus 139
Graaff-Reinet,6280

Die Landbouvoorligter
Posbus 22
Jansenville,6265

Die Landbouvoorligter
Posbus 92
Kenhardt,8900

Die Landbouvoorligter
Posbus 6
Laingsburg,6900

Die Landbouvoorligter
Posbus 193
Middelburg,5900

Die Landbouboorligter
Posbus 176
Prieska,8940

Die Landbouvoorligter
Posbus 133
Somerset-Oos,5850

Die Landbouvoorligter
Posbus 47
Victoria-Wes,7070

APPENDIX D

Listing of the weather stations and the calculations of the climatic factor.
For each station, the name is followed by the latitude and longitude and the calculation of the climatic factor on an annual and seasonal basis according to the different methods discussed in the text.

```
     BOONTJIE   3412      1921

     ANNUAL  WINTER  SUMMER    JANUARY  FEBRUARY MARCH    APRIL    MAY      JUNE     JULY     AUGUST   SEPTEMBEROCTOBER  NOVEMBER DECEMBER
1973 0.00006 0.00006 0.002301  ANNUAL
1974 0.00001 0.00000 0.000502  0.000039 0.000031 0.000019 0.000009 0.000009 0.000011 0.000008 0.000012 0.000017 0.000027 0.000030 0.000032
1975 0.00002 0.00001 0.001848
1976 0.00001 0.00001 0.000260  SEASONAL
1977 0.00001 0.00001 0.000308  0.001132 0.000954 0.000587 0.000017 0.000015 0.000019 0.000013 0.000021 0.000029 0.000855 0.000900 0.000966
1978 0.00002 0.00002 0.001402
1979 0.00001 0.00002 0.000214
1980 0.00002 0.00002 0.000462
1981 0.00000 0.00001 0.000109
1982 0.00002 0.00001 0.003239
1983 0.00001 0.00000 0.000873
1984 0.00001 0.00001 0.000153
1985 0.00000 0.00000 0.000103
1986 0.00000 0.00000 0.000256

AVG  0.00001 0.00001 0.000859


     CITRUSDA   3234      1859

1964 0.00005 0.00005 0.001238  ANNUAL
1965 0.00004 0.00002 0.015184  0.000045 0.000035 0.000023 0.000013 0.000005 0.000004 0.000005 0.000009 0.000015 0.000025 0.000037 0.000040
1966 0.00001 0.00001 0.002791
1967 0.00001 0.00001 0.001874  SEASONAL
1968 0.00008 0.00005 0.003948  0.003135 0.002792 0.001608 0.000019 0.000008 0.000007 0.000007 0.000014 0.000022 0.001621 0.002558 0.002574
1970 0.00002 0.00001 0.007559
1971 0.00003 0.00001 0.007799
1972 0.00002 0.00001 0.002384
1973 0.00001 0.00001 0.000870
1974 0.00000 0.00000 0.000788
1975 0.00000 0.00000 0.001303
1976 0.00000 0.00000 0.000056
1977 0.00000 0.00000 0.000310
1978 0.00001 0.00000 0.000937
1979 0.00001 0.00000 0.000963
1980 0.00000 0.00000 0.000312
1981 0.00000 0.00000 0.002513
1982 0.00000 0.00000 0.000144
1983 0.00000 0.00000 0.001422
1984 0.00000 0.00000 0.000081
1985 0.00000 0.00000 0.000103
1986 0.00000 0.00000 0.001763
```

```
AVG   0.00001 0.00001 0.002470


      CONCORDI    3341       1951

1980 0.00000 0.00002 0.000044   ANNUAL
1981 0.00000 0.00000 0.000007   0.000004 0.000004 0.000003 0.000003 0.000005 0.000005 0.000005 0.000005 0.000006 0.000005 0.000005 0.000006
1982 0.00000 0.00000 0.000121
1983 0.00000 0.00000 0.000525   SEASONAL
1984 0.00000 0.00002 0.000051   0.000112 0.000148 0.000086 0.000009 0.000014 0.000012 0.000012 0.000014 0.000016 0.000098 0.000095 0.000126
1985 0.00000 0.00000 0.000011
1986 0.00000 0.00001 0.000065

AVG   0.00000 0.00001 0.000118


      DARLING     3323       1823

1982 0.00003 0.00002 0.001674   ANNUAL
1983 0.00001 0.00001 0.001200   0.000036 0.000039 0.000029 0.000013 0.000008 0.000006 0.000005 0.000006 0.000012 0.000026 0.000029 0.000031
1984 0.00001 0.00001 0.000351
1985 0.00001 0.00000 0.000858   SEASONAL
1986 0.00001 0.00000 0.002968   0.001721 0.001608 0.001092 0.000019 0.000012 0.000009 0.000008 0.000010 0.000018 0.000039 0.001257 0.001498

AVG   0.00001 0.00001 0.001410


      DE DOORN    3328       1940

1965 0.00003 0.00005 0.000387   ANNUAL
1966 0.00002 0.00002 0.002782   0.000028 0.000021 0.000015 0.000010 0.000008 0.000010 0.000015 0.000024 0.000026 0.000030 0.000028 0.000032
1967 0.00002 0.00003 0.002194
1968 0.00002 0.00002 0.000730   SEASONAL
1969 0.00008 0.00014 0.000754   0.001322 0.001018 0.000738 0.000019 0.000015 0.000017 0.000025 0.000045 0.000049 0.001256 0.001310 0.001434
1970 0.00002 0.00002 0.006192
1971 0.00002 0.00002 0.001189
1972 0.00006 0.00006 0.004587
1973 0.00001 0.00002 0.001287
1974 0.00000 0.00000 0.001001
1975 0.00001 0.00001 0.000463
1976 0.00000 0.00000 0.000044
1977 0.00000 0.00000 0.000386
1978 0.00002 0.00004 0.000259
1979 0.00001 0.00001 0.001408
1980 0.00001 0.00003 0.000072
1981 0.00000 0.00000 0.000039
1982 0.00000 0.00000 0.000536
1983 0.00000 0.00000 0.000520
1984 0.00000 0.00000 0.000036
1985 0.00000 0.00000 0.000022
1986 0.00000 0.00000 0.000192

AVG   0.00001 0.00002 0.001140
```

```
      DE KEUR     3258       1918

1975 0.00000 0.00000 0.000032   ANNUAL
1976 0.00000 0.00000 0.000012   0.000003 0.000002 0.000002 0.000001 0.000002 0.000002 0.000003 0.000004 0.000003 0.000003 0.000002 0.000003
1977 0.00000 0.00000 0.000104
1978 0.00000 0.00000 0.000042   SEASONAL
1979 0.00000 0.00000 0.000258   0.000188 0.000153 0.000139 0.000003 0.000004 0.000005 0.000006 0.000007 0.000006 0.000170 0.000163 0.000164
1980 0.00000 0.00001 0.000037
1981 0.00000 0.00000 0.000243
1982 0.00000 0.00001 0.000061
1983 0.00000 0.00000 0.000507
1984 0.00000 0.00000 0.000020
1985 0.00000 0.00000 0.000026
1986 0.00000 0.00000 0.000535

AVG  0.00000 0.00000 0.000156


      DENNEHOE    3352       2351

1979 0.00000 0.00002 0.000000   ANNUAL
1980 0.00000 0.00000 0.000004   0.000001 0.000001 0.000001 0.000001 0.000001 0.000001 0.000001 0.000001 0.000001 0.000002 0.000001 0.000002
1981 0.00000 0.00000 0.000001
1982 0.00000 0.00000 0.000008   SEASONAL
1983 0.00000 0.00000 0.000012   0.000007 0.000007 0.000005 0.000006 0.000007 0.000007 0.000007 0.000005 0.000007 0.000010 0.000008 0.000009
1984 0.00000 0.00001 0.000015
1985 0.00000 0.00000 0.000004
1986 0.00000 0.00001 0.000014

AVG  0.00000 0.00000 0.000007


      DIE KRAN    3333       2141

1980 0.00001 0.00012 0.000045   ANNUAL
1981 0.00000 0.00002 0.000008   0.000041 0.000036 0.000017 0.000012 0.000049 0.000038 0.000027 0.000025 0.000039 0.000048 0.000046 0.000048
1982 0.00000 0.00000 0.000145
1983 0.00002 0.00004 0.000261   SEASONAL
1984 0.00017 0.00098 0.000517   0.000172 0.000148 0.000073 0.000077 0.000303 0.000207 0.000157 0.000152 0.000245 0.000179 0.000169 0.000198
1985 0.00000 0.00002 0.000016
1986 0.00000 0.00002 0.000065

AVG  0.00003 0.00017 0.000151

      ELANDSVL    3219       1934

1980 0.00048 0.00387 0.000144   ANNUAL
1981 0.00102 0.00328 0.004885   0.000693 0.000831 0.000542 0.000241 0.000162 0.000060 0.000066 0.000432 0.000223 0.000499 0.000515 0.000637
1982 0.00027 0.00021 0.006597
1983 0.00021 0.00013 0.042918   SEASONAL
1984 0.00031 0.00061 0.002102   0.019744 0.020397 0.009835 0.001415 0.000976 0.000312 0.000308 0.002502 0.001177 0.014501 0.013018 0.038540
1985 0.00010 0.00066 0.000416
1986 0.00010 0.00001 0.056416
```

```
AVG  0.00036 0.00125 0.016211

     ELGIN      3408     1902

1965 0.00000 0.00000 0.000015   ANNUAL
1966 0.00000 0.00000 0.000048   0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000
1967 0.00000 0.00000 0.000024
1968 0.00000 0.00000 0.000026   SEASONAL
1969 0.00000 0.00000 0.000034   0.000005 0.000004 0.000003 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000003 0.000003 0.000005
1970 0.00000 0.00000 0.000050
1971 0.00000 0.00000 0.000069
1972 0.00000 0.00000 0.000052
1973 0.00000 0.00000 0.000087
1974 0.00000 0.00000 0.000020
1975 0.00000 0.00000 0.000029
1976 0.00000 0.00000 0.000009
1977 0.00000 0.00000 0.000016
1978 0.00000 0.00000 0.000016
1979 0.00000 0.00000 0.000006
1980 0.00000 0.00000 0.000003
1981 0.00000 0.00000 0.000005
1982 0.00000 0.00000 0.000010
1983 0.00000 0.00000 0.000007
1984 0.00000 0.00000 0.000003
1985 0.00000 0.00000 0.000005
1986 0.00000 0.00000 0.000008

AVG  0.00000 0.00000 0.000025


     EXCELSIO   3257     1927

1976 0.00000 0.00000 0.000002   ANNUAL
1977 0.00000 0.00000 0.000021   0.000003 0.000002 0.000001 0.000001 0.000001 0.000001 0.000001 0.000002 0.000002 0.000002 0.000002 0.000002
1978 0.00000 0.00000 0.000102
1979 0.00000 0.00000 0.001623   SEASONAL
1980 0.00000 0.00000 0.000006   0.000652 0.000516 0.000316 0.000001 0.000001 0.000002 0.000002 0.000003 0.000003 0.000554 0.000480 0.000562
1981 0.00000 0.00000 0.000112
1982 0.00000 0.00000 0.000102
1983 0.00000 0.00000 0.001004
1984 0.00000 0.00000 0.000020
1985 0.00000 0.00000 0.000025
1986 0.00000 0.00000 0.002366

AVG  0.00000 0.00000 0.000489


     GRAAFWAT   3210     1836

1973 0.00004 0.00006 0.000603   ANNUAL
1974 0.00001 0.00001 0.001507   0.000019 0.000012 0.000008 0.000006 0.000009 0.000012 0.000013 0.000008 0.000009 0.000012 0.000012 0.000013
1975 0.00001 0.00001 0.001563
1976 0.00000 0.00000 0.000134   SEASONAL
1977 0.00000 0.00000 0.000227   0.001263 0.000726 0.000550 0.000012 0.000015 0.000019 0.000024 0.000014 0.000014 0.000691 0.000734 0.000910
1978 0.00001 0.00001 0.000055
```

```
1979 0.00001 0.00001 0.004812
1980 0.00000 0.00000 0.000086
1981 0.00001 0.00001 0.001153
1982 0.00001 0.00001 0.000139
1983 0.00000 0.00001 0.000398
1984 0.00000 0.00001 0.000040
1985 0.00000 0.00000 0.000035
1986 0.00000 0.00000 0.000154

AVG  0.00001 0.00001 0.000779


         5125 GRASRUG

1979 0.00002 0.00013 0.000013   ANNUAL
1980 0.00001 0.00003 0.000138   0.000022 0.000025 0.000015 0.000015 0.000019 0.000021 0.000015 0.000014 0.000013 0.000012 0.000020 0.000022
1981 0.00002 0.00002 0.000589
1982 0.00001 0.00001 0.000580   SEASONAL
1983 0.00002 0.00002 0.001047   0.000644 0.000655 0.000423 0.000039 0.000040 0.000043 0.000037 0.000034 0.000022 0.000396 0.000593 0.000663
1984 0.00001 0.00002 0.000245
1985 0.00001 0.00001 0.000447
1986 0.00001 0.00001 0.001274

AVG  0.00001 0.00003 0.000542


         5023 CONSTANTIA

1967 0.00000 0.00000 0.000025   ANNUAL
1968 0.00000 0.00000 0.000030   0.000001 0.000001 0.000000 0.000000 0.000000 0.000001 0.000002 0.000002 0.000002 0.000001 0.000001 0.000001
1969 0.00000 0.00000 0.000037
1970 0.00000 0.00000 0.000050   SEASONAL
1971 0.00000 0.00000 0.000130   0.000044 0.000037 0.000027 0.000000 0.000001 0.000002 0.000003 0.000003 0.000003 0.000061 0.000047 0.000046
1972 0.00000 0.00000 0.000063
1973 0.00000 0.00000 0.000089
1974 0.00000 0.00000 0.000058
1975 0.00000 0.00000 0.000050
1976 0.00000 0.00000 0.000007
1977 0.00000 0.00000 0.000031
1978 0.00000 0.00000 0.000043
1979 0.00000 0.00000 0.000016
1980 0.00000 0.00000 0.000018
1981 0.00000 0.00000 0.000066
1982 0.00000 0.00000 0.000036
1983 0.00000 0.00000 0.000030
1984 0.00000 0.00000 0.000008
1985 0.00000 0.00000 0.000033
1986 0.00000 0.00000 0.000016

AVG  0.00000 0.00000 0.000042


     HELDERVU    3249      1843

1979 0.00000 0.00000 0.000026   ANNUAL
```

```
1980 0.00000 0.00000 0.000005   0.000000 0.000000 0.000000 0.000000 0.000000 0.000001 0.000001 0.000001 0.000001 0.000000 0.000000 0.000000
1981 0.00000 0.00000 0.000038
1982 0.00000 0.00000 0.000007   SEASONAL
1983 0.00000 0.00000 0.000023   0.000027 0.000022 0.000017 0.000000 0.000001 0.000002 0.000001 0.000001 0.000001 0.000025 0.000028 0.000031
1984 0.00000 0.00000 0.000006
1985 0.00000 0.00000 0.000006
1986 0.00000 0.00000 0.000083

AVG  0.00000 0.00000 0.000024


     H.J.S.BO   3339     1852

1971 0.00001 0.00003 0.000375   ANNUAL
1972 0.00001 0.00000 0.000839   0.000022 0.000019 0.000016 0.000011 0.000007 0.000007 0.000008 0.000011 0.000010 0.000015 0.000024 0.000026
1973 0.00003 0.00003 0.001620
1974 0.00000 0.00000 0.000466   SEASONAL
1975 0.00001 0.00001 0.000609   0.000634 0.000602 0.000470 0.000018 0.000012 0.000012 0.000012 0.000018 0.000016 0.000443 0.000709 0.000744
1976 0.00000 0.00000 0.000322
1977 0.00000 0.00000 0.000793
1978 0.00003 0.00003 0.000745
1979 0.00002 0.00002 0.000327
1980 0.00001 0.00001 0.000138
1981 0.00000 0.00000 0.000181
1982 0.00000 0.00000 0.000293
1983 0.00000 0.00000 0.000524
1984 0.00000 0.00000 0.000165
1985 0.00000 0.00000 0.000275
1986 0.00000 0.00000 0.001017

AVG  0.00001 0.00001 0.000543


     HOEKO      3330     2122

1979 0.00001 0.00002 0.000127   ANNUAL
1980 0.00003 0.00012 0.000189   0.000032 0.000036 0.000022 0.000017 0.000036 0.000027 0.000047 0.000039 0.000049 0.000051 0.000042 0.000044
1981 0.00000 0.00002 0.000027
1982 0.00001 0.00001 0.000352   SEASONAL
1983 0.00003 0.00009 0.000275   0.000161 0.000172 0.000111 0.000101 0.000253 0.000162 0.000271 0.000187 0.000276 0.000315 0.000261 0.000282
1984 0.00012 0.00115 0.000276
1985 0.00000 0.00004 0.000023
1986 0.00001 0.00004 0.000069

AVG  0.00003 0.00019 0.000167


     JONASKRA   3424     1954

1973 0.00019 0.00016 0.012686   ANNUAL
1974 0.00004 0.00003 0.002060   0.000098 0.000096 0.000064 0.000041 0.000029 0.000025 0.000037 0.000035 0.000036 0.000064 0.000097 0.000095
1975 0.00007 0.00008 0.003093
1976 0.00001 0.00001 0.000437   SEASONAL
1977 0.00001 0.00003 0.000102   0.002391 0.002591 0.001768 0.000077 0.000055 0.000051 0.000068 0.000065 0.000068 0.001873 0.002598 0.002593
1978 0.00002 0.00005 0.000476
```

```
1979 0.00004 0.00005 0.000660
1980 0.00008 0.00013 0.001020
1981 0.00002 0.00005 0.000519
1982 0.00005 0.00003 0.005481
1983 0.00003 0.00003 0.001749
1984 0.00004 0.00005 0.000648
1985 0.00002 0.00002 0.000495
1986 0.00002 0.00003 0.000548

     0.00005 0.00005 0.002141


     KLAWER      3147       1838

1973 0.00020 0.00036 0.001986   ANNUAL
1974 0.00007 0.00006 0.004713   0.000210 0.000126 0.000138 0.000193 0.000080 0.000081 0.000079 0.000136 0.000122 0.000187 0.000201 0.000184
1975 0.00013 0.00010 0.013821
1976 0.00005 0.00005 0.001313   SEASONAL
1977 0.00003 0.00003 0.001891   0.005610 0.003171 0.003714 0.000343 0.000135 0.000139 0.000135 0.000228 0.000203 0.004323 0.003636 0.005062
1978 0.00057 0.00078 0.009124
1979 0.00029 0.00042 0.008271
1980 0.00007 0.00010 0.002325
1981 0.00008 0.00012 0.002262
1982 0.00006 0.00006 0.001340
1983 0.00002 0.00002 0.004398
1984 0.00006 0.00009 0.000630
1985 0.00001 0.00003 0.000182
1986 0.00001 0.00001 0.002493

    '0.00012 0.00016 0.003911


     LANDAU      3336       1858

1974 0.00000 0.00000 0.000113   ANNUAL
1975 0.00002 0.00002 0.001760   0.000038 0.000028 0.000023 0.000012 0.000009 0.000008 0.000008 0.000014 0.000016 0.000020 0.000031 0.000037
1976 0.00001 0.00001 0.000592
1977 0.00001 0.00000 0.001238   SEASONAL
1978 0.00006 0.00005 0.002854   0.001496 0.001076 0.000902 0.000021 0.000015 0.000013 0.000012 0.000023 0.000026 0.000745 0.001206 0.001338
1979 0.00004 0.00005 0.000914
1980 0.00002 0.00002 0.000485
1981 0.00001 0.00001 0.003164
1982 0.00001 0.00000 0.000842
1983 0.00001 0.00000 0.000860
1984 0.00000 0.00000 0.000123
1985 0.00000 0.00000 0.000284
1986 0.00000 0.00000 0.000526

AVG  0.00001 0.00001 0.001058


     LAINGKLO    3347       2335

1966 0.00003 0.00007 0.000219   ANNUAL
1967 0.00001 0.00001 0.000224   0.000019 0.000018 0.000012 0.000010 0.000012 0.000012 0.000015 0.000014 0.000013 0.000018 0.000018 0.000021
```

```
1968 0.00000 0.00001 0.000197
1969 0.00003 0.00009 0.000181   SEASONAL
1970 0.00002 0.00005 0.000115   0.000127 0.000118 0.000081 0.000042 0.000055 0.000052 0.000066 0.000058 0.000054 0.000114 0.000112 0.000134
1971 0.00000 0.00001 0.000129
1972 0.00000 0.00002 0.000061
1973 0.00001 0.00007 0.000068
1974 0.00000 0.00000 0.000032
1975 0.00001 0.00003 0.000057
1976 0.00000 0.00002 0.000014
1977 0.00000 0.00002 0.000054
1978 0.00000 0.00001 0.000052
1979 0.00000 0.00000 0.000042
1980 0.00001 0.00005 0.000056
1981 0.00000 0.00000 0.000019
1982 0.00000 0.00000 0.000391
1983 0.00000 0.00001 0.000077
1984 0.00007 0.00034 0.000296
1985 0.00000 0.00006 0.000019
1986 0.00001 0.00008 0.000036

AVG  0.00002 0.00008 0.000128


     WOLSELEY   3327      1912

1964 0.00000 0.00000 0.000120   ANNUAL
1965 0.00000 0.00002 0.000045   0.000007 0.000006 0.000005 0.000003 0.000002 0.000003 0.000003 0.000004 0.000004 0.000006 0.000007 0.000007
1966 0.00000 0.00000 0.000747
1967 0.00000 0.00000 0.000207   SEASONAL
1968 0.00000 0.00000 0.000025   0.000282 0.000275 0.000206 0.000005 0.000004 0.000005 0.000006 0.000008 0.000008 0.000237 0.000284 0.000290
1969 0.00001 0.00001 0.000236
1970 0.00000 0.00000 0.000489
1971 0.00000 0.00000 0.000585
1972 0.00001 0.00000 0.000553
1973 0.00000 0.00000 0.000365
1974 0.00000 0.00000 0.000088
1975 0.00000 0.00000 0.000147
1976 0.00000 0.00000 0.000021
1977 0.00000 0.00000 0.000140
1978 0.00000 0.00000 0.000561
1979 0.00000 0.00001 0.000117
1980 0.00000 0.00000 0.000032
1981 0.00000 0.00000 0.000149
1982 0.00000 0.00000 0.000084
1983 0.00000 0.00000 0.000560
1984 0.00000 0.00000 0.000045
1985 0.00000 0.00000 0.000087
1986 0.00000 0.00000 0.000520

AVG  0.00000 0.00000 0.000258


     LUTZVILL   3136      1826

1976 0.00004 0.00004 0.001673   ANNUAL
```

```
1977 0.00004 0.00004 0.002388    0.000364 0.000278 0.000199 0.000125 0.000117 0.000143 0.000117 0.000132 0.000185 0.000241 0.000321 0.000397
1978 0.00066 0.00088 0.010013
1979 0.00055 0.00059 0.020131    SEASONAL
1980 0.00009 0.00009 0.005467    0.009759 0.007700 0.005041 0.000247 0.000222 0.000268 0.000226 0.000249 0.000352 0.005787 0.007762 0.009654
1981 0.00013 0.00017 0.002881
1982 0.00019 0.00028 0.002842
1983 0.00013 0.00012 0.006831
1984 0.00015 0.00032 0.001194
1985 0.00006 0.00013 0.000495
1986 0.00012 0.00009 0.027453

AVG  0.00020 0.00025 0.007397


     MORREISB   3309      1841

1973 0.00004 0.00007 0.000710    ANNUAL
1974 0.00000 0.00000 0.000581    0.000038 0.000034 0.000026 0.000020 0.000013 0.000011 0.000013 0.000017 0.000019 0.000026 0.000036 0.000036
1975 0.00003 0.00002 0.001882
1976 0.00001 0.00001 0.000427    SEASONAL
1977 0.00001 0.00000 0.002508    0.001513 0.001470 0.001088 0.000033 0.000022 0.000017 0.000023 0.000028 0.000032 0.000948 0.001450 0.001653
1978 0.00004 0.00005 0.001626
1979 0.00003 0.00003 0.001765
1980 0.00001 0.00003 0.000095
1981 0.00002 0.00001 0.002710
1982 0.00001 0.00001 0.000439
1983 0.00001 0.00001 0.001067
1984 0.00001 0.00001 0.000294
1985 0.00001 0.00000 0.001077
1986 0.00002 0.00001 0.002542

AVG  0.00002 0.00002 0.001266


     NIETVOOR   3354      1852

1967 0.00001 0.00000 0.000544    ANNUAL
1968 0.00000 0.00000 0.000466    0.000012 0.000012 0.000007 0.000003 0.000002 0.000004 0.000004 0.000006 0.000007 0.000011 0.000013 0.000011
1969 0.00001 0.00001 0.000497
1970 0.00000 0.00000 0.000423    SEASONAL
1971 0.00000 0.00000 0.001123    0.000538 0.000681 0.000363        0        0        0        0        0        0 0.000535 0.000696 0.000531
1972 0.00000 0.00000 0.001073
1973 0.00001 0.00001 0.001474
1974 0.00000 0.00000 0.001038
1975 0.00000 0.00000 0.000642
1976 0.00000 0.00000 0.000075
1977 0.00000 0.00000 0.000271
1978 0.00001 0.00001 0.000199
1979 0.00000 0.00001 0.000127
1980 0.00000 0.00000 0.000138
1981 0.00000 0.00000 0.000354
1982 0.00000 0.00000 0.000182
1983 0.00000 0.00000 0.000185
1984 0.00000 0.00000 0.000086
1985 0.00000 0.00000 0.000347
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1986 0.00000 0.00000 0.000230

AVG  0.00000 0.00000 0.000474

     OUTENEQU   3355      2225

1967 0.00000 0.00000 0.000058   ANNUAL
1968 0.00000 0.00002 0.000059   0.000007 0.000006 0.000004 0.000004 0.000005 0.000008 0.000006 0.000007 0.000006 0.000007 0.000007 0.000007
1969 0.00001 0.00004 0.000095
1970 0.00000 0.00004 0.000036   SEASONAL
1971 0.00000 0.00000 0.000042   0.000046 0.000040 0.000027        0        0        0        0        0        0 0.000047 0.000048 0.000048
1972 0.00001 0.00004 0.000043
1973 0.00001 0.00004 0.000113
1974 0.00001 0.00004 0.000079
1975 0.00000 0.00001 0.000048
1976 0.00000 0.00002 0.000017
1977 0.00000 0.00001 0.000013
1978 0.00000 0.00002 0.000034
1979 0.00000 0.00000 0.000034
1980 0.00000 0.00001 0.000009
1981 0.00000 0.00000 0.000013
1982 0.00000 0.00001 0.000044
1983 0.00000 0.00001 0.000021
1984 0.00000 0.00003 0.000033
1985 0.00000 0.00005 0.000011
1986 0.00000 0.00003 0.000024

AVG  0.00000 0.00002 0.000041

     PORTERVI   3301      1901

1973 0.00000 0.00000 0.000286   ANNUAL
1974 0.00000 0.00000 0.000220   0.000005 0.000004 0.000002 0.000002 0.000002 0.000002 0.000002 0.000002 0.000002 0.000003 0.000004 0.000005
1975 0.00000 0.00000 0.000343
1976 0.00000 0.00000 0.000097   SEASONAL
1977 0.00000 0.00000 0.000094   0.000197 0.000148 0.000100 0.000004 0.000004 0.000004 0.000004 0.000004 0.000005 0.000103 0.000140 0.000174
1978 0.00000 0.00001 0.000119
1979 0.00000 0.00000 0.000152
1980 0.00000 0.00000 0.000037
1981 0.00000 0.00000 0.000284
1982 0.00000 0.00000 0.000035
1983 0.00000 0.00000 0.000075
1984 0.00000 0.00000 0.000017
1985 0.00000 0.00000 0.000044
1986 0.00000 0.00000 0.000132

AVG  0.00000 0.00000 0.000138
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     PRINSKRAA    3438      2007

1973 0.000243 0.000218 0.007561   ANNUAL
1974 0.000102 0.000061 0.004790   0.000135 0.000148 0.000103 0.000055 0.000023 0.000016 0.000025 0.000031 0.000042 0.000090 0.000133 0.000117
1975 0.000113 0.000088 0.003424
1976 0.000024 0.000014 0.000826   SEASONAL
1977 0.000031 0.000034 0.000542   0.001944 0.002220 0.001601 0.000107 0.000050 0.000037 0.000048 0.000065 0.000092 0.001291 0.001910 0.001762
1978 0.000022 0.000030 0.000429
1979 0.000042 0.000086 0.000298
1980 0.000072 0.000129 0.000613
1981 0.000032 0.000032 0.000643
1982 0.000038 0.000025 0.001483
1983 0.000027 0.000022 0.000732
1984 0.000064 0.000058 0.001321
1985 0.000030 0.000021 0.000489
1986 0.000014 0.000011 0.000378

AVG  0.000061 0.000059 0.001681


     RIEBECK-W    3321      1852

1973 0.000014 0.000020 0.000479   ANNUAL
1974 0.000003 0.000004 0.000439   0.000011 0.000009 0.000006 0.000005 0.000005 0.000005 0.000007 0.000010 0.000009 0.000009 0.000011 0.000012
1975 0.000014 0.000014 0.001122
1976 0.000006 0.000006 0.000203   SEASONAL
1977 0.000004 0.000005 0.000504   0.000654 0.000579 0.000402 0.000008 0.000009 0.000008 0.000010 0.000015 0.000013 0.000494 0.000604 0.000740
1978 0.000017 0.000018 0.000993
1979 0.000008 0.000015 0.000131
1980 0.000008 0.000014 0.000096
1981 0.000008 0.000009 0.000566
1982 0.000005 0.000006 0.000172
1983 0.000004 0.000005 0.000786
1984 0.000003 0.000006 0.000027
1985 0.000004 0.000003 0.000205
1986 0.000008 0.000007 0.002128

AVG  0.000008 0.000009 0.000561


     RIVERSDAL    3405      2116

1973 0.000011 0.000016 0.000125   ANNUAL
1974 0.000008 0.000015 0.000065   0.000014 0.000014 0.000008 0.000004 0.000004 0.000004 0.000005 0.000005 0.000006 0.000010 0.000014 0.000014
1975 0.000009 0.000009 0.000252
1976 0.000003 0.000006 0.000031   SEASONAL
1977 0.000004 0.000013 0.000026   0.000096 0.000098 0.000059 0.000015 0.000019 0.000014 0.000018 0.000020 0.000024 0.000076 0.000095 0.000108
1978 0.000001 0.000007 0.000008
1979 0.000009 0.000012 0.000129
1980 0.000011 0.000036 0.000059
1981 0.000003 0.000006 0.000025
1982 0.000004 0.000003 0.000151
1983 0.000008 0.000014 0.000105
1984 0.000023 0.000078 0.000109
1985 0.000005 0.000015 0.000025
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1986 0.000005 0.000007 0.000093

AVG  0.000007 0.000017 0.000086


     ROBERTSON     3350       1954

1964 0.000002 0.000003 0.000023   ANNUAL
1965 0.000006 0.000012 0.000064   0.000019 0.000015 0.000011 0.000008 0.000013 0.000012 0.000019 0.000025 0.000026 0.000025 0.000023 0.000026
1966 0.000019 0.000020 0.002133
1967 0.000011 0.000012 0.000413   SEASONAL
1968 0.000013 0.000013 0.000465   0.000393 0.000325 0.000250 0.000019 0.000030 0.000027 0.000035 0.000057 0.000059 0.000498 0.000454 0.000484
1969 0.000018 0.000024 0.000242
1970 0.000016 0.000036 0.000233
1971 0.000005 0.000005 0.000168
1972 0.000019 0.000023 0.000458
1973 0.000022 0.000031 0.000642
1974 0.000006 0.000007 0.000197
1975 0.000021 0.000032 0.000694
1976 0.000008 0.000016 0.000072
1977 0.000006 0.000015 0.000096
1978 0.000025 0.000085 0.000125
1979 0.000029 0.000045 0.000588
1980 0.000024 0.000068 0.000134
1981 0.000004 0.000013 0.000022
1982 0.000009 0.000008 0.000422
1983 0.000021 0.000026 0.000937
1984 0.000043 0.000132 0.000238
1985 0.000013 0.000024 0.000124
1986 0.000024 0.000058 0.000182

AVG  0.000016 0.000031 0.000377


     OUTDSHOOR     3338       2215

1970 0.000021 0.000027 0.000349   ANNUAL
1971 0.000002 0.000000 0.000133   0.000042 0.000037 0.000020 0.000011 0.000007 0.000006 0.000010 0.000012 0.000014 0.000029 0.000040 0.000037
1972 0.000015 0.000029 0.000104
1973 0.000040 0.000053 0.000438   SEASONAL
1974 0.000019 0.000030 0.000182   0.000313 0.000251 0.000135 0.000038 0.000024 0.000020 0.000036 0.000041 0.000052 0.000202 0.000263 0.000271
1975 0.000006 0.000003 0.000164
1976 0.000009 0.000028 0.000050
1977 0.000003 0.000001 0.000092
1978 0.000045 0.000061 0.000554
1979 0.000023 0.000022 0.000634
1980 0.000018 0.000060 0.000088
1981 0.000004 0.000005 0.000047
1982 0.000005 0.000003 0.000273
1983 0.000016 0.000025 0.000196
1984 0.000060 0.000155 0.000344
1985 0.000010 0.000021 0.000067
1986 0.000011 0.000016 0.000146

AVG  0.000018 0.000032 0.000227
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     SERJEANTS    3408      1931

1973 0.000007 0.000014 0.000120   ANNUAL
1974 0.000006 0.000004 0.000303   0.000036 0.000029 0.000025 0.000014 0.000007 0.000005 0.000008 0.000014 0.000011 0.000016 0.000029 0.000030
1975 0.000017 0.000010 0.001369
1976 0.000004 0.000003 0.000087   SEASONAL
1977 0.000006 0.000007 0.000135   0.000439 0.000483 0.000456 0.000027 0.000015 0.000011 0.000017 0.000032 0.000023 0.000243 0.000415 0.000511
1978 0.000036 0.000049 0.000641
1979 0.000038 0.000056 0.000503
1980 0.000045 0.000061 0.000539
1981 0.000005 0.000005 0.000100
1982 0.000009 0.000007 0.000416
1983 0.000004 0.000003 0.000353
1984 0.000009 0.000015 0.000076
1985 0.000004 0.000003 0.000069
1986 0.000003 0.000002 0.000113

AVG  0.000014 0.000017 0.000345


     TYGERHOEK    3408      1954

1975 0.000008 0.000011 0.000172   ANNUAL
1976 0.000013 0.000015 0.000220   0.000029 0.000024 0.000016 0.000008 0.000008 0.000007 0.000016 0.000012 0.000013 0.000023 0.000030 0.000035
1977 0.000020 0.000038 0.000185
1978 0.000012 0.000018 0.000145   SEASONAL
1979 0.000020 0.000023 0.000384   0.000296 0.000252 0.000170 0.000022 0.000023 0.000019 0.000035 0.000030 0.000034 0.000280 0.000344 0.000418
1980 0.000017 0.000041 0.000111
1981 0.000008 0.000012 0.000125
1982 0.000010 0.000006 0.000762
1983 0.000012 0.000013 0.000273
1984 0.000027 0.000061 0.000191
1985 0.000010 0.000015 0.000093
1986 0.000008 0.000009 0.000148

AVG  0.000014 0.000022 0.000234


     VELDRESER    3339      1927

1975 0.000018 0.000019 0.000820   ANNUAL
1976 0.000067 0.000138 0.000470   0.000123 0.000103 0.000059 0.000039 0.000049 0.000038 0.000041 0.000067 0.000073 0.000104 0.000123 0.000135
1977 0.000025 0.000026 0.002376
1978 0.000215 0.000323 0.002882   SEASONAL
1979 0.000101 0.000106 0.003885   0.003239 0.002868 0.001611 0.000085 0.000100 0.000083 0.000079 0.000137 0.000148 0.002738 0.002962 0.003573
1980 0.000092 0.000144 0.000981
1981 0.000026 0.000071 0.000153
1982 0.000052 0.000033 0.005699
1983 0.000052 0.000045 0.007565
1984 0.000030 0.000044 0.000493
1985 0.000030 0.000042 0.000363
1986 0.000064 0.000061 0.003683
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AVG  0.000064 0.000088 0.002447


     WELTEVRED     3356     2037

1978 0.000008 0.000008 0.000216   ANNUAL
1979 0.000004 0.000003 0.000363   0.000007 0.000007 0.000003 0.000003 0.000002 0.000002 0.000002 0.000003 0.000004 0.000006 0.000008 0.000009
1980 0.000009 0.000016 0.000075
1981 0.000000 0.000002 0.000005   SEASONAL
1982 0.000001 0.000001 0.000155   0.000150 0.000140 0.000073 0.000008 0.000006 0.000004 0.000005 0.000008 0.000011 0.000114 0.000135 0.000174
1983 0.000001 0.000001 0.000185
1984 0.000010 0.000021 0.000083
1985 0.000001 0.000004 0.000008
1986 0.000003 0.000005 0.000047

AVG  0.000004 0.000007 0.000126


     ADDO          3334     2542

1975 0.000000 0.000001 0.000003   ANNUAL
1976 0.000005 0.000043 0.000016   0.000027 0.000023 0.000012 0.000007 0.000008 0.000007 0.000006 0.000011 0.000016 0.000021 0.000024 0.000030
1977 0.000006 0.000021 0.000030
1978 0.000030 0.000062 0.000225   SEASONAL
1979 0.000002 0.000002 0.000122   0.000133 0.000120 0.000058 0.000067 0.000068 0.000070 0.000061 0.000094 0.000155 0.000094 0.000117 0.000151
1980 0.000015 0.000176 0.000037
1981 0.000003 0.000011 0.000015
1982 0.000012 0.000011 0.000250
1983 0.000011 0.000013 0.000221
1984 0.000039 0.000114 0.000201
1985 0.000017 0.000212 0.000043
1986 0.000024 0.000262 0.000064

AVG  0.000014 0.000077 0.000102


     CALVINIA      3128     1946

1979 0.000005 0.000033 0.000008   ANNUAL
1980 0.000014 0.000044 0.000116   0.000008 0.000009 0.000007 0.000006 0.000021 0.000026 0.000032 0.000018 0.000018 0.000014 0.000011 0.000009
1981 0.000024 0.000066 0.000187
1982 0.000012 0.000023 0.000256   SEASONAL
1983 0.000009 0.000016 0.000418   0.000250 0.000229 0.000165 0.000016 0.000049 0.000053 0.000066 0.000043 0.000041 0.000287 0.000263 0.000165
1984 0.000019 0.000065 0.000104
1985 0.000006 0.000049 0.000016
1986 0.000005 0.000009 0.000350

AVG  0.000012 0.000038 0.000182


     CAPE PADR     3345     2627

1977 0.000012 0.000075 0.000029   ANNUAL
1978 0.000013 0.000039 0.000071   0.000025 0.000030 0.000019 0.000017 0.000013 0.000012 0.000013 0.000019 0.000023 0.000030 0.000028 0.000028
1979 0.000010 0.000015 0.000179
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1980 0.000039 0.000119 0.000208   SEASONAL
1981 0.000010 0.000035 0.000046   0.000155 0.000181 0.000111 0.000059 0.000046 0.000044 0.000047 0.000070 0.000090 0.000173 0.000158 0.000166
1982 0.000036 0.000072 0.000328
1983 0.000014 0.000026 0.000178
1984 0.000031 0.000060 0.000293
1985 0.000011 0.000064 0.000039
1986 0.000015 0.000046 0.000075

AVG  0.000019 0.000055 0.000145


     CARNAVON       3058      2200

1978 0.000384 0.006634 0.000418   ANNUAL
1979 0.000311 0.001391 0.001164   0.000545 0.000481 0.000270 0.000307 0.000266 0.000255 0.000246 0.000318 0.000460 0.000562 0.000617 0.000762
1980 0.000252 0.002063 0.000698
1981 0.000271 0.001132 0.001055   SEASONAL
1982 0.000567 0.001043 0.005188   0.002862 0.002465 0.001463 0.002017 0.001613 0.001312 0.001378 0.002058 0.002956 0.002541 0.002728 0.003322
1983 0.000261 0.000930 0.001164
1984 0.000641 0.001627 0.003973
1985 0.000081 0.000800 0.000213
1986 0.000394 0.000536 0.006310

AVG  0.000351 0.001795 0.002243


     CRADOCK        3213      2541

1976 0.000002 0.000035 0.000004   ANNUAL
1977 0.000028 0.000123 0.000106   0.000078 0.000056 0.000030 0.000015 0.000017 0.000018 0.000018 0.000027 0.000041 0.000060 0.000066 0.000081
1978 0.000048 0.000329 0.000157
1979 0.000028 0.000102 0.000128   SEASONAL
1980 0.000065 0.001629 0.000144   0.000221 0.000159 0.000085 0.000420 0.000428 0.000484 0.000402 0.000789 0.001154 0.000147 0.000176 0.000211
1981 0.000019 0.000130 0.000061
1982 0.000040 0.000053 0.000444
1983 0.000028 0.000050 0.000245
1984 0.000046 0.000168 0.000207
1985 0.000012 0.001691 0.000023
1986 0.000065 0.001598 0.000152

AVG  0.000035 0.000537 0.000152


     DE AAR         3039      2401

1980 0.000000 0.000001 0.000003   ANNUAL
1981 0.000000 0.000001 0.000002   0.000120 0.000116 0.000080 0.000041 0.000032 0.000034 0.000024 0.000032 0.000062 0.000087 0.000115 0.000144
1982 0.000005 0.000010 0.000051
1983 0.000006 0.000009 0.000046   SEASONAL
1984 0.000073 0.000218 0.000376   0.000243 0.000243 0.000157 0.000867 0.000590 0.000661 0.000465 0.000632 0.001220 0.000167 0.000237 0.000292
1985 0.000043 0.001139 0.000095
1986 0.000271 0.003038 0.000737

AVG  0.000057 0.000631 0.000187
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     DE TUIN       2956      2008

1979 0.000772 0.003114 0.003151   ANNUAL
1980 0.000963 0.003457 0.004275   0.003156 0.002746 0.001323 0.000744 0.000765 0.000602 0.000747 0.000923 0.001257 0.002148 0.002610 0.003393
1981 0.000696 0.003744 0.002350
1982 0.000873 0.000760 0.030138   SEASONAL
1983 0.006229 0.131542 0.014717   0.012933 0.010197 0.005168 0.018111 0.024078 0.011648 0.020757 0.025573 0.033755 0.007661 0.010841 0.013107
1984 0.001760 0.002306 0.019700
1985 0.000145 0.025466 0.000262
1986 0.000472 0.001309 0.002509

AVG  0.001489 0.021462 0.009638


     DOHNE         3231      2728

1976 0.000000 0.000007 0.000000   ANNUAL
1977 0.000004 0.000071 0.000008   0.000007 0.000008 0.000006 0.000005 0.000009 0.000013 0.000010 0.000009 0.000010 0.000010 0.000007 0.000008
1978 0.000003 0.000034 0.000009
1979 0.000005 0.000017 0.000033   SEASONAL
1980 0.000016 0.000560 0.000020   0.000017 0.000018 0.000013 0.000117 0.000159 0.000226 0.000177 0.000215 0.000219 0.000024 0.000017 0.000019
1981 0.000008 0.000141 0.000013
1982 0.000018 0.000155 0.000041
1983 0.000013 0.000110 0.000027
1984 0.000009 0.000137 0.000017
1985 0.000003 0.000492 0.000003
1986 0.000007 0.000126 0.000013

AVG  0.000008 0.000168 0.000017


     ELLIOT        3121      2751

1980 0.000004 0.000023 0.000014   ANNUAL
1981 0.000004 0.000041 0.000008   0.000003 0.000003 0.000002 0.000002 0.000005 0.000006 0.000009 0.000012 0.000012 0.000008 0.000008 0.000007
1982 0.000003 0.000051 0.000007
1983 0.000010 0.000125 0.000016   SEASONAL
1984 0.000003 0.000053 0.000005   0.000007 0.000007 0.000004 0.000052 0.000078 0.000111 0.000116 0.000136 0.000141 0.000022 0.000023 0.000021
1985 0.000001 0.000199 0.000001
1986 0.000001 0.000096 0.000002

AVG  0.000004 0.000084 0.000007


     KAKAMAS       2846      2037

1972 0.000198 0.002340 0.002417   ANNUAL
1973 0.000210 0.002194 0.000490   0.001665 0.001320 0.000878 0.000501 0.000489 0.000585 0.000509 0.000577 0.000897 0.001234 0.001438 0.001847
1974 0.000012 0.000496 0.000112
1975 0.000129 0.005995 0.000357   SEASONAL
1976 0.000041 0.000432 0.000181   0.014210 0.011037 0.007663 0.010361 0.010799 0.006139 0.008565 0.013127 0.016142 0.010470 0.011832 0.015813
1977 0.000080 0.000342 0.000317
1978 0.000736 0.010044 0.003423
1979 0.001335 0.002122 0.012292
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1980 0.001371 0.003623 0.006500
1981 0.001109 0.002921 0.005513
1982 0.000834 0.001816 0.004925
1983 0.001143 0.003677 0.008276
1984 0.001115 0.000835 0.057802
1985 0.000637 0.091579 0.001249
1986 0.004624 0.021075 0.070019

AVG  0.000905 0.009966 0.011592


     KEIMOS        2824     2058

1972 0.000055 0.001595 0.000372   ANNUAL
1973 0.000048 0.000540 0.000107   0.000277 0.000188 0.000131 0.000071 0.000062 0.000117 0.000111 0.000105 0.000246 0.000274 0.000335 0.000363
1974 0.000018 0.000889 0.000144
1975 0.000043 0.001212 0.000304   SEASONAL
1976 0.000010 0.000152 0.000044   0.001550 0.001018 0.000734 0.000722 0.000641 0.000885 0.000972 0.000946 0.002352 0.001478 0.001881 0.001998
1977 0.000040 0.000105 0.000305
1978 0.000147 0.001445 0.001105
1979 0.000001 0.000002 0.000007
1980 0.000014 0.000120 0.000038
1981 0.000028 0.000102 0.000120
1982 0.000185 0.000845 0.000628
1983 0.000326 0.001355 0.001346
1984 0.000231 0.000237 0.003916
1985 0.000069 0.000838 0.000295
1986 0.001241 0.003781 0.011928

AVG  0.000164 0.000881 0.001377


     KLIPFONTE     3236     2544

1980 0.000037 0.000515 0.000085   ANNUAL
1981 0.000019 0.000261 0.000044   0.000034 0.000029 0.000016 0.000019 0.000026 0.000035 0.000035 0.000032 0.000031 0.000030 0.000030 0.000032
1982 0.000027 0.000116 0.000116
1983 0.000018 0.000085 0.000072   SEASONAL
1984 0.000060 0.000577 0.000158   0.000100 0.000088 0.000048 0.000278 0.000332 0.000443 0.000513 0.000499 0.000493 0.000085 0.000084 0.000096
1985 0.000008 0.000935 0.000012
1986 0.000009 0.000268 0.000004

AVG  0.000025 0.000394 0.000070


     LIDNEY        3340     2600

1981 0.000003 0.000006 0.000135   ANNUAL
1982 0.000017 0.000086 0.000083   0.000014 0.000015 0.000010 0.000012 0.000011 0.000014 0.000013 0.000015 0.000015 0.000021 0.000018 0.000019
1983 0.000005 0.000033 0.000028
1984 0.000024 0.000088 0.000133   SEASONAL
1985 0.000012 0.000032 0.000105   0.000063 0.000071 0.000077 0.000095 0.000077 0.000085 0.000083 0.000106 0.000125 0.000176 0.000144 0.000119
1986 0.000023 0.000104 0.000101

AVG  0.000014 0.000058 0.000097
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     MEINTSPRU    3129     2458

1979 0.000024 0.000710 0.000054   ANNUAL
1980 0.000111 0.001789 0.000247   0.000047 0.000048 0.000026 0.000033 0.000053 0.000041 0.000040 0.000076 0.000124 0.000125 0.000088 0.000096
1981 0.000013 0.000089 0.000063
1982 0.000042 0.000107 0.000271   SEASONAL
1983 0.000026 0.000445 0.000045   0.000159 0.000171 0.000088 0.000917 0.000887 0.000894 0.001198 0.003226 0.005345      ERR      ERR      ERR
1984 0.000075 0.000301 0.000357
1985 0.000015 0.004169 0.000020
1986 0.000133 0.057054 0.000073

AVG  0.000055 0.008083 0.000141

     MIDDLETON    3259     2550

1980 0.000053 0.000702 0.000140   ANNUAL
1981 0.000019 0.000202 0.000047   0.000054 0.000045 0.000023 0.000017 0.000017 0.000019 0.000021 0.000027 0.000034 0.000051 0.000049 0.000051
1982 0.000022 0.000037 0.000258
1983 0.000024 0.000052 0.000202   SEASONAL
1984 0.000064 0.000214 0.000356   0.000191 0.000162 0.000080 0.000235 0.000238 0.000331 0.000286 0.000451 0.000580 0.000177 0.000165 0.000182
1985 0.000011 0.000322 0.000026
1986 0.000021 0.000789 0.000052

AVG  0.000031 0.000331 0.000154


     OPWEG        2853     2152

1972 0.000070 0.005044 0.000955   ANNUAL
1973 0.000094 0.001215 0.000176   0.000343 0.000336 0.000189 0.000128 0.000121 0.000141 0.000132 0.000170 0.000238 0.000326 0.000358 0.000359
1974 0.000005 0.000033 0.000072
1975 0.000042 0.002407 0.000119   SEASONAL
1976 0.000019 0.000257 0.000058   0.001787 0.001861 0.001006 0.005639 0.006748 0.003634 0.004278 0.008063 0.009631 0.001614 0.001703 0.001791
1977 0.000065 0.000301 0.000287
1978 0.000523 0.003111 0.004246
1979 0.000163 0.000139 0.004991
1980 0.000140 0.003077 0.000284
1981 0.000269 0.001532 0.000837
1982 0.000360 0.001619 0.001313
1983 0.000192 0.001221 0.000656
1984 0.000350 0.000439 0.005472
1985 0.000205 0.065626 0.000376
1986 0.000743 0.003708 0.002579

AVG  0.000216 0.005982 0.001495


     PATENSIE     3347     2450

1979 0.000001 0.000002 0.000028   ANNUAL
1980 0.000006 0.000039 0.000036   0.000002 0.000001 0.000001 0.000001 0.000001 0.000002 0.000003 0.000002 0.000002 0.000002 0.000002 0.000002
1981 0.000002 0.000022 0.000005
1982 0.000006 0.000010 0.000107   SEASONAL
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1983 0.000005 0.000011 0.000041    0.000006 0.000004 0.000004 0.000017 0.000015 0.000024 0.000033 0.000025 0.000022
1984 0.000029 0.000098 0.000166
1985 0.000006 0.000052 0.000027
1986 0.000009 0.000070 0.000039

AVG  0.000008 0.000038 0.000056


     QUEENSTOW     3154     2652

1979 0.000000 0.000000 0.000003    ANNUAL
1980 0.000018 0.000297 0.000047    0.000014 0.000011 0.000007 0.000005 0.000008 0.000008 0.000009 0.000011 0.000013 0.00001
1981 0.000011 0.000109 0.000026
1982 0.000014 0.000068 0.000050    SEASONAL
1983 0.000021 0.000066 0.000120    0.000043 0.000039 0.000024 0.000082 0.000102 0.000187 0.000165 0.000282 0.000293 0.00003
1984 0.000007 0.000058 0.000019
1985 0.000002 0.000277 0.000002
1986 0.000007 0.000300 0.000010

AVG  0.000010 0.000147 0.000035


     SOMERSET      3244     2535

1980 0.000022 0.000299 0.000044    ANNUAL
1981 0.000013 0.000091 0.000033    0.000012 0.000009 0.000006 0.000006 0.000011 0.000011 0.000012 0.000017 0.000013 0.00001
1982 0.000000        0 0.000039
1983 0.000008 0.000035 0.000018    SEASONAL
1984 0.000016 0.000212 0.000022    0.000039 0.000028 0.000016 0.000092 0.000117 0.000169 0.000132 0.000204 0.000176 0.00002
1985 0.000002 0.000147 0.000003
1986 0.000005 0.000187 0.000007

AVG  0.000009 0.000139 0.000024


     GENR STEY     3324     2520

1981 0.000023 0.000114 0.000081    ANNUAL
1982 0.000041 0.000062 0.000545    0.000065 0.000057 0.000033 0.000028 0.000037 0.000031 0.000035 0.000033 0.000044 0.00005
1983 0.000029 0.000058 0.000304
1984 0.000111 0.000984 0.000284    SEASONAL
1985 0.000016 0.000427 0.000031    0.000272 0.000236 0.000147 0.000289 0.000392 0.000339 0.000362 0.000372 0.000522 0.00020
1986 0.000042 0.000531 0.000098

AVG  0.000044 0.000362 0.000224


     SUTHERLAN     2332     2040

1980 0.000033 0.000113 0.000161    ANNUAL
1981 0.000025 0.000082 0.000134    0.000035 0.000031 0.000029 0.000026 0.000024 0.000039 0.000031 0.000027 0.000024 0.00006
1982 0.000033 0.000069 0.000308
1983 0.000017 0.000025 0.000834    SEASONAL
1984 0.000017 0.000035 0.000197    0.000280 0.000247 0.000233 0.000063 0.000059 0.000095 0.000076 0.000066 0.000060 0.00052
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1986 0.000006 0.000008 0.000480

AVG  0.000019 0.000050 0.000304

     UGIE          3113       2816

1980 0.000004 0.000160 0.000004   ANNUAL
1981 0.000001 0.000034 0.000003   0.000001 0.000000 0.000001 0.000001 0.000001 0.000001 0.000000 0.000002 0.000003 0.000003 0.000003 0.000002
1982 0.000001 0.000010 0.000002
1983 0.000001 0.000203 0.000001   SEASONAL
1984 0.000000 0.000004 0.000001   0.000001 0.000001 0.000001 0.000045 0.000102 0.000061 0.000019 0.000116 0.000220 0.000005 0.000006 0.000004
1985 0.000000 0.000014 0.000000
1986 0.000000 0.000009 0.000000

AVG  0.000001 0.000062 0.000002


     UPINGTON      2827       2115

1975 0.000008 0.000585 0.000011   ANNUAL
1976 0.000009 0.000078 0.000027   0.000153 0.000101 0.000043 0.000029 0.000018 0.000022 0.000028 0.000037 0.000058 0.000317 0.000250 0.000246
1977 0.000012 0.000044 0.000054
1978 0.000081 0.000731 0.000236   SEASONAL
1979 0.000045 0.000054 0.000906   0.000964 0.000654 0.000420 0.000489 0.000347 0.000257 0.000499 0.000452 0.000842 0.001451 0.001411 0.001432
1980 0.000038 0.000376 0.000107
1981 0.000051 0.000433 0.000141
1982 0.000092 0.000710 0.000266
1983 0.000050 0.000504 0.000130
1984 0.000195 0.000157 0.006675
1985 0.000020 0.001073 0.000047
1986 0.000091        0 0.002287

AVG  0.000058 0.000396 0.000907


     VAN WYKSV     3021       2149

1978 0.000025 0.000328 0.000052   ANNUAL
1979 0.000288 0.000454 0.002526   0.001009 0.000978 0.000567 0.000297 0.000320 0.000301 0.000211 0.000337 0.000603 0.000809 0.001041 0.001050
1980 0.000319 0.000544 0.003070
1981 0.000143 0.000487 0.000673   SEASONAL
1982 0.000115 0.000382 0.000538   0.004004 0.003856 0.002207 0.001965 0.001855 0.001565 0.001392 0.002325 0.003888 0.003233 0.004306 0.004285
1983 0.000125 0.000160 0.002335
1984 0.003761 0.009785 0.021447
1985 0.000023 0.005184 0.000042
1986 0.000192 0.000836 0.000761

AVG  0.000555 0.002018 0.003494


     WELVERDIE     3043       2643

1979 0.000001 0.000008 0.000002   ANNUAL
1980 0.000028 0.000454 0.000071   0.000026 0.000019 0.000007 0.000004 0.000005 0.000003 0.000003 0.000006 0.000017 0.000018 0.000024 0.000021
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1981 0.000005 0.000013 0.000030
1982 0.000006 0.000012 0.000049    SEASONAL
1983 0.000012 0.000023 0.000100    0.000070 0.000055 0.000023 0.000099 0.000101 0.000066 0.000052 0.000140 0.000406 0.000043 0.000059 0.00005
1984 0.000015 0.000051 0.000074
1985 0.000005 0.000270 0.000011
1986 0.000004 0.000052 0.000011

AVG  0.000010 0.000110 0.000044


     WHYTEBANK     3225       2614

1981 0.000013 0.000112 0.000028    ANNUAL
1982 0.000015 0.000075 0.000048    0.000010 0.000011 0.000007 0.000009 0.000024 0.000035 0.000033 0.000022 0.000019 0.000015 0.000010 0.00000
1983 0.000023 0.000185 0.000043
1984 0.000020 0.000350 0.000027    SEASONAL
1985 0.000006 0.000498 0.000006    0.000029 0.000031 0.000020 0.000155 0.000283 0.000518 0.000407 0.000351 0.000325 0.000039 0.000026 0.00002
1986 0.000014 0.000674 0.000014

AVG  0.000015 0.000316 0.000028


     WINTERBER     3247       2638

1976 0.000003 0.000063 0.000007    ANNUAL
1977 0.000006 0.000048 0.000016    0.000032 0.000029 0.000016 0.000014 0.000015 0.000020 0.000064 0.000020 0.000024 0.000029 0.000031 0.00003
1978 0.000026 0.000082 0.000133
1979 0.000010 0.000033 0.000054    SEASONAL
1980 0.000052 0.000469 0.000131    0.000091 0.000083 0.000044 0.000164 0.000163 0.000218 0.000661 0.000252 0.000308 0.000080 0.000085 0.00009
1981 0.000016 0.000128 0.000044
1982 0.000035 0.000087 0.000225
1983 0.000041 0.000303 0.000106
1984 0.000043 0.000488 0.000079
1985 0.000009 0.000685 0.000014
1986 0.000016 0.000205 0.000037

AVG  0.000023 0.000236 0.000077


     BIEN DONN     3350       1859

1941 0.000001 0.000001 0.000137    ANNUAL
1942 0.000001 0.000001 0.000850    0.000008 0.000008 0.000005 0.000002 0.000001 0.000001 0.000001 0.000003 0.000004 0.000006 0.000008 0.00000
1943 0.000003 0.000002 0.000147
1944 0.000002 0.000001 0.000183    SEASONAL
1945 0.000002 0.000001 0.002217    0.000478 0.000426 0.000286 0.000004 0.000002 0.000001 0.000002 0.000005 0.000006 0.000319 0.000430 0.00041
1946 0.000004 0.000002 0.000291
1947 0.000006 0.000004 0.000572
1948 0.000002 0.000001 0.000145
1949 0.000004 0.000002 0.000330
1950 0.000002 0.000001 0.000246
1951 0.000001 0.000000 0.000233
1952 0.000001 0.000001 0.000108
1953 0.000001 0.000000 0.000409
1954 0.000001 0.000000 0.000194
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APPENDIX E

WIND INDEX

	LAT	LONG	SUMMER	AUTUMN	WINTER	SPRING
Boontjieskraal	34.12	19.21	0.059	0.077	0.061	0.042
Citrusdal	32.34	18.59	0.089	0.111	0.079	0.042
Concordia	33.41	19.51	0.084	0.105	0.080	0.047
Darling	33.23	18.23	0.043	0.061	0.049	0.037
De Doorns	33.28	19.40	0.087	0.109	0.084	0.050
De Keur	32.58	19.18	0.121	0.148	0.101	0.044
Dennehoek	33.52	23.51	0.024	0.030	0.024	0.018
Die Krans	33.33	21.41	0.027	0.034	0.022	0.011
Elandsvlei	32.19	19.34	0.190	0.227	0.143	0.044
Elgin	34.08	19.02	0.057	0.075	0.061	0.043
Exselcior	32.57	19.27	0.134	0.163	0.109	0.044
Graafwater	32.10	18.36	0.090	0.110	0.077	0.040
Grasrug	33.28	18.50	0.075	0.097	0.087	0.063
Constantia	34.02	18.25	0.036	0.052	0.040	0.031
Heldervue	32.49	18.43	0.069	0.073	0.048	0.032
H.J.S. Boland	33.39	18.52	0.122	0.149	0.142	0.101
Hoeko	33.30	21.22	0.039	0.049	0.032	0.013
Jonaskraal	34.24	19.54	0.060	0.077	0.059	0.037
Klawer	31.47	18.38	0.107	0.126	0.084	0.040
Landau	33.36	18.58	0.143	0.172	0.166	0.117
Langebaanweg	32.58	18.10	0.065	0.084	0.063	0.040
Laingkloof	33.47	23.35	0.023	0.028	0.022	0.016
Woseley	33.27	19.12	0.086	0.109	0.091	0.060
Lutzville	31.36	18.26	0.106	0.123	0.082	0.040
Morreisberg	33.09	18.41	0.059	0.078	0.065	0.047
Nietvoorby	33.54	18.52	0.134	0.163	0.157	0.112
Outenequa	33.55	22.25	0.006	0.007	0.006	0.007
Porterville	33.01	19.01	0.084	0.106	0.085	0.054
Prinskraal	34.38	20.07	0.056	0.070	0.051	0.030
Riebeck West	33.21	18.52	0.072	0.093	0.082	0.059
Riversdal	34.05	21.16	0.033	0.041	0.029	0.015
Robertson	33.50	19.54	0.080	0.101	0.077	0.046
Outdshoorn	33.38	22.15	0.003	0.009	0.005	0.003
Serjeantsfontein	34.08	19.31	0.061	0.079	0.063	0.042
Tygerhoek	34.08	19.54	0.063	0.080	0.062	0.039
Veldreserve	33.39	19.27	0.083	0.104	0.086	0.055
Weltevrede	33.56	20.37	0.075	0.092	0.062	0.027
Addo	33.34	25.42	0.020	0.022	0.025	0.023
Barkley East	30.58	27.36	0.091	0.089	0.054	0.039
Bavianskloof	33.34	24.04	0.028	0.034	0.028	0.023
Beaufort West	32.18	22.40	0.053	0.065	0.043	0.022
Beldhouersfontein	32.10	23.55	0.038	0.051	0.038	0.027
Calvinia	31.28	19.46	0.001	0.008	0.010	0.007
Cape Padronne	33.45	26.27	0.025	0.026	0.024	0.023
Carnarvon	30.58	22.00	0.058	0.067	0.045	0.024
Cradock	32.12	25.41	0.066	0.088	0.064	0.047
De Aar	30.39	24.01	0.073	0.105	0.073	0.060
De Tuin	29.56	20.08	0.007	0.005	0.017	0.008
Dohne	32.31	27.28	0.146	0.157	0.075	0.044
Elliot	31.21	27.51	0.028	0.026	0.020	0.021

Kakamas	28.46	20.37	0.059	0.061	0.040	0.033
Keimos	28.24	20.58	0.487	0.508	0.120	0.104
Klipfontein	32.36	25.44	0.918	0.956	0.181	0.177
Lidney	33.40	26.00	0.051	0.068	0.050	0.042
Meintspruit	31.29	24.58	0.023	0.025	0.025	0.023
Middleton	32.59	25.50	0.243	0.401	0.258	0.213
Onseepkans	28.47	19.17	0.038	0.047	0.037	0.032
East London	33.01	27.48	0.183	0.188	0.090	0.061
Opwag	28.53	21.52	0.021	0.016	0.013	0.018
Patensie	33.47	24.50	0.961	1.000	0.181	0.182
Pofadder	29.08	19.23	0.025	0.029	0.027	0.024
Queenstown	31.54	26.52	0.161	0.166	0.086	0.055
Rhebokrand	34.06	24.38	0.066	0.082	0.055	0.046
Rietbron	32.54	23.09	0.025	0.029	0.027	0.023
Rietpoort House	31.45	23.47	0.023	0.031	0.024	0.016
Somerset East	32.44	25.35	0.046	0.061	0.046	0.039
Spitskop	29.35	22.50	0.075	0.079	0.044	0.027
Genr. Steyn	33.24	25.20	0.022	0.024	0.026	0.023
Sutherlabnd	32.23	20.40	0.069	0.082	0.047	0.004
Ugie	31.13	28.16	0.058	0.057	0.037	0.030
Upington	28.27	21.15	0.072	0.075	0.054	0.031
Van Wyksvlei	30.21	21.49	0.081	0.092	0.054	0.028
Welverdiend	30.43	26.43	0.054	0.056	0.008	0.009
Whyte Bank	32.25	26.14	0.045	0.055	0.040	0.035
Winterberg	32.47	26.38	0.035	0.038	0.029	0.027
Bien Donne	33.50	18.59	0.032	0.036	0.038	0.026

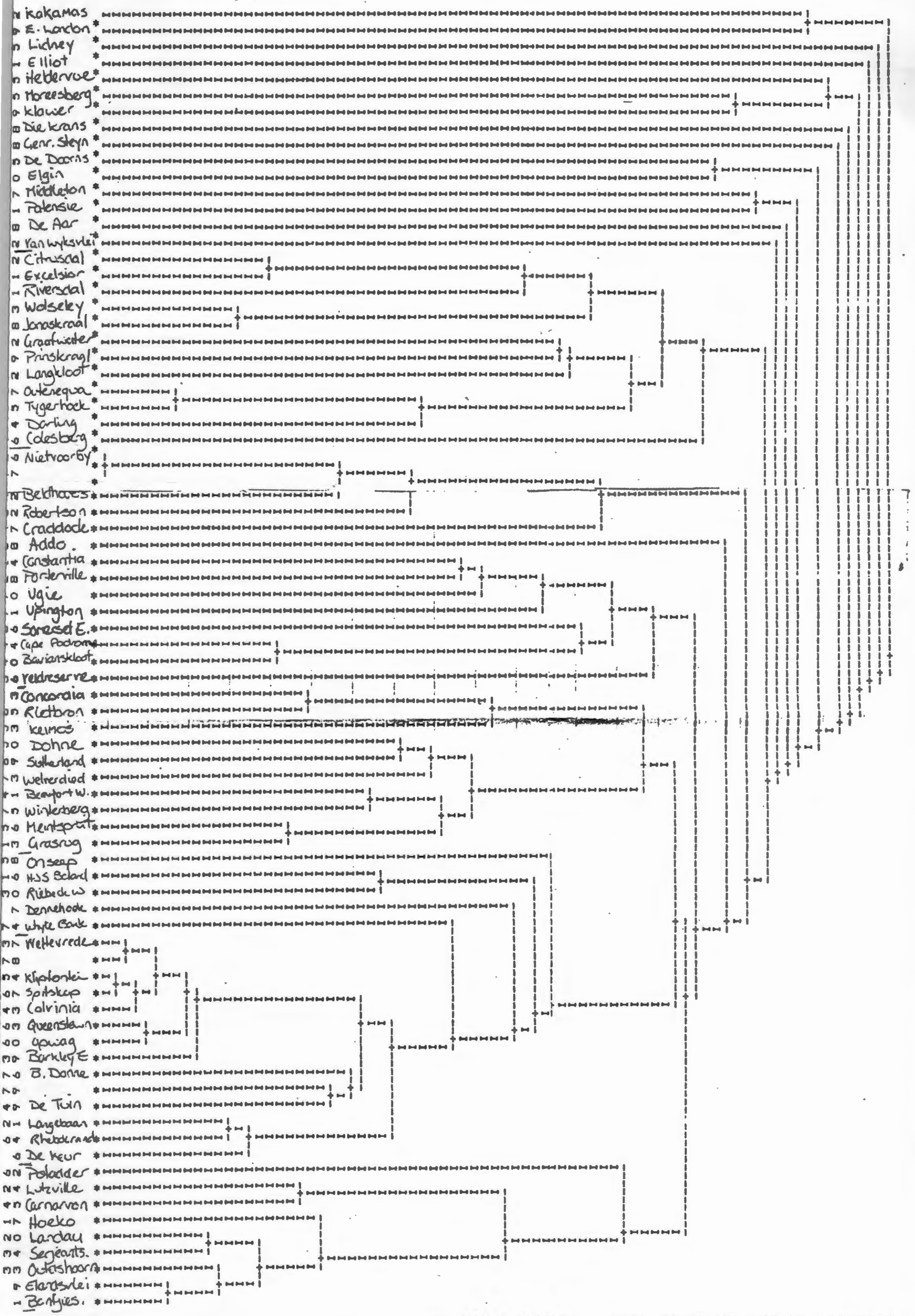
APPENDIX F

ARIDITY INDEX

	LAT	LONG	SUMMER	AUTUMN	WINTER	SPRING
Boontjieskraal	34.12	19.21	0.004	0.002	0.000	0.000
Citrusdal	32.34	18.59	0.034	0.013	0.000	0.003
Concordia	33.41	19.51	0.009	0.000	0.000	0.000
Darling	33.23	18.23	0.014	0.000	0.000	0.000
De Doorns	33.28	19.40	0.061	0.016	0.003	0.003
De Keur	32.58	19.18	0.057	0.017	0.003	0.000
Dennehoek	33.52	23.51	0.037	0.000	0.000	0.000
Die Krans	33.33	21.41	0.037	0.000	0.000	0.000
Elandsvlei	32.19	19.34	0.065	0.028	0.014	0.005
Elgin	34.08	19.02	0.061	0.033	0.011	0.000
Exselcior	32.57	19.27	0.069	0.024	0.008	0.005
Graafwater	32.10	18.36	0.061	0.022	0.017	0.011
Grasrug	33.28	18.50	0.062	0.032	0.013	0.009
Constantia	34.02	18.25	0.067	0.032	0.016	0.016
Heldervue	32.49	18.43	0.065	0.027	0.012	0.007
H.J.S. Boland	33.39	18.52	0.076	0.029	0.009	0.006
Hoeko	33.30	21.22	0.000	0.000	0.000	0.000
Jonaskraal	34.24	19.54	0.008	0.000	0.000	0.000
Klawer	31.47	18.38	0.000	0.000	0.000	0.000
Landau	33.36	18.58	0.006	0.000	0.000	0.000
Langebaanweg	32.58	18.10	0.049	0.017	0.000	0.000
Laingkloof	33.47	23.35	0.058	0.026	0.000	0.000
Woseley	33.27	19.12	0.068	0.019	0.000	0.000
Lutzville	31.36	18.26	0.042	0.017	0.000	0.000
Morreisberg	33.09	18.41	0.050	0.016	0.000	0.000
Nietvoorby	33.54	18.52	0.078	0.028	0.000	0.004
Outenequa	33.55	22.25	0.081	0.030	0.000	0.000
Porterville	33.01	19.01	0.081	0.030	0.000	0.000
Prinskraal	34.38	20.07	0.081	0.028	0.000	0.002
Riebeck West	33.21	18.52	0.081	0.030	0.000	0.000
Riversdal	34.05	21.16	0.004	0.004	0.000	0.000
Robertson	33.50	19.54	0.019	0.004	0.000	0.000
Outdshoorn	33.38	22.15	0.019	0.004	0.000	0.000
Serjeantsfontein	34.08	19.31	0.019	0.005	0.000	0.000
Tygerhoek	34.08	19.54	0.023	0.012	0.000	0.000
Veldreserve	33.39	19.27	0.024	0.013	0.000	0.000
Weltevrede	33.56	20.37	0.024	0.013	0.000	0.000
Addo	33.34	25.42	0.045	0.018	0.000	0.005
Barkley East	30.58	27.36	0.045	0.017	0.000	0.007
Baviaanskloof	33.34	24.04	0.000	0.000	0.000	0.000
Beaufort West	32.18	22.40	0.000	0.000	0.000	0.000
Beldhouersfontein	32.10	23.55	0.037	0.000	0.000	0.000
Calvinia	31.28	19.46	0.037	0.000	0.000	0.000
Cape Padronne	33.45	26.27	0.037	0.000	0.000	0.000
Carnarvon	30.58	22.00	0.063	0.004	0.000	0.000
Cradock	32.12	25.41	0.049	0.006	0.000	0.000
De Aar	30.39	24.01	0.069	0.007	0.021	0.000
De Tuin	29.56	20.08	0.056	0.000	0.019	0.000
Dohne	32.31	27.28	0.040	0.004	0.022	0.004
Elliot	31.21	27.51	0.083	0.000	0.028	0.000

Kakamas	28.46	20.37	0.107	0.048	0.063	0.060
Keimos	28.24	20.58	0.078	0.039	0.061	0.050
Klipfontein	32.36	25.44	0.106	0.039	0.078	0.044
Lidney	33.40	26.00	0.040	0.012	0.069	0.054
Meintspruit	31.29	24.58	0.054	0.012	0.081	0.077
Middleton	32.59	25.50	0.069	0.023	0.083	0.074
Onseepkans	28.47	19.17	0.067	0.024	0.087	0.067
East London	33.01	27.48	0.067	0.024	0.087	0.067
Opwag	28.53	21.52	0.069	0.023	0.083	0.074
Patensie	33.47	24.50	0.111	0.042	0.106	0.088
Pofadder	29.08	19.23	0.059	0.015	0.077	0.071
Queenstown	31.54	26.52	0.073	0.024	0.093	0.093
Rhebokrand	34.06	24.38	0.107	0.044	0.111	0.091
Rietbron	32.54	23.09	0.093	0.037	0.111	0.120
Rietpoort House	31.45	23.47	0.120	0.042	0.106	0.106
Somerset East	32.44	25.35	0.093	0.037	0.111	0.120
Spitskop	29.35	22.50	0.120	0.042	0.106	0.106
Genr. Steyn	33.24	25.20	0.120	0.042	0.106	0.106
Sutherlabnd	32.23	20.40	0.104	0.042	0.104	0.118
Ugie	31.13	28.16	0.117	0.050	0.100	0.111
Upington	28.27	21.15	0.120	0.051	0.106	0.106
Van Wyksvlei	30.21	21.49	0.053	0.019	0.088	0.073
Welverdiend	30.43	26.43	0.120	0.051	0.116	0.106
Whyte Bank	32.25	26.14	0.117	0.050	0.111	0.111
Winterberg	32.47	26.38	0.097	0.039	0.114	0.092
Bien Donne	33.50	18.59	0.071	0.019	0.094	0.086

APPENDIX G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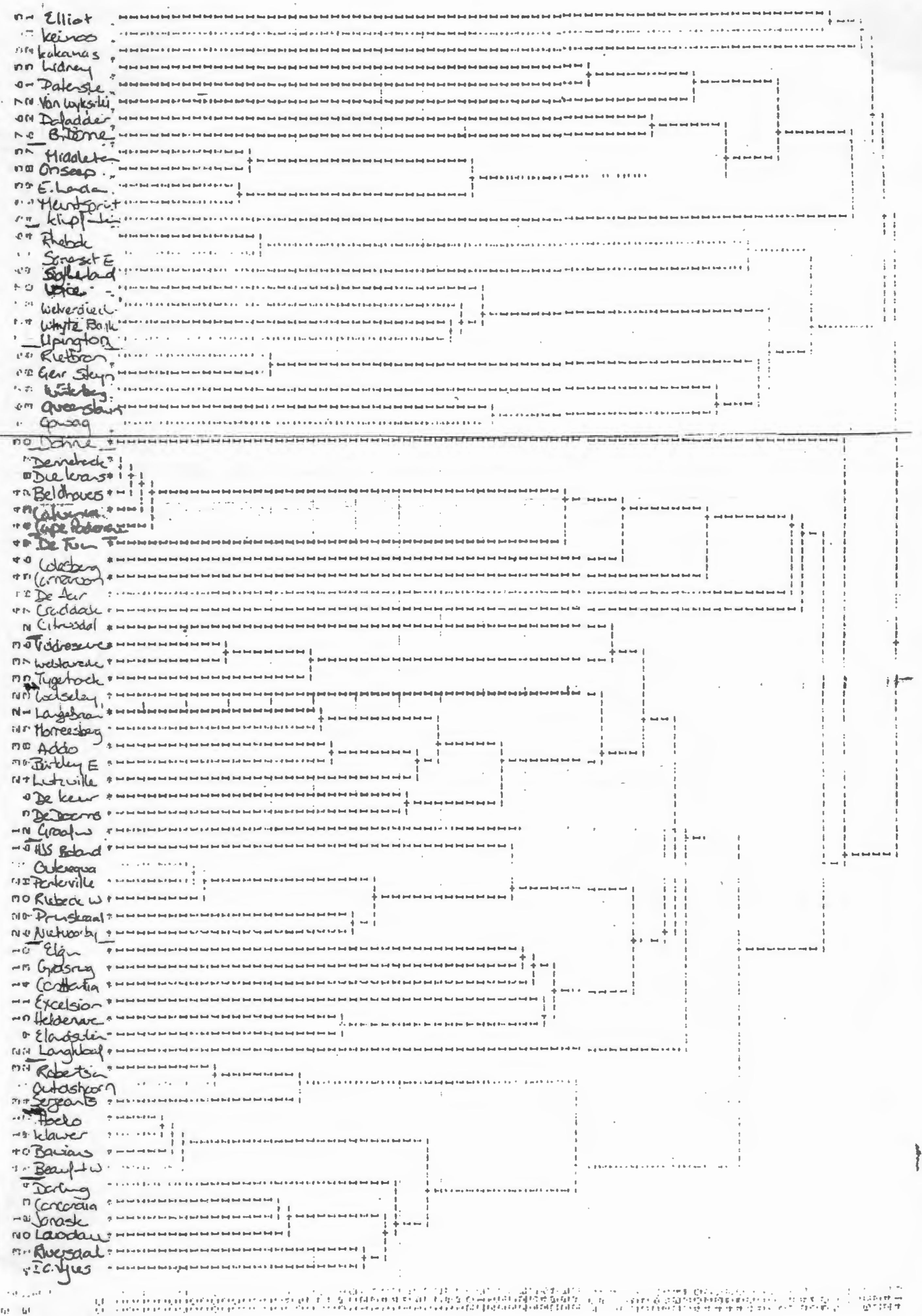
Lichey
Elliot
Helderrue
Moreesberg
Klawer
Die Krans
Genr. Steyn
De Doorns
Elgin
Middleton
Patensie
De Aar
Van Wyksvlei
Citrusdal
Excelsior
Riversdal
Wolseley
Jonaskraal
Graafwater
Prinskraal
Langkloof
Outenequa
Tygerhoek
Darling
Colesberg
Nietvoorby
Bekhoves
Robertson
Craddock
Addo
Constantia
Porterville
Ugie
Upington
Somerset E.
Cape Podrome
Baviaanskloof
Veldreserve
Concordia
Rietbron
Keimos
Dohne
Sutherland
Welverdiend
Beaufort W.
Winterberg
Meintspruit
Grasrug
Onseep
HJS Boland
Riebeeck W
Dennehoek
Whyte Bank
Weltevrede
Klipfontein
Spitskop
Calvinia
Queenstown
Opwag
Barkley E
B. Donne
De Tuin
Langebaan
Rhebokrand
De Keur
Potadder
Lutzville
Carnarvon
Hoeko
Landau
Sergeants.
Oudtshoorn
Elandsvlei
Bontjies.

APPENDIX H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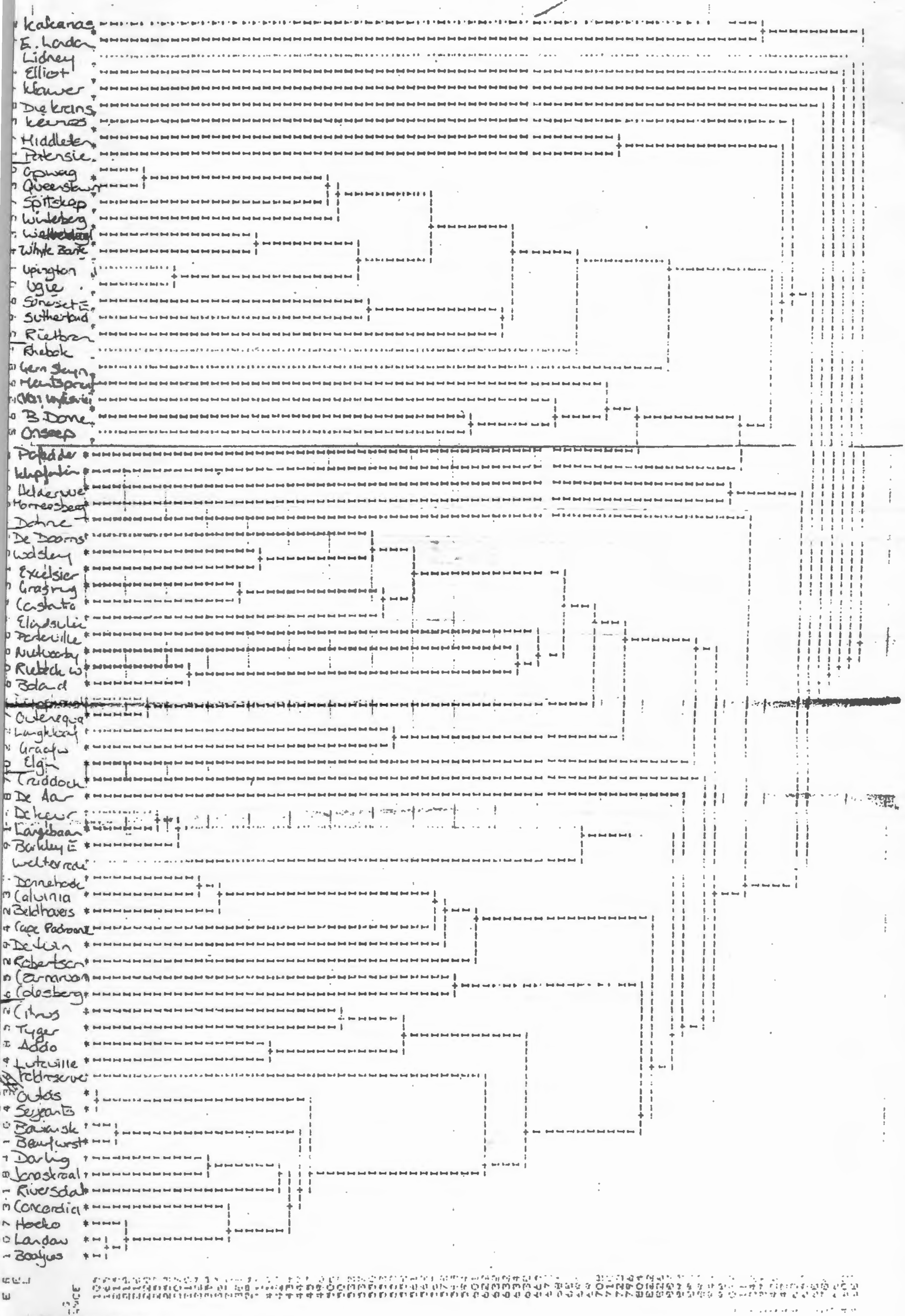
Keimoes
Kakamas
Lidney
Paterstie
Van Wyksvlei
Daladdie
Britome
Middleton
Onseep
E. Londen
Meulspruit
Klipfontein
Rhebok
Somerset E
Sutherland
Venice
Welverdiend
Whyte Bank
Upington
Rietbron
Gen Steyn
Uitenberg
Queenstown
Gousag
Dohne
Dernebock
Die Krans
Beldhoves
Calvinia
Cape Pedorax
De Fum
Colesberg
Carnarvon
De Aar
Cradock
Citrusdal
Tidresewe
Welstande
Tygerhoek
Wolseley
Langebaan
Horreesberg
Addo
Bitley E
Lutzville
De Keur
De Doorns
Graafw
HS Boland
Outeniqua
Porterville
Riebeck W
Prinskraal
Nietvoorbij
Elgin
Grasrug
Constantia
Excelsior
Helderrave
Elandsdrift
Langhoek
Robertson
Oudtshoorn
Sergeants
Hoekio
Klawer
Bavians
Beaufort W
Darling
Concordia
Jonask
Laudau
Riversaal
I.C. Yves

APPENDIX I


Kakamas
E. London
Lidney
Elliot
Klawer
Die krans
Keimoes
Middleton
Patensie
Gpwag
Queenstown
Spitskop
Winterberg
Whyte Bank
Upington
Ugie
Somerset E.
Sutherland
Rietbron
Rhebok
Gem Skeyn
Mentspruit
Van Wyksvlei
B. Done
Onseep
Pofadder
Klipfontein
Uitervue
Morreesburg
Dohne
De Doorns
Wolseley
Excelsier
Grasrug
Castato
Elandsvlei
Porterville
Nietvoorbij
Riebeck W
Boland
Outeniqua
Langkloof
Graafw
Elgin
Cradock
De Aar
Dekeur
Langebaan
Barkley E
Welterrede
Donnehoek
Calvinia
Beldhavens
Cape Padrone
De Kuin
Robertson
Carnarvon
Colesberg
Citrus
Tyger
Addo
Lutzville
Feldreserve
Outdas
Serjeants
Baviansk
Beaufort West
Darling
Jonaskraal
Riversdale
Concordia
Hoeko
Landau
Boofus