STATISTICAL CHARACTERISTICS OF WIND POWER IN KENYA

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LIST OF CONTENTS

CONTENTS PAGE

CONTENTS PAGE

ABSTRACT

The statistical characteristics of wind power in Kenya were investigated in this study with the data consisting of daily maximum, minimum and mean wind speed values from 24 sites in Kenya.

The method of Principal Component Analysis (PCA) was initially applied to the wind speed data in order to determine the spatial similarity in the wind characteristics over Kenya. The results from PCA indicated that the method was able to describe the spatial patterns of the wind by some few uncorrelated factors (eigenvectors). Eleven homogeneous wind categories could be delineated from the spatial patterns of the dominant eigenvectors. Detailed characteristics of the wind power within the eleven regions were then investigated.

The second part of the study fitted several statistical models to the wind speed data. The fitted models included the Lognormal distribution with parameters 2 and 3, the Pearson III and Log Pearson III distributions as well as the Weibull 2 and 3 parameter distributions. It was noted that the 3 parameter Weibull distribution was the best distribution since it fitted the data well at all of the locations considered. The model was subsequently used to estimate the wind power potential at the various homogeneous sites.

It was observed from the weibull estimations that maximum wind power were located around Marsabit/ Maralal regions as well as along the coastal strip of Kenya. Substantial powers were also obtained around Nairobi and Eldoret. The seasonal variability of wind powers at the various locations indicated that the patterns of the total wind powers closely resembled the seasonal characteristics of the winds.

Finally, the variations of wind powers with height were examined at the various locations. The best vertical wind power profile were obtained using the three parameter Weibull distribution. These results generally indicated that the optimum level for wind power generation over Kenya was approximately between 25-30m above the ground level. The cost and benefit factors were however, not considered here.

LIST OF FIGURES

DESCRIPTION PAGE

DESCRIPTION PAGE

DESCRIPTION PAGE

DESCRIPTION | PAGE

LIST OF TABLES

DESCRIPTION PAGE

CHAPTER ONE

1.0 INTRODUCTION

Energy has become the most pervasive problem facing mankind for the last few years. More and more energy is currently required to match the world's rapid rates of population and industrial growths

The present energy crisis that affects most countries of the world to varying degrees is essentially an oil crisis due to the increasing demand for this product. The oil prices have been on the increase year after year though currently these prices have significantly dropped. This current trend may only be temporary.

Before the energy crisis came to light, no significant effort was made in many countries to search for alternative sources of energy to supplement or replace the fossil fuels like coal, petroleum and natural gas. The alternative sources of energy include the geothermal, water, wind and solar energy.

The alternative natural energy like wind and solar energy have several advantages including the fact that they are continuously renewable, cheaper, universally available and do not have harmful ecological effects such as water or air pollution.

The main advantages of these energy sources with particular reference to developing countries is the simplicity, low costs of tapping,maintenance and operations of some of their machines e.g. windmills.

Kenya's population growth rate is about 4% per annum. There has also been a significant growth of the industrial sector in many parts of the country. The major sources of energy in Kenya are firewood, charcoal and oil. Over 70% of Kenya's land is either arid or semi arid. The energy supply from plants (firewood and charcoal) are therefore quite limiting for the fast increasing population and industrial growths.

All the oil used in Kenya is imported with the foreign exchange gained from the exports of the agricultural products. The agricultural products however, depend mainly on rain water which is highly variable in both time and space. The foreign exchange available for oil imports therefore vary significantly from one year to another.

Kenya, like many other nations of the world, therefore urgently requires some alternative sources of energy. The major objective of this work is to study the wind power characteristics in Kenya. The wind power components investigated here include the time and space characteristics of wind and wind power over Kenya. Details of these are discussed in the next section which outlines the objective of the study.

1.1 OBJECTIVES OF THE STUDY

The major objective of this study is to investigate the spatial and temporal characteristics of wind power in Kenya. In order to investigate the spatial and temporal characteristics of wind power in Kenya, the study has been divided mainly into four parts. The first part investigates the spatial and temporal similarities in the characteristics of the winds over Kenya. Most of these characteristics were derived from Principal Component Analysis (PCA).

In the second phase, the best statistical model(s) which may be used to describe the wind characteristics over Kenya were investigated. The statistical models fitted included the Lognormal distributions with 2 and 3 parameters, the Pearson III and Log Pearson III distributions as well as the Weibull 2 and 3 parameter distributions. In the third part, the various characteristics of the wind power in Kenya were examined using the best fitted distribution.

Since the standard level for wind measurements are at 10m above the surface, while the optimum wind powers are often at higher levels. The final part of the study investigated the vertical characteristics of the wind power at various parts of Kenya so as to determine the optimum level for wind power utilization. The methods used in this case included the Weibull extrapolations formula, the $1/7^{th}$ power law and the logarithmic power profile. In the next section, the literature which were relevant to the study are reviewed.

1.2 LITERATURE REVIEW

Wind power studies have been carried out by many scientists, institutions and research organisations. (Putnam, 1948; W.M.O., 1954; Golding, 1955; Skibin, 1984).

World Meteorological Organisation (1954) outlines some of the simple procedures which may be considered for any planned project on the utilization of wind as an energy source.

Putnam (1948) and Golding (1955) carried out intensive study on utilization of wind power for the generation of electricity. They suggested a number of useful procedures which may be followed during site selection for wind powered generators. They observed that the best sites for such generators were smooth rounded hills with little or no obstructions. Daniels, Ramage, Schroeder and Thompson (1977); Daniels and Oshiro (1980) and Norman (1981) also made similar suggestions from their wind power studies in Hawaii.

Skibin (1984) suggested that for any method to represent an area and predict the wind power at a particular site within it, the area should be reasonably flat, homogeneous and not too large since large areas (diameter $\geq 10^3$km) may contain different climates, ridges and other local changes. He observed that if a region is not homogeneous, surface properties like land - sea - lake interfaces or variable roughness parameters might strongly influence the local wind velocity profile.

A number of investigators have also sought simple wind speed distributions which could be parameterized solely by the mean wind speed for use in various applications. (Hennessey, 1977; Justus, Hargrave and Amir, 1978; Tackle and Brown, 1978; Stewart and Essenwanger, 1978; Mage, 1979; Stanton and Brett, 1983).

Hennessey (1977) examined some of the aspects of wind power statistics for wind generators. He observed that the existing wind power studies based solely on the total mean power density do omit much of the valuable information about the wind power potential of a site. For instance, he observed that while the average power output of a wind powered generator not only depends on the mean wind speeds, but has also a dependence on a factor like the variance of the wind speed about the mean. He stressed that the most accurate method for computing the wind power density was to use the general relationship between the expectation of the third non-central moment and the mean, standard deviation and skewness of the wind speed.

Justus, Hargrave and Amir (1978), Tackle and Brown (1978), Stewart and Essenwanger (1978), Mage

(1979), Stanton and Brett (1983) examined the characteristics of the Weibull distribution in relation to the surface wind speed distribution. They found that the Weibull distribution was a good model that adequately describes most wind speed distribution. They observed that with the Weibull model, it was easier to obtain the frequency distribution of the wind speed cubed for wind power analysis. Justus et al (1978) subsequently used the Weibull distribution to compute the power output from wind generators in the United States.

Van der Auwera (1980) successfully fitted the observed wind speed data for Belgium to four statistical distributions namely, the Lognormal, Gamma, Rayleigh and the Weibull parameter distributions. He observed that the wind power density estimates were strongly dependent on the hypothesized density function. His results showed that the Weibull density function with 3 parameters gave the best fit to the wind speed frequency data. He observed that once the mean of the cube of the wind speeds have been determined, it was easier using the Weibull distribution to determine the total wind power. He concluded that the Weibull distribution generally gave a good fit to the observed wind speed distribution due to its flexibility at its tails.

The standard recording level for most of wind instruments are at 10m above the surface. Optimum level for wind power outputs are however, generally at higher levels. Many attempts have therefore been made to study the vertical variation of the wind and wind power potentials (Carruthers, 1943; Demarrais, 1959; Justus and Michael, 1976; Doran and Verholek, 1978; Fraenkel 1979).

Carruthers (1943) and Demarrais (1959) proposed two forms of the wind power profile at a projected wind power site which can be used to estimate the power at various heights above the ground. They observed that these formulae tended to give reasonable power estimates at the levels set for wind generators. They also observed that stronger winds do prevail at higher levels of approximately 100-200m above the ground. They similarly observed that there was generally a rapid increase of wind speed with height upto 200m.

Justus and Michael (1976) proposed a set of formulae which allowed for vertical extrapolation of wind power from the Weibull scale parameter (α) and shape parameter (β). These formulae were later examined by Doran and Verholek (1978) who found that they were sufficiently useful for ensemble averages but tended to slightly give over-estimates in individual cases.

The power law has also been widely used to study the vertical profile of the wind speeds. Fraenkel (1979) used the method to estimate wind speeds at various levels above the ground using an exponent of 0.17 for average ground surface. The computed values of wind speeds at these levels were in close agreement with the observed wind speeds.

In Kenya, Chipeta (1976) studied monthly and annual surface mean scalar wind speeds in relation to wind power. He computed the wind power by cubing the wind speeds in the frequency tables after correcting for mean air density. However, according to Hennessey (1977), errors are inherent in such computations due to the small number of frequency classes. Chipeta's results revealed that high wind speeds are generally recorded between 12.00 - 15.00 hours local time.. He also found that higher wind power values were mainly concentrated around the Eastern province and the coastal strip of Kenya. Low values of the wind power were centred around the central and Rift Valley regions.

In this study, the statistical characteristics of wind power in Kenya are examined using some statistical models. The horizontal and vertical variations in the wind power are also investigated. The data used are presented in the next section.

1.3 THE DATA USED IN THE STUDY

The data used in this study consisted of daily wind speeds from 24 stations all over Kenya. The daily wind components available included daily maximum, minimum and mean wind speed values and direction. The daily wind data were within the period 1946 - 1980. For some comparison purposes, the standard period 1975 - 1980 was used. This period was determined by the availability of continuous daily wind records from all stations.

The spatial distribution of the wind stations used are presented in Figure 1. All the wind data were collected from the Kenya Meteorological Department in Dagoretti. It should be noted that although most of the observational sites are located mainly at airports or airstrips and other town centers which may not be representative of other specific sites proposed for the utilization of wind power, the wind measuring instruments are, however, generally located over relatively homogeneous surfaces hence permitting a large scale comparative assessment.

Table 1 presents the heights of the various sites above mean sea level (MSL). Before discussing the basic methods which were used in the study, the wind climatology is briefly presented in the next section.

1.4 THE CLIMATOLOGY OF WINDS OVER KENYA

The general flow pattern of the atmospheric winds are determined by the pressure gradients induced by the differential solar heating over the globe. Although the diurnal and the seasonal characteristics of the winds are controlled by the diurnal and the seasonal patterns of the solar radiation, regional factors like topography and large water surfaces significantly modify the mean wind flow pattern at the low and middle levels. The locally induced wind circulations like Anabatic/Katabatic winds, Channel winds, Land/Sea breezes cannot be neglected since they may be dominant in some areas. Figure 2 shows a schematic illustration of some of the local factors that influence the wind at low levels.

The seasonal patterns of the wind over East Africa are dominated mainly by the two monsoonal wind systems, namely the South East and the North East Monsoonal winds. The North East Monsoon occurs during the southern hemisphere summer season while the South East Monsoonal winds occur during the northern hemisphere summer season. The North East Monsoon air current has two dominant tracts. One tract is hot and dry continental air mass, while the other is a moist maritime component. The North-East Monsoons are generally drier due to their large tract over land. Some examples of the mean seasonal wind patterns in Kenya are presented in figures 3 and 4. Detailed characteristics of the seasonal winds can be obtained from Anyamba (1984).

Due to complex topographical patterns and the existence of many large inland lakes, the synoptic wind patterns are significantly modified at low levels over many regions. The large water surface include the Indian Ocean, Lake Victoria and Lake Turkana. Lake Victoria is one of the largest fresh water lakes in the world. Majority of the small water bodies are confined mainly within the Rift Valley. They include Lake Nakuru, Naivasha, Magadi and Elementaita. The complex topography range from the sea level to heights of over 2500m in the central, southern and western parts of Kenya. Figure 5 shows the topographical features of Kenya. Very strong mean winds have been observed in some areas due to channeling effects of these winds by mountains. (Asnani and Kinuthia, 1984).

In the next section, we will present the various methods which were used in this study to investigate the wind power characteristics over Kenya.

Fig. I SPATIAL DISTRIBUTION OF THE 24 SITES USED IN THE STUDY.

TABLE 1 - STATIONSUSED IN THE ANALYSIS, THEIR HEIGHTS ABOVE MSL, LONGITUDINAL AND LATITUDINAL LOCATIONS

Station Name	Station Code No.	Height (AMSL)	Latitude °	Latitude '	Longitude °	Longitude ' E	Number of Years of Observation.
Nyeri	1	1829	0	26S	36	57	12
Marsabit	2	1345	2	19N	37	59	17
Mombasa	3	16	4	04S	39	42	14
Malindi	4	566	3	07N	35	37	22
Lodwar	5	1113	3	43S	39	03	24
Moyale	6	331	3	56N	41	52	23
Mandera	7	2133	1	06N	36	43	15
Maralal	8	3	3	13S	40	07	17
Kericho	9	1982	0	23S	35	17	9
Kisumu	10	1146	0	06S	34	35	5
Wajir	11	244	1	45S	40	04	31
Eldoret	12	2084	0	30N	35	18	35
Meru	13	1554	0	03N	37	38	9
Kitale	14	1829	0	54N	34	55	8
Thika	15	1549	1	01S	37	06	14
NRB Wilson	16	1891	1	15S	36	44	10
NRB Dagoretti	17	1891	1	15S	36	44	16
Makindu	18	1000	2	17S	35	50	23
Lamu	19	9	2	16S	40	54	11
Voi	20	560	3	24S	38	34	33
Narok	21	1890	1	08S	35	50	31
NRB—Embakasi	22	1891	1	15S	36	44	11
Garissa	23	128	0	26S	39	38	30
Nakuru	24	1851	1	43S	36	26	6

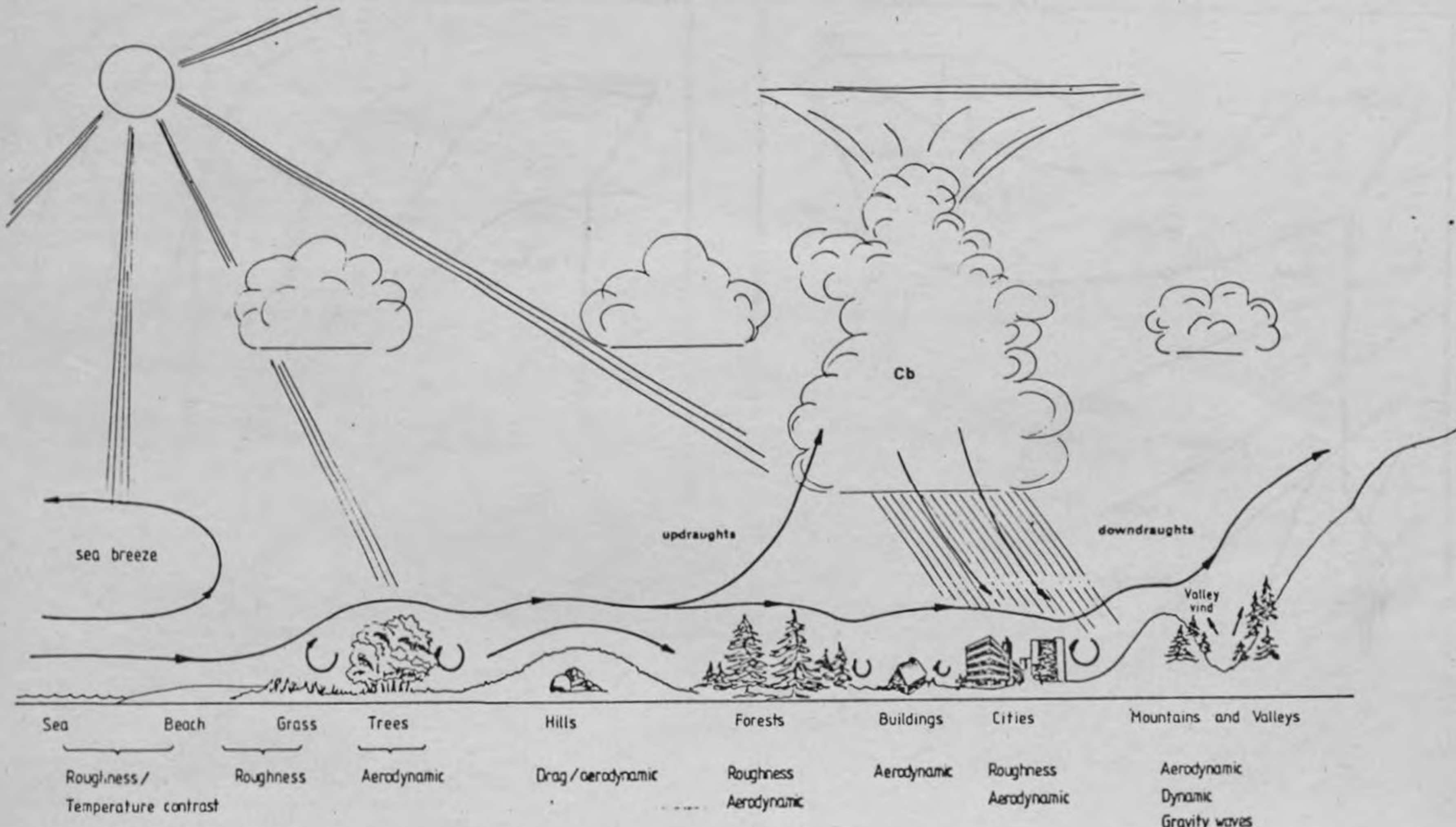


Figure 2 - Schematic illustration of local factors influencing the wind (W.M.O., 1981).

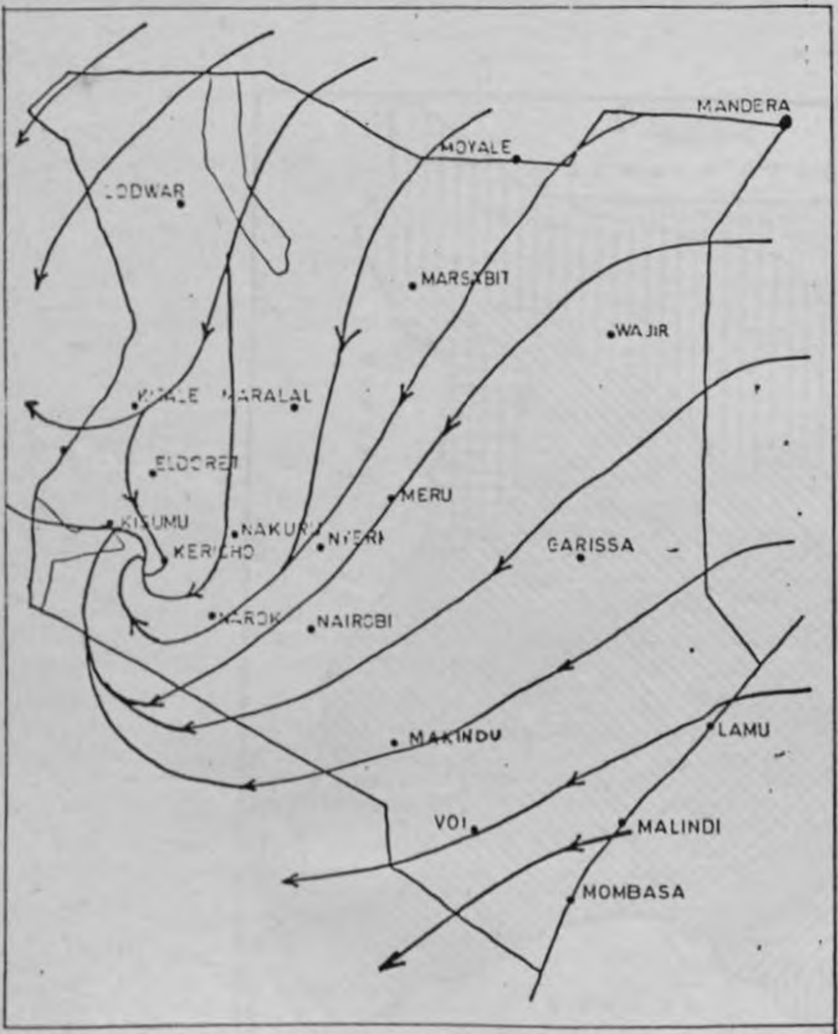


FIG. 3 :— MEAN WIND FLOW FIELD PATTERN OVER KENYA IN JANUARY AT SURFACE LEVELS (ANYAMBA, 1984)

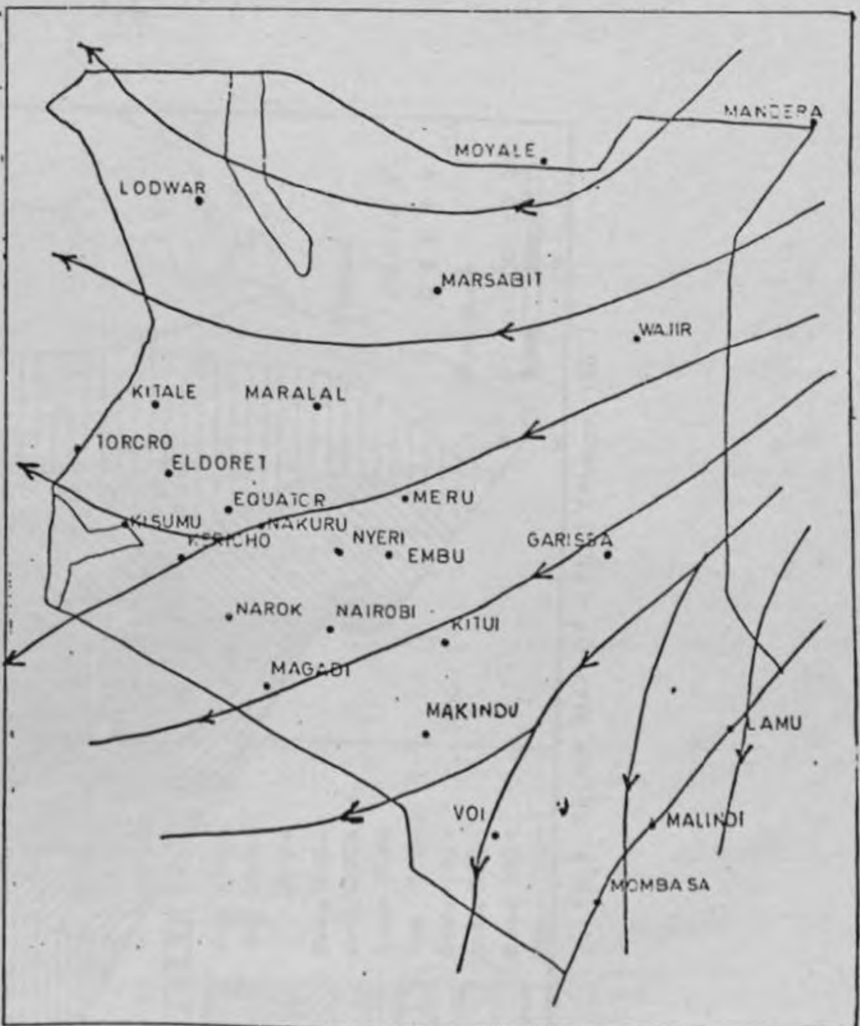


FIG. 4:— MEAN WIND FLOW PATTERN OVER KENYA IN DECEMBER AT 1525 m (ANYAMBA, 1984)

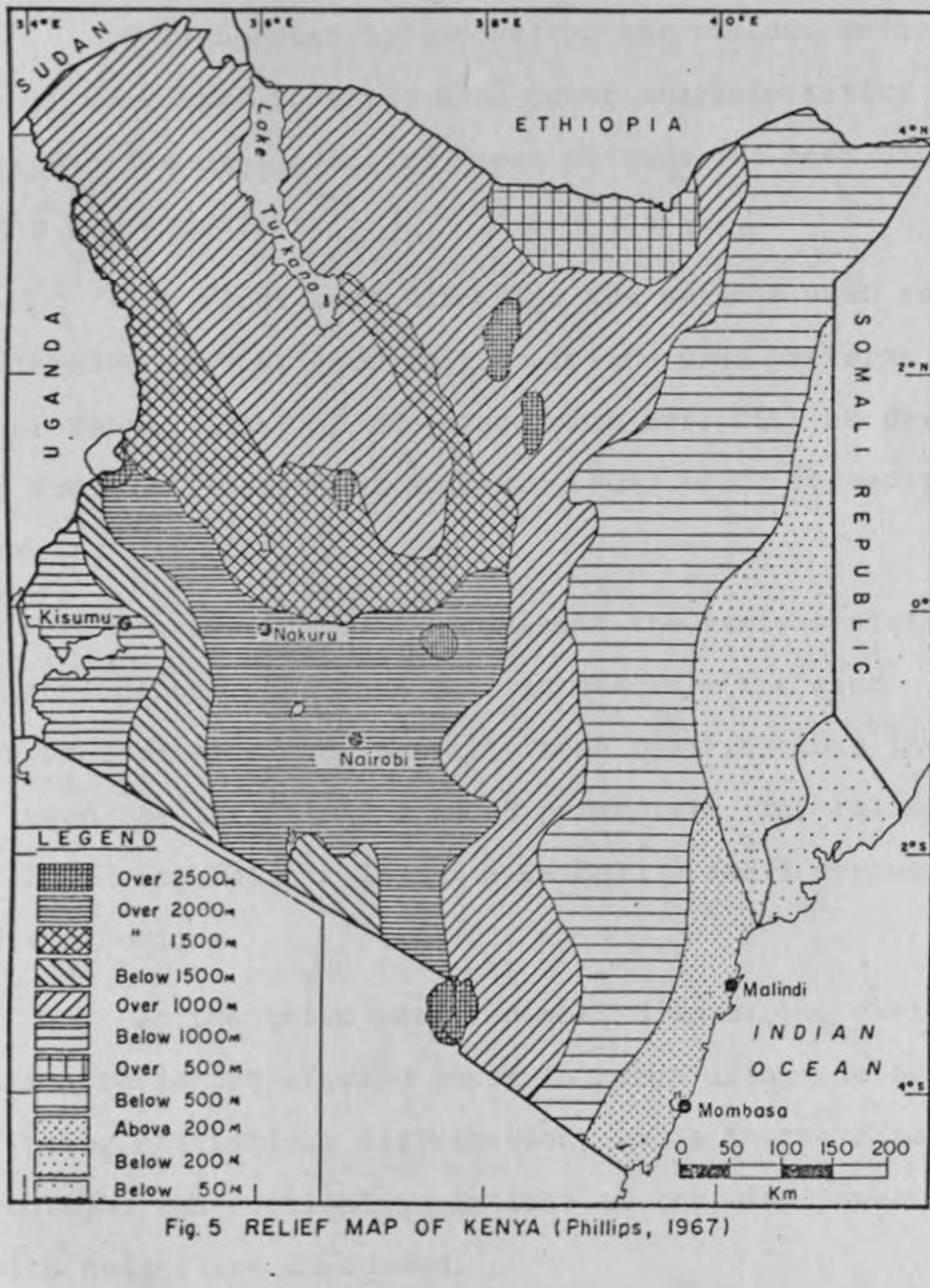


Fig. 5 RELIEF MAP OF KENYA (Phillips, 1967)

CHAPTER TWO

2.0 METHODOLOGY

This chapter is devoted to the various methods which were used to study wind power characteristics in Kenya. The discussion of these methods has been divided into four sections.

The first part discusses the methods used to determine spatial similarities in the wind patterns over Kenya. Most of the discussion here will be devoted to Principal Component Analysis (PCA) which formed the core of the section.

In section two, we present the various statistical distributions that were used to describe the wind characteristics over Kenya. These distributions included the Log-normal 2 and 3 parameters, the Pearson III and Log-Pearson III, the Weibull 2 and 3 parameter distributions.

In the third part, we will discuss the various characteristics of wind power in Kenya using the best fitting statistical distribution, while in the final section, the vertical variations of the wind power with height are discussed.

2.1 PRINCIPAL COMPONENT ANALYSIS

A number of investigators have used the method of Principal Component Analysis to examine the spatial and temporal patterns of some meteorological paramemeters.

Walsh and Mostek (1980) for example, constructed eigenvectors of surface temperatures, precipitation and sea level pressure anomaly fields over the United States for the period 1900 - 1977. Wallace and Gutzler (1981) used the method to examine the teleconnection patterns in the winter-time planetary circulations by statistical techniques.

Gregory (1975), Dyer (1977), Ogallo (1980) and many others have used the method to delineate rainfall stations into homogeneous regions.

Basically, the principles of PCA are derived from the concepts of variance. The first step usually involves the computation of some measures of association for the set of variables. This is usually done by using the correlation or covariance matrix of the variables. This is then followed by the construction of a set of orthogonal functions that are finally used to represent the variables.

The Principal Component Analysis in terms of m empirical orthogonal functions may be expressed as:

$$Z_j = a_{j1}F_1 + a_{j2}F_2 + \dots + a_{jm}F_m + \beta_i u_j \quad \dots (1)$$

where the normalised measured variable Z_j is described linearly in terms of m uncorrelated components (eigenvectors) $F_1, F_2, \ldots, F_m$

a_{ji} - standard multiple regression coeffients of variable j on factor i (factor loading)

$\beta_i U_j$ - The unique (error) component of the variance.

For many meteorological variables, the unique component of the variable $\beta_i U_j$ is difficult to estimate and is often neglected. Equation (1) then reduces to the simple Factor Analysis model. This simplified model of PCA was employed in this study to determine the spatial characteristics of the winds in Kenya. Details of the method may be obtained from Harman (1967), Child (1978) and many others.

The orthogonal functions are mathematically independent while the physical processes associated with many meteorological variables are generally not orthogonal. Several methods have been used to readjust the frames of referance for the orthogonal functions. These processes of adjusting the frames are known as rotations. (Harman, 1967). In this study the orthogonal varimax rotations were used (Kaiser, 1958). This involves the rotation of the significant eigenvectors through 90°.

Several methods have also been used to determine the number of significant eigenvectors to be retained in the rotated solutions. These include the Kaisers criterion (Kaiser, 1958), Scree test (Child, 1978), Lev method (Craddock, 1973) and Sampling errors in the eigenvalues (North et al, 1982).

Kaiser's criterion retains eigenvalues greater than unity during the rotation, while in the Scree test the eigenvalues are plotted against the factor numbers. The cut off value for the rotation is determined from the ordinate point when the graph develops into a linear relationship. In the case of Lev method, the logarithms of the eigenvalue are plotted instead of the actual eigenvalues. In the last method, the sampling errors in the eigenvalues are used to determine the number of significant orthogonal functions which could be retained for the rotations.

Both the Kaisers criterion and the Scree test were used in this study in order to determine the number of eigenvectors to be subjected to orthogonal varimax rotations. The rotated solution and the unrotated solutions obtained with the spatial correlation matrix were then used to describe the spatial similarity in the characteristics of the winds in Kenya. The rotated eigenvectors are generally easier to explain physically than are the unrotated eigenvectors.

Usually the first eigenvectors are viewed as the single best summary of linear relationships exhibited in the data. The second components are defined as the second best linear combination of variables under the condition that the second component is orthogonal to the first and so on.

The spatial patterns of the significant eigenvectors can be used to determine the temporal characteristics of some spatial variables (Gregory, 1975; Dyer, 1977; Ogallo, 1980). All spatial variables with similar characteristics will cluster together under similar eigenvectors.

The method was employed here to determine the spatial similarity in the characteristics of the winds over Kenya. Under this method, the spatial patterns of the regression weights (a_{ji}) on the various eigenvectors were used to determine the similarity in the wind characteristics between the locations. Stations with similar wind characteristics will cluster on identical eigenvectors. These patterns were then used to group the various stations into homogeneous wind divisions.

In order to conform the patterns of the regional groups, the rotated components were further presented graphically in a two dimensional vector space of the pairs of reference axes determined by the significant eigenvectors. Interstation correlations were also examined.

The spatial characteristics derived from these methods were useful especially with respect to determining the regional data to be used under statistical modelling as discussed in the next section.

2.2. STATISTICAL DISTRIBUTIONS FITTED

Many statistical distributions have been used to describe the characteristics of the wind speeds and wind power. This section is devoted to the statistical distributions which were used in the study.

These distributions included the two and three parameter Lognormal, the Pearson type III and the Log-Pearson III, the Weibull 2 and 3 parameter distributions. Details of these distributions are discussed independently in the following sections.

2.2.1 THE LOGNORMAL 2 AND 3 PARAMETER DISTRIBUTIONS

Consider the transformation $Y = \ell n(x)$. It can be shown that if x is lognormal then Y is normal. Here it may be emphasized that x cannot assume zero values since the transformation $Y = \log(x)$ is not defined at $x = 0$. However, there are ways of solving such problems whenever they arise.

The Lognormal-2 parameter PDF can be written as

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left[-\tfrac{1}{2}\left(\frac{\ell n(x)-\mu}{\sigma}\right)^2\right] \quad \ldots\ldots (2)$$

where the two parameters are:

μ is the location parameter (mean of the logs).

σ is the scale parameter (standard deviation of the logs).

The mean and the variance are given by

$$\mu_x = e^{(\mu+\frac{1}{2}\sigma^2)} \qquad \text{.... (3)}$$

$$\sigma_x^2 = e^{(2\mu+\sigma^2)} \cdot \left[e^{\sigma^2}-1\right] \qquad \text{.... (4)}$$

The coefficient of variation is

$$z = \frac{\sigma_x}{\mu_x} = (e^{\sigma^2}-1)^{\frac{1}{2}} \qquad \text{.... (5)}$$

while the skewness and kurtosis are

$$\lambda_3 = z^3+3z \qquad \text{.... (6)}$$

$$\lambda_4 = z^8+6z^6+15z^4+16z^2+3 \qquad \text{.... (7)}$$

The cumulative distribution of the 2 parameter Lognormal is given by

$$F(x) = \frac{1}{\sigma\sqrt{2\pi}}\int_0^x \frac{1}{x}\exp\left[-\frac{(\ell n(x)-\mu)}{2\sigma}\right]^2 dx \qquad \text{....(8)}$$

It can be seen that this distribution is always positively skewed and the greater the value of σ^2, the greater is the skewness. Similarly the kurtosis is always positive as indicated by equations (6) and (7) respectively.

The 3 parameter Lognormal distribution may be obtained by replacing x with $(x-x_o)$ in the R.H.S. of equation (2) where x_o is a lower boundary.

The probability density function and the cumulative density function then becomes:

$$f(x) = \frac{1}{(x-x_o)\sigma\sqrt{2\pi}} \exp\left[-\left(\frac{\ln(x-x_o)-\mu}{2\sigma}\right)\right]^2 \quad \ldots\ldots (9)$$

$$F(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} \frac{1}{(x-x_o)} \exp\left[-\left(\frac{\ln(x-x_o)-\mu}{2\sigma}\right)\right]^2 dx \quad \ldots. (10)$$

respectively.

The parameters μ, σ and x_o are called the scale (mean of $\ln(x-x_o)$), the shape (standard deviation of $\ln(x-x_o)$) and the location parameter respectively. This distribution can be applied to positive or negative valued events provided $(x-x_o) > 0$.

The mean, the variance and the location parameters are given by

$$\mu = x_o + \exp(\mu + \sigma^2/2) \quad \ldots. (11)$$

$$\sigma^2 = [\exp(\sigma^2)-1] \exp(2\mu + \sigma^2) \quad \ldots. (12)$$

$$x_o = \mu - \sigma/z_2 \quad \ldots. (13)$$

respectively.

where $z_2 = (\sigma/\mu - x_o)$

The coefficient of skew is given by

$$\gamma = 3z_2 + z_2^3 \qquad \text{.... (14)}$$

2.2.2 THE PEARSON TYPE III DISTRIBUTION

This is a Gamma distribution with three parameters. The probability density function of the Pearson III is of the form.

$$f(x) = \frac{1}{\alpha\Gamma(\beta)}\{\frac{x-x_o}{\alpha}\}^{\beta-1} \exp\{-(\frac{x-x_o}{\alpha})\} \qquad \text{.... (15)}$$

$$\alpha > 0, \beta > 0, \quad x_o \leq x < \infty$$

where α and β are the scale and shape parameters respectively and x_o is the location parameter. $\Gamma(\beta)$ is the usual Gamma function.

The cumulative distribution for pearson type III takes the form.

$$F(x) = \frac{1}{\alpha\Gamma(\beta)}\int_o^x \{\frac{x-x_o}{\alpha}\}^{\beta-1} \exp\{-(\frac{x-x_o}{\alpha})\}dx \qquad \text{.... (16)}$$

The mean, the variance, skewness and kurtosis takes the forms

$$\mu = \alpha\beta + x_o$$

$$\sigma^2 = \alpha^2\beta \qquad \text{.... (17,a,b,c,d)}$$

$$\gamma = 2\sqrt{\beta}$$

$$k = 3(1 + \gamma^2/_2)$$

respectively

2.2.3 THE LOG-PEARSON TYPE III DISTRIBUTION

If the logarithms, $\ell n\ (x)$ of a variable x are distributed as a Pearson type III variate then the variable x will be distributed as Log-Pearson type III probability density function and takes the form

$$f(x) = \frac{1}{\alpha\Gamma(\beta)} \cdot \frac{1}{x}.\{\frac{\ell n(x)-y_o}{\alpha}\}^{\beta-1}\exp\{-(\frac{\ell n(x)-y_o}{\alpha})\} \quad \text{.... (18)}$$

for $0 < x < \infty$

where α, β and $y_o = (\ell nx)_o$ are the scale, shape and location parameters in the log domain respectively.

The probability density function for the cumulatives of the log Pearson is given by the expression.

$$F(x) = \frac{1}{\alpha\Gamma(\beta)}\int_o^x \frac{1}{x}\ \{\frac{\ell n(x)-y_o}{\alpha}\}^{\beta-1}.\exp\{-(\frac{\ell n(x)-y_o}{\alpha})\}dx \quad \text{... (19)}$$

The PDF of the Log-Pearson III may be J - shaped, reverse J-shaped, U-shaped, inverted U-shaped with inflexion, bell shaped with upper or lower bounds e.t.c.

2.2.4 THE WEIBULL 2 AND 3 PARAMETER DISTRIBUTION

The Weibull distribution with two and three parameters has been widely used in wind power analysis. The Weibull two parameter distribution is a special case of the generalised three parameter Gamma distribution and has a density function given by

$$f(x) = \frac{\beta}{\alpha} \left(\frac{x}{\alpha}\right)^{\beta-1} \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right] \qquad \dots . \ (20)$$

$x \geq 0, \ \beta > 0, \ \alpha > 0$

$= 0$, otherwise

where α and β are the scale and a dimensionless quantity called the shape parameter respectively.

The cumulative distribution function for the Weibull 2 parameter distribution is given by

$$F(x) = 1-\exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right], \quad x \geq 0 \qquad \dots . \ (21)$$

$= 0$, otherwise

This Pdf has its mean and variance in terms of Gamma function.

$$\mu = \alpha\Gamma(1 + 1/_{\beta}) \qquad \text{.... (22) (a,b)}$$

$$\sigma^2 = \alpha^2\left[\Gamma(1+2/\beta) - \Gamma^2(1+1/_{\beta})\right]$$

The third and fourth moments are similarly in terms of the Gamma function but will not be discussed here.

The expectation of its third non-central moments is

$$E(x^3) = \alpha^3\left[\Gamma(1+{}^3/_{\beta})\right] \qquad \text{....(23)}$$

For cases where the Weibull model adequately describes the wind speed distribution, it is always possible to determine the frequency distribution of the speed cubed. With the transformation $Y = x^3$, the Weibull distribution becomes

$$f(Y) = \alpha^{-\beta}(\beta/_3)Y^{\beta/_3 - 1}\exp\left[-\alpha^{-\beta}Y^{\beta/_3}\right] \qquad \text{.... (24)}$$

$$Y > 0$$

$$= 0, \text{ otherwise}$$

The expectation and variance of Y in terms of the parameter μ and β are

$$E(Y) = \mu^3\left[\Gamma(1+{}^1/_{\beta})\right]^{-3}\Gamma(1 + 3/_{\beta}) \qquad \text{.... (25)}$$

$$\text{Var}(Y) = \mu^6 \left[\Gamma(1+{}^1/_\beta)\right]^{-6} \left[(1+{}^6/_\beta)-\Gamma^2(1+{}^3/_\beta)\right] \quad \text{.... (26)}$$

where E(Y) is the mean of the pdf for the speed cubed. Var(Y) is the variance of the total power density in the wind since this is the variance of the speed cubed.

In the case of Weibull 3 parameter distribution, X and α in the right hand side of equation (20) are replaced by $(x-x_o)$ and $(\alpha-x_o)$ respectively where x_o is the lower bound of x. The cumulative distribution function for the 3 parameter Weibull distribution is expressed as:

$$F(x) = \exp\{-(\frac{x-x_o}{\alpha-x_o})^\beta\} \quad \text{.... (27)}$$

The mean and variance of Weibull 3 parameter distribution is given by

$$\mu = x_o+(\alpha-x_o)\Gamma(1+{}^1/_\beta) \quad \text{.... (28a)}$$

$$\sigma^2= (\alpha-x_o)^2\{\Gamma(1+{}^2/_\beta)-\Gamma^2(1+{}^1/_\beta)\} \quad \text{.... (28b)}$$

The Weibull three parameter (hypergamma or modified gamma) probability distribution function is a more powerful family of probability density curves (Var der Auwera, 1980). It is a generalisation of more conventional probability density functions. The relationship between the 3 parameter Weibull pdf with some of the probability density functions is summarised in Table 2 below.

Table 2 - Probability Density Functions Derivable from Weibull - 3 Parameter pdf.

PDF	Parameter		
Weibull 3	α	β	x_o
Weibull 2	α	β	α
Gamma	1	β	α
Chi	2	$\alpha\beta^2/2$	α
Rayleigh	2	$\beta^2/2$	2
Exponential	1	β	1

Detailed discussions of other uses of the Weibull distribution will be given in the later sections.

The first step in fitting any type of models is the estimation of the model parameters. In the next section, we will describe the various methods which were used to estimate the model parameters in this study.

2.2.5 ESTIMATION OF MODEL PARAMETERS

There are several methods that can be used to estimate the parameters of a distribution. This section will however, be devoted to the two methods which were used in this study.

The two methods were the method of moments and the method of maximum likelihood. Detailed discussions of the other methods can be obtained from Beck (1977).

2.2.5.1 METHOD OF MOMENTS

The method of moments utilizes either the general equation for calculating the r^{th} moment about the origin of distribution f(x).

$$\mu'_r = \int_{-\infty}^{\infty} x^r f(x)dx \qquad \text{.... (29)}$$

or the corresponding equation for central moments of the distribution

$$\mu_r = \int_{-\infty}^{\infty} (x-\mu'_1)^r f(x)\, dx \qquad \text{.... (30)}$$

where the first moment μ_1 corresponds to the arithmetic mean and the second moment μ_2 is the variance e.t.c. The method of moments often relates the derived moments to the parameters of the distribution.

2.2.5.2 THE METHOD OF MAXIMUM LIKELIHOOD

The principle of maximum likelihood states that for a distribution with a probability density function $f(x, \alpha, \beta .....,)$, the probability of obtaining a given value x, x_i, and the joint probability, L of obtaining a sample of n values x_1, x_2,...., x_n is proportional to the product

$$L = \prod_{i=1}^{n} f(x_i, \alpha, \beta, ...,) \qquad .... (31)$$

where α, β ,.... are the distribution parameters to be estimated. This is called the likelihood. The method of maximum likelihood is to estimate the parameters α, β,...., such that L is miximised. This is obtained by partially differentiating the parameters and equating to zero. Frequently, $\ell n(L)$ is used instead of L to simplify the computations. The method of maximum likelihood is more laborious but usually gives reliable results compared to the method of moments which is simpler.

In the following sections we will discuss the methods which were used to estimate the parameters of the individual distributions.

2.2.5.3 THE PARAMETER ESTIMATION FOR LOGNORMAL 2 AND 3 DISTRIBUTIONS.

The method of moments for estimating the two parameter Lognormal is given as

$$\hat{\mu} = \frac{1}{N} \sum_{i=1}^{N} \ell n(x_i) \qquad ....(32)$$

$$\hat{\sigma} = \{ \sum_{i=1}^{N} \frac{\left[(\ell n(x_i)-\mu\right]^2}{N} \}^{\frac{1}{2}} \qquad \text{....(33)}$$

The maximum likelihood estimators of the log-normal 2 are the same as the moment estimators. The procedure is however, different for the Lognormal 3 distribution.

By differentiating the log-likelihood function of the Lognormal 3 density function with respect to μ, σ, and x_o then equation to zero, it can be shown that the equation solutions are:

$$\hat{\mu} = \sum_{i=1}^{N} \ell n(x_i - x_o)/N \qquad \text{.... (34a)}$$

$$\hat{\sigma}^2 = \sum_{i=1}^{N} \left[\ell n(x_i - x_o) - \mu\right]^2 \Big/ N \qquad \text{.... (34b)}$$

and

$$\sum_{i=1}^{N} (x_i - x_o)^{-1} (\mu - \sigma^2) = \sum_{i=1}^{N} \left[\left({}^{1}\!\Big/_{(x_i - x_o)} \right) \ell n(x_i - x_o) \right] \qquad \text{....(34c)}$$

where $\hat{\mu}$, $\hat{\sigma}$ and x_o are the likelihood estimates required.

2.2.5.4 PARAMETER ESTIMATION FOR THE PEARSON AND LOG-PEARSON DISTRIBUTIONS

Substituting the probability density function of the Pearson type III distribution into the general equation for moments about the origin, it can be shown that the first moment about the origin for r = 1 that yields the mean is

$$\mu_1' = \frac{2\Gamma(\beta+1)}{\Gamma(\beta)} + x_o \frac{\Gamma(\beta)}{\Gamma(\beta)}$$

or

$$\mu_1' = \alpha\beta + x_o \qquad ....(35)$$

Higher moments can similarly be computed.

The likelihood function for Pearson type III is set up as follows:

$$\ell n(L) = -N\ell n\ \Gamma(\beta) - \frac{1}{\alpha}\sum_{i=1}^{N}(x_i - x_o) + (\beta-1)\sum_{i=1}^{N}(x_i - x_o) - N\beta\ell n(\alpha) \qquad ....(36)$$

Differentiating with respect to α, β, and x_o and equating to zero gives the following three equations.

$$\frac{\partial \ell n(L)}{\partial \alpha} = \frac{1}{\alpha^2}\sum_{i=1}^{N}(x_i - x_o) - \frac{N\beta}{\alpha} = 0 \qquad ....(37a)$$

$$\frac{\partial \ell n(L)}{\partial \beta} = -N\Gamma'(\beta)/\Gamma(\beta) + \sum_{i=1}^{N}\ell n(x_i - x_o) - N\ell n(\alpha) = 0 \qquad ....(37b)$$

$$\frac{\partial \ell n(L)}{\partial x_o} = \frac{N}{\alpha} - (\beta-1)\sum_{i=1}^{N}\left({}^{1}/_{(x_i - x_o)}\right) = 0 \qquad ....(37c)$$

The psi or digamma function $\psi(\beta)$ or $\Gamma'(\beta)/\Gamma(\beta)$ in equation (37b) above is calculated using an assymptotic equation of the form

$$\psi(\beta) = \ln(\beta+2) - \frac{1}{2(\beta+2)} - \frac{1}{12(\beta+2)^2} + \frac{1}{120(\beta+2)^4} - \frac{1}{252(\beta+2)^6} - \frac{1}{(\beta+1)} - \frac{1}{\beta} \quad \ldots\ (38)$$

It can be shown that the solutions for α and β from these simultaneous equations are

$$\alpha = \left[\sum_{i=1}^{N} \frac{(x_i - x_o)}{N}\right] - \left[\frac{N}{\sum_{i=1}^{N} \left({}^{1}/_{(x_i - x_o)}\right)}\right] \quad \ldots\ldots(39)$$

and

$$\beta = {}^{1}/\left[1 - \frac{N^2}{\sum_{i=1}^{N} (x_i - x_o) \sum_{i=1}^{N} \left({}^{1}/(x_i - x_o)\right)}\right]$$

2.2.5.5 PARAMETER ESTIMATION FOR THE WEIBULL 2 AND 3 DISTRIBUTIONS

The general expression for the rth moment, $\mu_r^{x_o}$ about the lower bound, x_o of the Weibull the type III distribution is obtained from the expression below.

$$\mu_r^{x_o} = \int_o^\infty (x-x_o)^r \frac{\beta}{(\alpha-x_o)} \left\{\frac{x-x_o}{\alpha-x_o}\right\}^{\beta-1} \exp\left\{\frac{x-x_o}{\alpha-x_o}\right\} dx \quad \ldots\ (40)$$

Substituting y for $\left[\{(x-x_o)/(\alpha-x_o)\}^\beta\right]$ and simplifying gives

$$\mu_r^{x_o} = (\alpha - x_o)^r \int_o^\infty y^{r/\beta} e^{-y}\, dy \qquad \text{.... (42)}$$

or $$\mu_r^{x_o} = (\alpha - x_o)\Gamma(1 + {}^r/_\beta) \qquad \text{.... (43)}$$

Substituting for r = 1, 2,.... gives the various parameters. If only the mean wind speed $\overline{v}$ and the standard deviation σ are available from the wind speed distribution where $\sigma^2 = (v-\overline{v})^2$, then parameters α and β of the Weibull distribution can be estimated from these statistics since α and β are related to $\overline{v}$ and σ by

$$\overline{v} = \alpha\Gamma(1 + {}^2/_\beta) \qquad \text{....(44)}$$

$$\frac{(\sigma)^2}{\overline{V}} = \left[\Gamma(1 + {}^2/_\beta)/\Gamma^2(1 + {}^1/_\beta)\right] - 1 \qquad \text{.... (45)}$$

where Γ is the usual gamma function and $\sigma/\overline{v}$ is the coefficient of variation.

The α and β parameters are then estimated by

$$\beta = \frac{(\sigma)}{\overline{V}}^{-1.086} \qquad \text{.... (46).}$$

$$\alpha = \overline{V}/\ (1 + {}^{1/}_\beta) \qquad \text{.... (47)}$$

Estimates of the Weibull parameters (α, β, x_o) can be obtained by the maximum likelihood technique through solving the following set of maximum likelihood equations.

$$\frac{\alpha}{N}\sum_{i=1}^{N} \ell n(x_i) + \ell n(\beta) - \psi(x_o/\alpha) = 0 \qquad \text{.... (47a)}$$

$$\frac{\alpha\beta}{N}\sum_{i=1}^{N} x_i^{\alpha} - x_o = 0 \qquad \text{.... (47b)}$$

$$\frac{\alpha\beta}{N}\sum_{i=1}^{N} x_i^{\alpha}\ \ell n x_i - \frac{x_o}{N}\sum_{i=1}^{N} \ell n x_i - 1 = 0 \qquad \text{.... (47c)}$$

where $\psi(x) = \frac{d}{dx}\ \ell n\Gamma(x)$.

In this study the two methods (moment and maximum likelihood) were both used in the estimation of the parameters whenever the estimates are theoretically different.

Once the model parameters have been estimated the next step is to determine the best model from all the sets of the fitted models (Tests of goodness of fit). Several statistical methods are available for these tests.

The three methods presented here are the Root mean square (residual) error, the Chi-square and the Kolmogorov-Smirnov tests. Details of these verification methods are presented in the next section.

2.2.6 TESTS OF GOODNESS OF FIT

Under this section the details of the three methods which were used to determine the goodness of fit of the wind data onthe various statistical distributions are discussed . The methods include the Root mean square residual error (RMS), the Chi-square (χ^2) and the Kolmogorov-Smirnov (KS) tests.

2.2.6.1 THE ROOT MEAN SQUARE (RESIDUAL) ERROR TEST

In this test the square of the errors (ε^2) are computed and cumulated. ε^2 can then be used as a preliminary test of "goodness of fit" of a distribution (Stanton, 1983).

The root mean square (residual) error test (ε^2) may be given by the expression

$$\varepsilon^2 = \frac{1}{N} \sum_{i=1}^{N} \left[p(x) - f(x) \right] \qquad \ldots\ (48)$$

where p(x) and f(x) are the observed and calculated cumulative frequency distributions respectively. More details of the method can be obtained from Beck (1977).

2.2.6.2 THE CHI-SQUARE TEST

The Chi-square (χ^2) goodness of fit test has been widely used and discussed by many authors (Bury, 1976; Beck, 1977). It is however, less accurate for continuous distributions because it is necessary to group the data into fictitious, descrete cells and compare them. The Chi-square test is not good for small samples with sample size less than 20.

If a continuous variable is divided into K class interval and f_i is their relative frequency for a sample size N with P_i being their respective probabilities, then

$$\chi^2 = \sum_{i=1}^{K} (\frac{N_i - Np_i}{Np_i})^2 \qquad \text{..... (49)}$$

will have Chi-square distribution with number of degrees of freedom ν equal to k-1 for sufficiently large N.

where N_i are the observable frequencies and Np_i are the expected frequencies.

The test statistics measures the discrepancy between the observed and theoretical (postulated) class frequencies. The observed values of χ^2 should be small. The critical values of χ_c^2 can be obtained from the χ^2 tables for any given values of significance level (α) and degrees of freedom (ν).

2.2.6.3 THE KOLMOGOROV-SMIRNOV TEST

The Kolmogorov-Smirnov test (K-S) is usually a better test than the Chi-square test (Kite, 1977). If two sub-samples are from the same population, then their cumulatives probabilities should be fairly close to each other. If the two cumulative distributions are "significantly different" at any point, then the sub-samples may be from different populations.

This significant deviation is enough evidence for rejecting a hypothesis that the two sub-samples are from the same population. Using this test, a cumulative probability distribution is prepared for each sub-sample and the largest difference in cumulative functions is determined, i.e.

$$D_n = \text{Max}|f(x) - p(x)| \quad \text{.... (5o).}$$

where p(x) is the sample cumulative distribution and f(x) is the cumulative normal distribution function with $\mu = \overline{x}$, the sample mean and $\sigma^2 = s^2$, the sample variance.

The maximum absolute difference, which forms the basis of the Kolmogorov-Smirnov goodness of-fit test, is simply the greatest difference between the computed and the observed cumulative distribution function over the entire range of the observations.

More details of the test can be obtained from Burry (1976) and many other standard statistical literatures. In the next section we will discuss the various methods of estimating wind power from the wind speed characteristics.

2.3 ESTIMATION OF WIND POWER FROM WIND SPEED CHARACTERISTICS

Once the spatial and temporal characteristics of the winds in Kenya were determined through PCA, and the best statistical distribution fitted, attempts were then made to study the characteristics of wind power from the computed wind speed characteristics.

2.3.1 THE WIND POWER CHARACTERISTICS

In this section the various methods which were used to derive some of the wind power characteristics are reviewed. These include the methods used to estimate the wind power density and the various characteristics of wind power.

2.3.2 ESTIMATION OF MEAN WIND POWER DENSITY

The kinetic energy of motion of the atmosphere is expressed by the term

$$K.E. = \tfrac{1}{2} MV^2 \qquad \text{.... (51)}$$

where M is the mass and V is the wind velocity

Power is equal to the energy per unit time. If AV represents the volume of the air passing through an area A in unit time, then the power (p) is given by

$$P = \tfrac{1}{2}\rho AV.V^2 = \tfrac{1}{2}\rho AV^3 \qquad \text{.... (52)}$$

In theory therefore, the instantaneous power density (Wm^{-2}) available in a flow of air through a unit cross-section area normal to the flow is simply

$$P = \frac{1}{2}\rho A V^3 \qquad \ldots.(53)$$

where V is the instantaneous wind speed in (Ms^{-1}) and ρ is the air density ≅ 1.23kgm^3 at sea level.

The expectation of power ($\bar{P}$) i.e. the mean power density per unit area is then

$$E(P) = \frac{1}{2}E(\rho V^3) \qquad \ldots. (54)$$

Wind power estimates however, have been based on the assumption that density is not correlated with the wind speed and in this case,

$$E(P) = \frac{1}{2}(\rho).E(V^3) \qquad \ldots. (55)$$

Here the mean air density is estimated from the U.S. standard atmosphere and the problem of determining the mean wind power density at a given location is reduced to determining the mean of the wind speed cubed as given above. This approach was used in Kenya by Chipeta (1976) with some classes of wind categories. The error induced in this method of estimating the expected wind power density on a constant pressure surface is usually in the order of 5% (Justus et al, 1976).

The mean air density ($\bar{\rho}$) can be estimated using the expression

$$\bar{\rho} = 1.30 \times \frac{p}{1013.25(1 + {}^{T}/273)} \qquad \ldots. (56)$$

where p is the barometric pressure in (mb) and T is the mean air temperatures in (^{o}C) . Usually the density decreases slightly with increasing content of water vapour but corrections for this are negligibly small in wind power computations.

The mean wind speed cubed can be determined more accurately using the location (x_o), shape (β) and the skewness parameter of a distribution (Hennessey, 1977). The expected wind speed cubed may be expressed as

$$E(V^3) = \sigma^2 \left[\sqrt{\beta}_1 + 3\mu/_\sigma + (\mu/_\sigma)^3\right] \quad \text{....(57)}$$

This is simply the third moment of the wind speed about zero where μ, σ and $\sqrt{\beta_1}$ are the mean (location parameter), the standard deviation (shape parameter) and the skewness of the wind speed respectively. If however, the skewness is neglible, then equation (57) reduces to the form

$$E(V^3) = 3\mu\sigma^2 + \mu^3 \quad \text{.... (58)}$$

Equations (56) and (57) can be used to estimate the mean wind power density once the parameter μ, σ and β are estimated from any given distribution that best fits the wind observations.

It will be seen from the results that the 3 parameter Weibull distribution fitted the wind speed data best at all stations. This distribution was then used to estimate wind power potential at all locations. The next section is devoted to the methods of estimating wind power potential from the Weibull distribution.

2.3.3 ESTIMATION OF WIND POWER POTENTIAL USING THE WEIBULL DISTRIBUTION

Methods of estimating wind power from the three parameter Weibull distribution has been discussed by many authors including Tackle and Brown (1978), Hennessey (1977). Only a brief account of the method will be included here.

If a random variable x follows a Weibull 3 pdf with parameters (a,b,c), the probability density function (pdf) of the random variable $Y = x^r$ is yet another Weibull 3 parameter pdf with paraters (a/r, b,c/r), respectively.

The non-central moment of order r of the Weibull 3 pdf is then given by

$$E(x^r) = b^{-r/a}\Gamma\left[(c+r)/_a\right]/\Gamma(c/_a) \qquad \ldots. \ (59)$$

Therefore the skewness (third moment), Kurtosis forth moment) and the coefficient of variation are all function of a and c only (Täckle and Brown, 1978).

For r = 3, the expectation of Y in terms of μ and β is of the form

$$E(Y) = \mu^3 \left[\Gamma(1+{}^1/_\beta)\right]^{-3} \Gamma(1+{}^3/_\beta) \qquad \text{.... (60)}$$

whereas in terms of α and β, the expectation of $Y = X^3$ becomes

$$E(Y) = \alpha^3 \left[\Gamma(1+{}^3/_\beta)\right] \qquad \text{.... (61)}$$

where Γ is the gamma function.

The mean wind power potential using the Weibull distribution is then given by the relation

$$\bar{E} = \tfrac{1}{2}\bar{\rho}\alpha^3\Gamma(1+{}^3/_\beta) \quad W/m^2 \qquad \text{.... (62)}$$

where $\bar{\rho}$ is the mean air density as given by equation (56). Equation (62) have been used by Hennessey (1977), Tackle and Brown (1978), Stewart and Essenwanger (1978), Van der Auwera (1980) and many others to determine the wind power potential at any given locations. This approach will be adopted in this study.

In the next section, we will look at the vertical variation of the wind with height and briefly present the methods used for extrapolating surface wind powers. The surface here refers to 10m above the surface which is the standard level for most anemometers in Kenya.

2.3.4 VERTICAL VARIATIONS OF THE WIND

There is a general increase in the wind speed with height hence a corresponding increase in the available wind energy. Usually there are no direct measurements of wind speeds to heights extending upto 150m for operations of wind energy systems (WEC). Most of the wind measuring instruments are generally at 10m above the surface.

Many methods have been developed for vertical extrapolation of wind and wind power in order to determine the optimum level for wind power generation. These methods include the Logarithmic wind profile, the Power law and the Weibull extrapolation methods. These three methods are briefly discussed in the next sections.

2.3.4.1 THE LOGARITHMIC WIND PROFILE

Roughness of terrain retards the wind near the ground. The horizontal wind speeds will therefore be significantly different within the frictional layer. Relatively higher wind speeds may generally be expected above the frictional layer where the frictional effects are zero. It is therefore important to determine the optimum levels for the wind generators.

It has been found that for relatively uniform flat ground of defined surface roughness, the logarithmic wind law accurately describes the variation of wind with height upto at least 100m above the ground for adiabatic and slightly stable conditions (W.M.O.,1984).

The logarithmic wind profile equation takes the form.

$$U_z = \frac{U_*}{K}\ln\left[\frac{z}{z_o}\right] \qquad \text{.... (63)}$$

where U_z is the mean wind speed(ms^{-1}) at the height z

u_* is the frictional velocity (ms^{-1})

z_o is the roughness length – (parameter) (m) and is a measure of surface roughness. It is proportional to and smaller than the mean height of the roughness elements.

K is the Von Kerman's constant (≅ 0.40).

It has been observed that the only parameter affecting the wind speed ratio in equation (63) under near adiabatic conditions is the value of the roughness parameter z_o.

The logarithmic wind profile has mainly been applied in wind tunnel studies and is not particularly useful in the atmosphere because the lapse rate is rarely adiabatic.

Table 3 gives the observed values of the roughness parameter (z_o) for typical terrains. In practice, the smoother the ground the greater is the wind at levels near the ground. This suggests that if all other factor remain the same, location of a wind powered generator at smoothest, least obstructed site available is preffered. If location in rough terrain is unavoidable, the generator should be placed at much higher levels.

Table 3 - Observed Values for z_o for Typical Terrains
Source: Deacon (1949).

Description of Terrain	Value of z_o (cm)
Smooth mud flats	0.001
Sun baked sandy alluvium	0.03
Sand	0.05 - 0.1
Smooth snow on short grass	0.005
Mown grass	0.5 - 1.0
fallow field	2.1
low grass	3.2
high grass	3.9
wheat field	4.5
Ocean (depending on wind speed)	0.001 - 0.5
Tall grass	5.0
Cultivated field	0.95
Thick grass upto 50m	9.0
Forested area or city	50.00

2.3.4.2 THE POWER LAW

The empirical Power law expression takes the form :

$$\frac{v_1}{v_2} = \left(\frac{z_2}{z_1}\right)^{\alpha} \quad .... (64)$$

where α is an exponent while v_1 and v_2 are the mean wind speeds at levels z_1 and z_2 respectively. This power law expression has been suggested by Doran and Verholek (1978) as a useful tool for extrapolating measured winds to heights where measurements are not available.

The index (α) has been observed to be small during the day and large during the night with values of 0.10 and 0.143 respectively (Demarrais, 1959). The $1/7^{th}$ power law ($\alpha = 1/7$) has been used by many researchers and has been found to give good approximations to the observed and predicted profiles over surfaces of widely differing roughness (Davenport, 1963).

It should be noted that the assumption $\alpha = 1/7$ may not be realistic at a number of locations.

Many modifications have been made to both the logarithmic wind profile and the power law for use in extrapolating surface wind powers to various levels above the ground.

One such modification is given by equation (65) in terms of power potential (p_z) at height z.

$$p_z = p_r\left[\ln(z/z_o)/\ln(z_r/z_o)\right]^3 \quad \text{.... (65)}$$

where p_r is the power density at reference or surface level.

Demarrais (1959) have however, indicated that wind power estimates are not too sensitive to z_o provided the reference level is more than 10 times the roughness length. He suggested that the formula usually yields conservative but reasonable estimates of the total wind power whenever the reference level is greater than the surface roughness of a site. The equation was used in this study and the results compared with those from other methods.

2.3.4.3 THE WEIBULL EXTRAPOLATION FORMULAE

Justus and Mikhail (1976) proposed a set of formulae which can be used for vertical extrapolation of wind power from the Weibull scale factor (α) and shape factor (β). Once these two parameters have been extrapolated to desired levels, the values of α and β are then used to obtain the mean power densities using equation (62).

The relevant formulae based on the power law take the forms :

$$\beta_2 = \beta_1\{[1-0.0881\ln(^{z_1}/_{10})]/[1-0.0881\ln(^{z_2}/_{10})]\}$$

.... (66)

and

$$\alpha_2 = \alpha_1(^{z_2}/_{z_1})^{\gamma} \quad .... (67)$$

where β_2 and α_2 are the Weibull parameters at the extrapolated levels using the surface parameters β_1 and α_1.

γ is an exponent given by the expression

$$\gamma = (0.37-0.0881\ln\alpha_1)/[1-0.0881\ln(^{z_1}/10)] \quad .... (68)$$

z is measured in (m) while (α) in (ms^{-1}).

Doran and Verholek (1978) examined the characteristics of these formulae in details and found that they are sufficiently useful for ensemble averages, but tends to give overestimates in individual cases.

In this study the three methods were used for vertical extrapolation of wind power at levels 15, 20,25,30,50 and 75 meters. The results were then compared.

In the next chapter we will give the details of the results obtained with the various analyses.

CHAPTER THREE

3.0 RESULTS AND DISCUSSION

This chapter is devoted to discussing the results that were obtained from the various analyses used in this study. These results will be discussed under the various sections beginning with the spatial characteristics of the mean wind patterns as obtained through Principal Component Analysis (PCA).

In the second section, we will discuss the results obtained from the various statistical distributions. The best distribution is subsequently used in section three to discuss some of the wind power characteristics in Kenya.

The final section gives the wind power characteristics at various levels namely 10m, 15m, 20m, 25m, 50m and 75m above the ground level. We will, however, first present the mean seasonal characteristics of the winds at the various locations.

3.1 MEAN WIND CHARACTERISTICS OVER KENYA

Table 4 gives the mean annual wind speeds at the 24 Kenyan sites. It can be observed from the table that the mean minimum wind speeds are all above 1.4ms^{-1} while the mean maximum winds are above 4.0 ms^{-1} at majority of the sites. The mean wind speeds (half(minimum plus maximum)) lie between $2.0ms^{-1}$ and $6.0ms^{-1}$. Mean wind speeds of over $4.0\ ms^{-1}$ are concentrated mainly around Marsabit, Maralal, Lodwar, Mombasa and around Nairobi. The rest of the sites have relatively lower mean winds (less than $3.5\ ms^{-1}$).

The spatial patterns of the mean surface wind speeds from January to December are given in figures 6-17. These maps shows some remarkable seasonal and geographical variations. They also show that some areas have persistent mean winds of over $5.0ms^{-1}$ while others have less than $3.0ms^{-1}$ throughout the year. Some however, had high speeds only during some seasons. Areas with persistent higher winds throughout the year include Marsabit, Maralal, Malindi, Mombasa and Nairobi areas.

The higher mean winds around the Marsabit areas have been attributed to the channeling effects induced by topography patterns (Asnani and Kinuthia, 1984).

The higher winds around the Nairobi area can be attributed to site exposures. Most sites chosen from this area were mainly airports and airstrips which have little obstructions within them. These large open fields allow the surface winds to gain considerable speeds due to less interference from the obstruction effects.

Other regions with fairly high winds were concentrated along the coastal strip. These can be due to the mutual effects of the land/sea breezes and their interactions with the large scale monsoonal wind systems. These land/sea breezes have been observed to extend several kilometers inland (Asnani and Kinuthia,1979).

The lake region generally have low wind speeds throughout the year. This was also observed by Chipeta (1976). It appears that on the seasonal time scale, the lake breeze has relatively slight effects on the magnitudes of the mean wind speeds over the lake station used in this study. However, on a diurnal basis, the lake breeze can have marked influence on wind speeds along the shores. Topographical patterns around the lake may also be playing some significant role in the reduction of the strength of the breezes. The summaries of the mean seasonal characteristics at the various locations are given in table 5.

The spatial distribution of the maximum and minimum winds respectively are given in figures 18-19. It can be seen from these figures that the maximum winds were centred around Marsabit, Maralal, Malindi, Eldoret and Mombasa. The minimum winds (figure 19) show that in general, areas around Lake Victoria, Nakuru, Makindu and parts of the southern Rift Valley had minimum winds of less than 2.5 ms^{-1}. Over the rest of the country minimum winds were greater than 3.0 ms^{-1}.

Figure 20 shows the spatial distribution of the range. The map shows that the largest ranges were generally concentrated over many sites which had small mean wind speeds. These informations would be very important in determining the type of wind generators at any given site.

In the next section we will attempt to determine the spatial similarity between the wind patterns using the method of Principal Component Analysis (PCA). PCA will also be used to group these patterns into homogeneous wind categories.

TABLE 4 - MEAN WINDS AT VARIOUS SITES

Station Name	mean Maximum Wind Speeds ms^{-1}	Mean Minimum Wind Speeds ms^{-1}	Mean Wind Speeds ms^{-1}
Nyeri	4.72	2.52	3.62
Marsabit	6.55	5.29	5.92
Mombasa	6.57	4.21	5.39
Lodwar	6.87	4.09	5.48
Moyale	4.45	3.36	3.91
Mandera	4.58	3.88	4.23
Maralal	5.13	4.65	4.89
Malindi	6.21	5.29	5.75
Kericho	4.52	3.70	4.11
Kisumu	4.64	2.43	3.54
Wajir	5.17	4.14	4.65
Eldoret	5.24	4.16	4.70
Meru	4.44	3.01	3.73
Thika	4.48	2.00	3.24
Kitale	3.54	2.34	2.94
NRB Wilson	5.49	3.76	4.63
NRB Dagoretti	5.74	3.66	4.70
Makindu	3.16	1.70	2.43
Lamu	4.71	3.29	4.00
Voi	4.01	3.36	3.69
Narok	3.09	2.51	2.80
NRB Embakasi	4.92	2.59	3.76
Garissa	4.51	4.04	4.28
Nakuru	2.96	1.42	2.19

TABLE 5 - SEASONAL CHARACTERISTICS OF THE WIND SPEEDS.

Seasons	Mean Wind Speed Cnaracteristics (Fig. 6 - 17).
Nortnern Hemisphere winter (Dec.-Feb.)	Tne North East Monsoon is dominant in East Africa and particularly over Kenya. The major features from the maps include. (1) Mean wind speeds above 5.5ms^{-1} at Mandera, Malindi, Maralal and Eldoret. Similar magnitudes were also centred around Nairobi area. Tne regions around Mt. Kenya nad steady mean winds of about 3.0ms^{-1}. (2) Tne mean maximum winds were centred in Marsabit and tne coastal areas of Mombasa and Malindi wnile the mean minimum winds were centred around tne lake snores of Victoria, Nakuru and Makindu. (3) Majority of areas nad wind speeds lying between 3.5ms^{-1} and 4.5ms^{-1}. (4) Tne nignest montnly range of 8.5ms^{-1} were found around Makindu.

TABLE 5 - CONTI'D

Seasons	Mean Wind Speed Characteristics
(Dec - Feb)	(5) The month to month variation of the mean winds was fairly minimal except for slight differences in the orientation of the isolines.
Northern Spring (March-May)	The S.E. and N.E. monsoon winds converge over most of the Kenyan region bringing the Long Rains. The dominant features here were:- (1) Marked cells of strong winds around Marsabit, Eldoret, the Nairobi area and the coastal regions of Malindi and Mombasa. Marsabit had the heighest mean wind speeds of over $6.0ms^{-1}$. (2) Most of the country had mean winds generally greater than $3.0ms^{-1}$ except for the lake region and Makindu areas which maintaned calm winds.
Northern Summer (June-August)	The S.E. monsoons are well established. Most of the country had wind speeds below $5.5ms^{-1}$ apart from Mombasa, Marsabit

TABLE 5 - CONT'D

	and Mandera. The major differences within month to month variations were observed in August.
Northern Autumn (Sept.-Nov.)	This is another rainy season (short rains) with the S.E. and N.E. monsoons converging over most of the country. The dominant features here were the picking up of the higher winds over Marsabit and the coastal regions. The lake region showed a marked increase in the winds speeds. In general more than half of the country had mean wind speeds greater than $4.0ms^{-1}$.

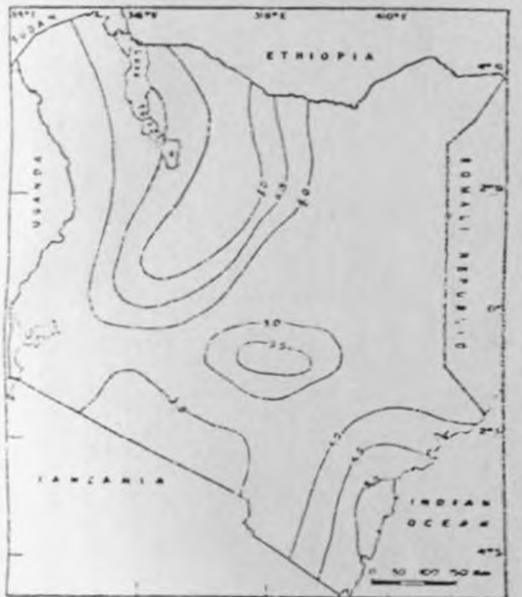


Fig 6 SPATIAL DISTRIBUTION OF THE MEAN MONTHLY WIND SPEEDS IN Ms^{-1} FOR JANUARY.

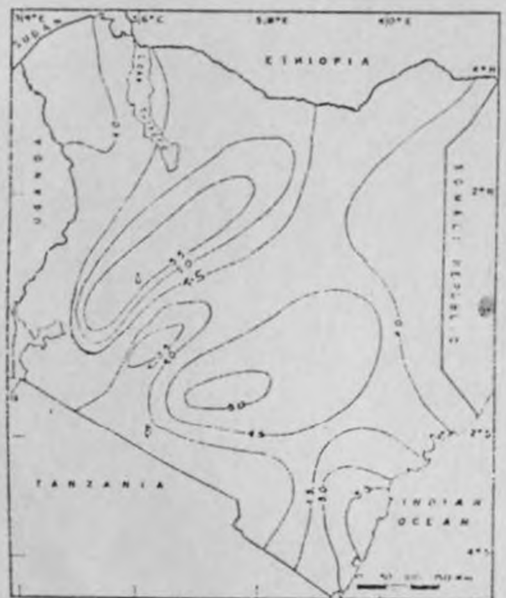


Fig 7 SPATIAL DISTRIBUTION OF THE MEAN MONTHLY WIND SPEEDS IN Ms^{-1} FOR FEBRUARY.

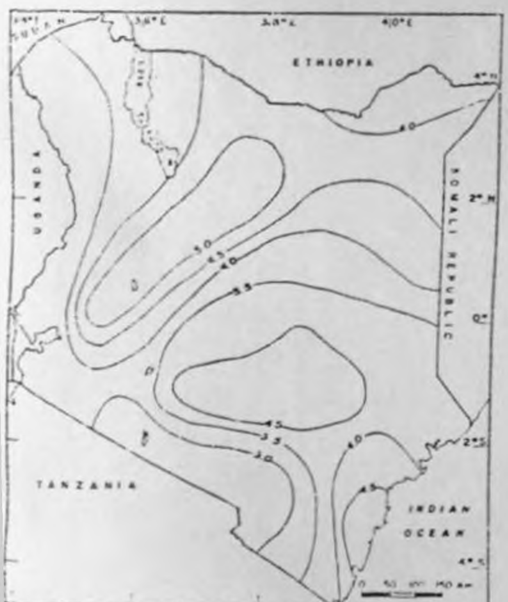


Fig 8 SPATIAL DISTRIBUTION OF MEAN MONTHLY WIND SPEEDS IN Ms^{-1} FOR MARCH.

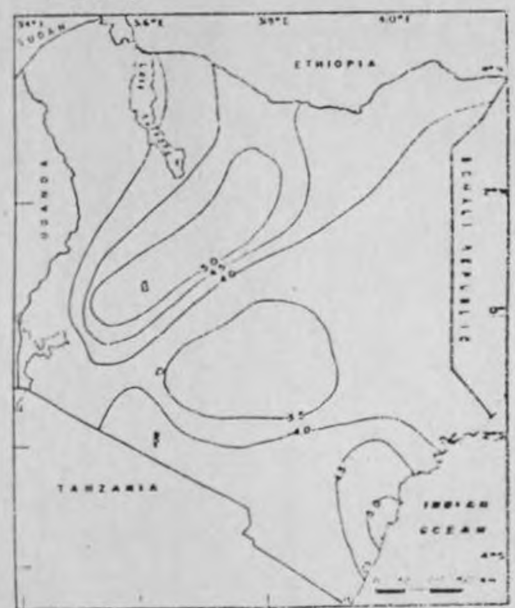


Fig 9 SPATIAL DISTRIBUTION OF THE MEAN MONTHLY WIND SPEEDS IN Ms^{-1} FOR APRIL.

Fig. 6 - Spatial Distribution of the mean monthly wind speeds in ms^{-1} for Jan.

Fig.7 - Spatial Distribution of the mean monthly wind speeds in ms^{-1} for Feb.

Fig.8 - Spatial Distribution of the mean monthly wind speeds in ms^{-1} for March.

Fig.9 - Spatial Distribution of the mean monthly wind speeds in ms^{-1} for April.

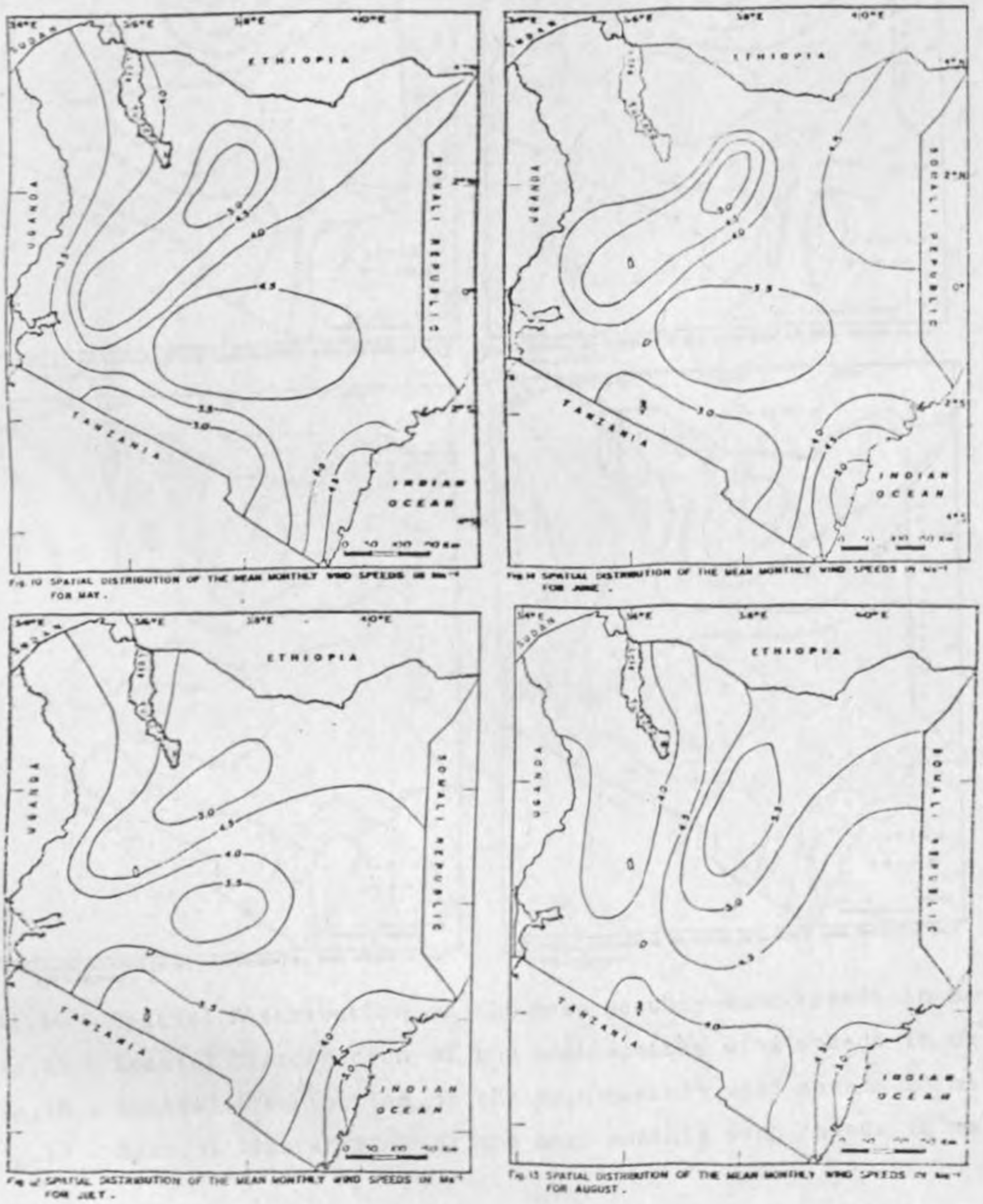


Fig.10 - Spatial Distribution of the mean monthly wind speeds in ms^{-1} for May.
Fig.11 - Spatial Distribution of the mean monthly wind speeds in ms^{-1} for June.
Fig.12 - Spatial Distribution of the mean monthly wind speeds in ms^{-1} for July.
Fig.13 - Spatial Distribution of the mean monthly wind speeds in ms^{-1} for August.

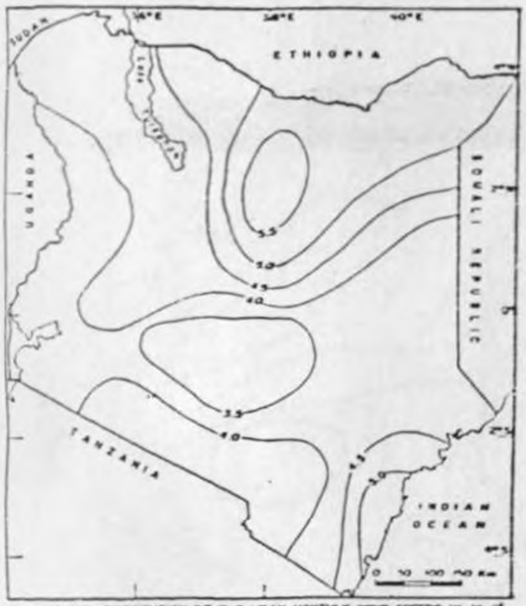


Fig. 14 SPATIAL DISTRIBUTION OF THE MEAN MONTHLY WIND SPEEDS IN Ms^{-1} FOR SEPTEMBER.

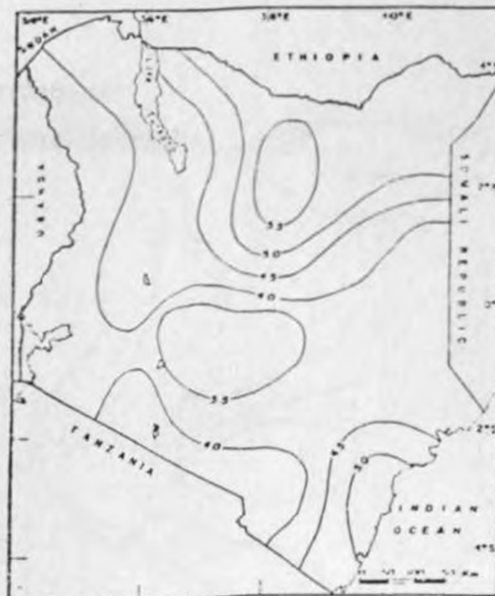


Fig. 15 SPATIAL DISTRIBUTION OF THE MEAN MONTHLY WIND SPEEDS IN Ms^{-1} FOR OCTOBER.

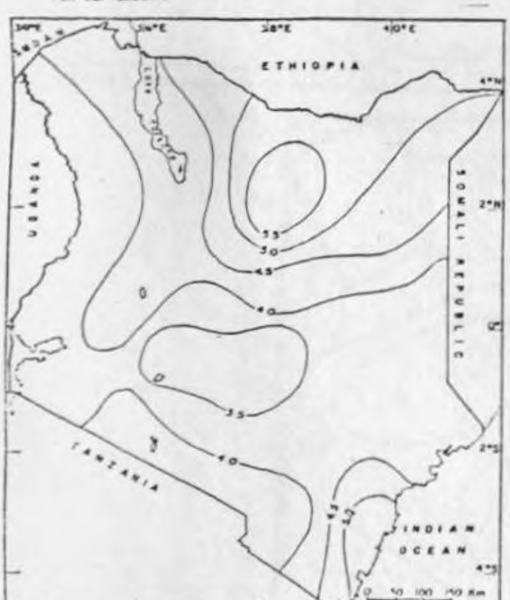


Fig. 16 SPATIAL DISTRIBUTION OF THE MEAN MONTHLY WIND SPEEDS IN Ms^{-1} FOR NOVEMBER.

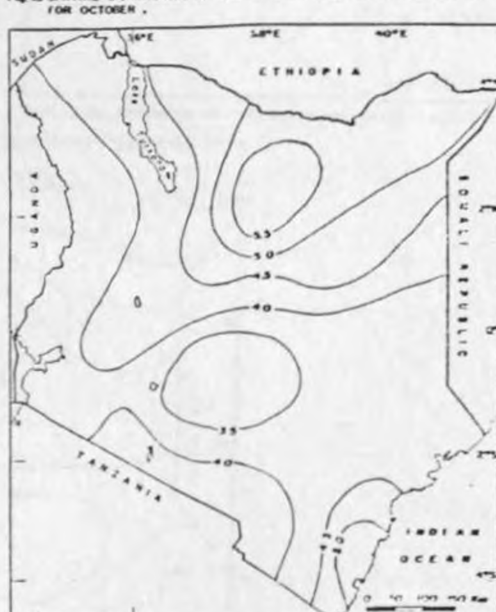


Fig. 17 SPATIAL DISTRIBUTION OF THE MEAN MONTHLY WIND SPEEDS IN Ms^{-1} FOR DECEMBER.

Fig.14 - Spatial Distribution of the mean monthly wind speeds in ms^{-1} for Sept.

Fig.15 - Spatial Distribution of the mean monthly wind speeds in ms^{-1} for Oct.

Fig.16 - Spatial Distribution of the mean monthly wind speeds in ms^{-1} for Nov.

Fig.17 - Spatial Distribution of the mean monthly wind speeds in ms^{-1} for Dec.

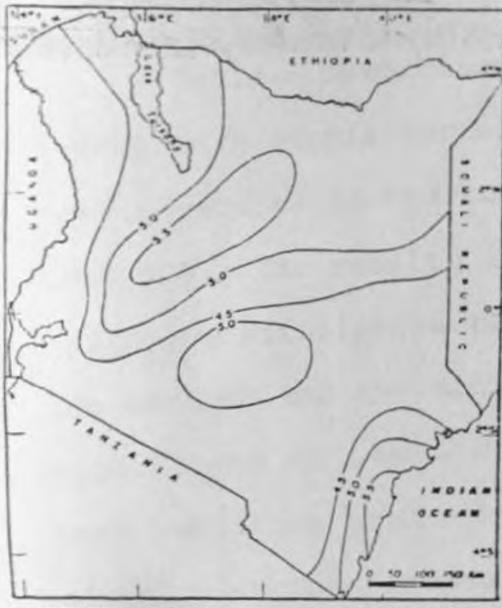


Fig.18 SPATIAL DISTRIBUTION OF THE MAXIMUM WIND SPEEDS IN Ms^{-1}

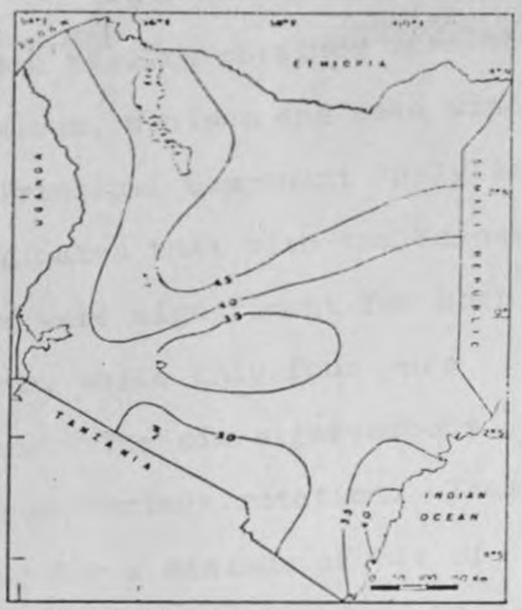


Fig.19 SPATIAL DISTRIBUTION OF THE MINIMUM WIND SPEEDS IN Ms^{-1}

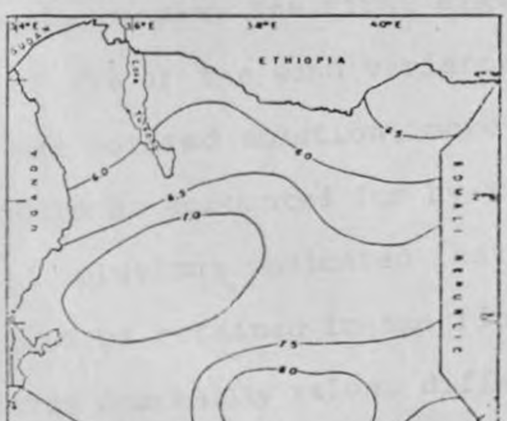


Fig.20 SPATIAL DISTRIBUTION OF THE WIND SPEEDS RANGE IN Ms^{-1}

Fig.18 - Spatial Distribution of the maximum wind speeds in ms^{-1}

Fig.19 - Spatial Distribution of the mean minimum wind speeds in ms^{-1}

Fig.20 - Spatial Distribution of the wind speed range in ms^{-1}

3.2 RESULTS FROM PRINCIPAL COMPONENT ANALYSIS

Table 6 summarises the results obtained when the correlation matrix for maximum, minimum and mean wind speeds were subjected to Principal Component Analysis (P.C.A.). The results indicated that with the Kaisers criterion six eigenvectors were significant for both the maximum and the minimum, while only four were significant with mean winds. The six eigenvectors were subjected to orthogonal varimax rotation. These six eigenvectors accounted for a minimum of 76% of the wind variance with the first eigenvector explaining a minimum of 30% of the wind variance.

In the rotated solution, more than 41% of the variance could be accounted for by the first eigenvectors. The rotated solutions indicated that only four eigen-vectors could be retained in the final solutions. The estimated communality values differed significantly from station to station with a minimum value of 0.22 observed at Makindu and a maximum value of 0.85 at Marsabit.

The communality in this case indicates the proportion of the total variance at each station that is explained by the common empirical orthogonal vectors. The large variance in the communality values indicate the high spatial variations in the wind characteristics over Kenya.

Figures 21(a) and 21(b) presents the spatial distribution of the first and second eigenvectors for the mean wind speeds.

The first eigenvector was significant over most parts of Kenya. Large positive values of the order of about 0.8 were concentrated around Marsabit, Maralal and Eldoret. Large positive values were also concentrated along the coastal region.

The second eigenvector was significant east of the central highlands. Maximum values were centred around Garissa and Mandera. Large negative values were also observed over western Kenya.

It was noted that around the Lake Victoria region (western Kenya) the first two eigenvectors were significant over most of the locations. High spatial correlations within the various regions can also be seen in Figure 22 which gives the spatial clusters of the 24 stations onto the two dominant eigenvectors. Similar characteristics were discernible from the interstation correlations.

From the results of the Principal Component Analysis, it was evident that some stations tend to cluster together into similar eigenvectors, indicating higher degree of associations among them. Such stations were therefore put under one homogeneous wind categories.

In order to classify the various wind stations into the various homogeneous regional groups, the eigenvector(s) which were significantly correlated with each station were noted. The groupings were then finally based on the spatial patterns formed by these major eigenvector(s).

Figure 23 presents the homogeneous wind categoreis as obtained from the spatial patterns formed by the major eigenvector(s). A total of eleven homogeneous groups were discernible from the orthogonal varimax solution. These were designated by the letters A,B,....,K as shown in the figure. Similar spatial coherence were obtained from the spatial patterns of the dominant eigenvector(s) with both the maximum and minimum winds. The boundaries between the various homogeneous groups were, however, difficult to delineate with the 24 stations used.

The regional groupings as given in Figure 23 generally signifies the influence of the relief and the large water bodies (Figure 5).

The mean month to month patterns of the winds are given in Figures 24-34 for the various regional groups. Marked seasonal differences in the wind patterns are discernible over the various regions. Detailed differences are summarized in Table 7.

Figures 26a and 26b give the month to month patterns of winds at Nairobi Embakasi and Wilson which are located in the same homogeneous group (region C). The seasonal patterns of the winds are quite similar at these two sites. Significant differences between the seasonal wind characteristics within the various homogeneous groups are also quite evident in figures 24-34 and Table 7.

The seasonal patterns observed from the groups (Figures 24-34 and Table 7) indicate that, although the seasonal migration of the sun plays some significant role in the seasonal distribution of the winds over many areas, the local factors such as topography, large water bodies and vegetation also play some significant role.

In the next section, we will present the results obtained with the various statistical distributions.

TABLE 6 - RESULTS OF THE PRINCIPAL COMPONENT ANALYSIS FOR THE WINDS.

Maximum Winds						
Unrotated Solution				Rotated Solution		
Eigen Value No.	Eigen Value	% of Total Variance extracted	% of cumulative Variance	Eigen Value	% of Total Variance extracted	% of Cumulative Variance
(A)	(B)	(C)	(D)	(E)	(F)	(G)
1	7.04	29.3	29.3	6.79	41.8	41.8
2	4.63	19.3	48.6	4.35	26.8	68.6
3.	2.54	10.6	59.2	2.30	14.1	82.8
4	1.60	6.7	65.9	1.29	8.0	90.7
5	1.28	5.3	71.2	0.91	5.6	96.4
6	1.14	4.8	76.0	0.59	3.6	100.0
7	0.87	3.6	79.6	-	-	-
8	0.73	3.1	82.7	-	-	-

Minimum Winds

(A)	(B)	(C)	(D)	(E)	(F)	(G)
1	8.56	35.7	35.7	8.33	50.6	50.6
2	3.33	13.9	49.5	3.14	19.1	69.7
3	2.68	11.2	60.7	2.33	14.2	83.9
4	1.46	6.1	66.9	1.13	6.9	90.7
5	1.26	5.3	72.1	0.80	4.8	95.5
6	1.18	4.9	77.0	0.73	4.5	100.0
7	0.82	3.4	80.5	-	-	-
8	0.74	3.1	83.5	-	-	-

Mean Winds

(A)	(B)	(C)	(D)	(E)	(F)	(G)
1	10.13	42.2	42.2	9.91	54.6	54.6
2	5.27	22.0	64.2	5.03	27.7	82.4
3	2.18	9.1	73.3	1.93	10.6	93.0
4	1.53	6.4	79.7	1.27	7.0	100.0
5	0.72	3.0	82.7	-	-	-
6	0.54	2.2	84.9	-	-	-

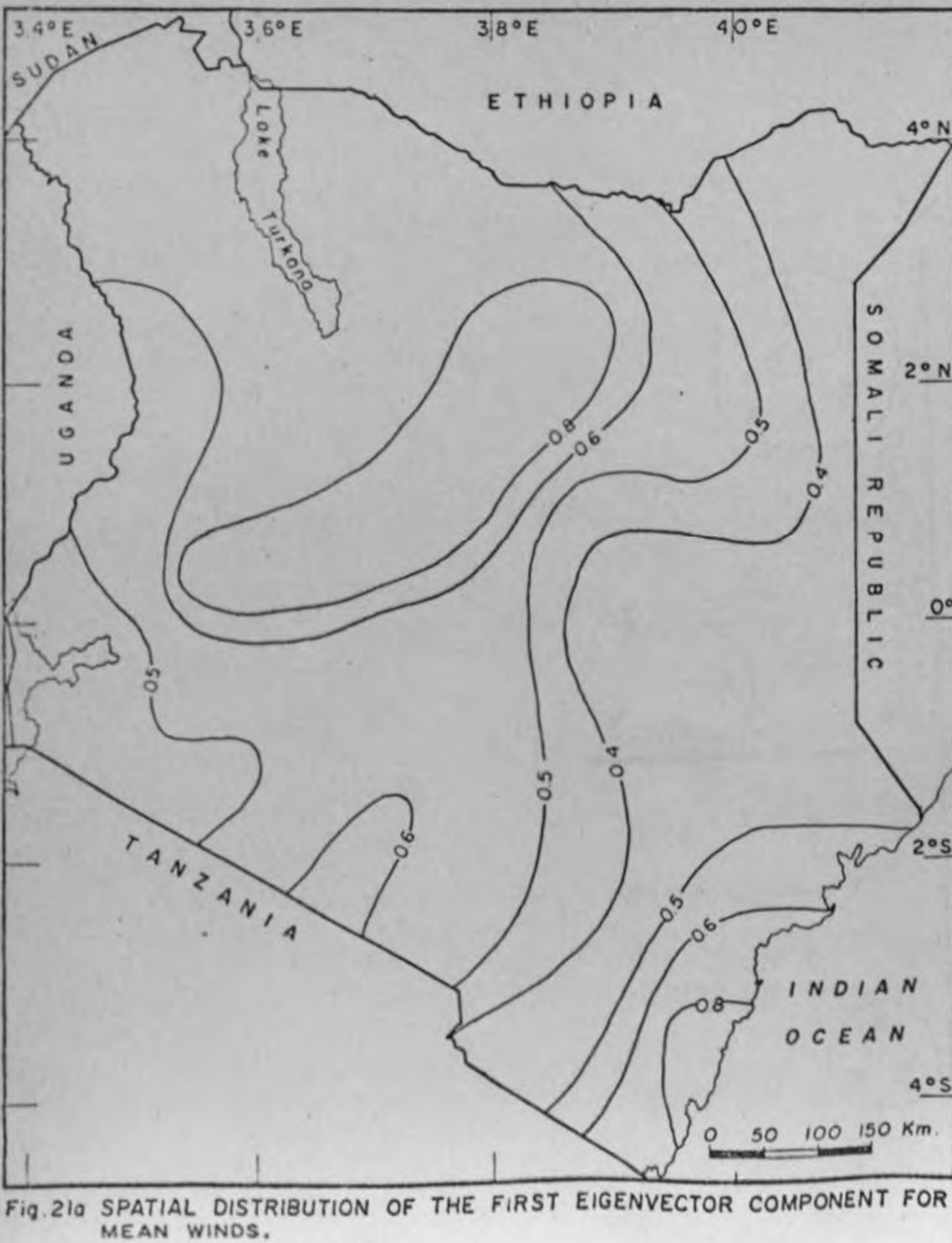


Fig.21a SPATIAL DISTRIBUTION OF THE FIRST EIGENVECTOR COMPONENT FOR MEAN WINDS.

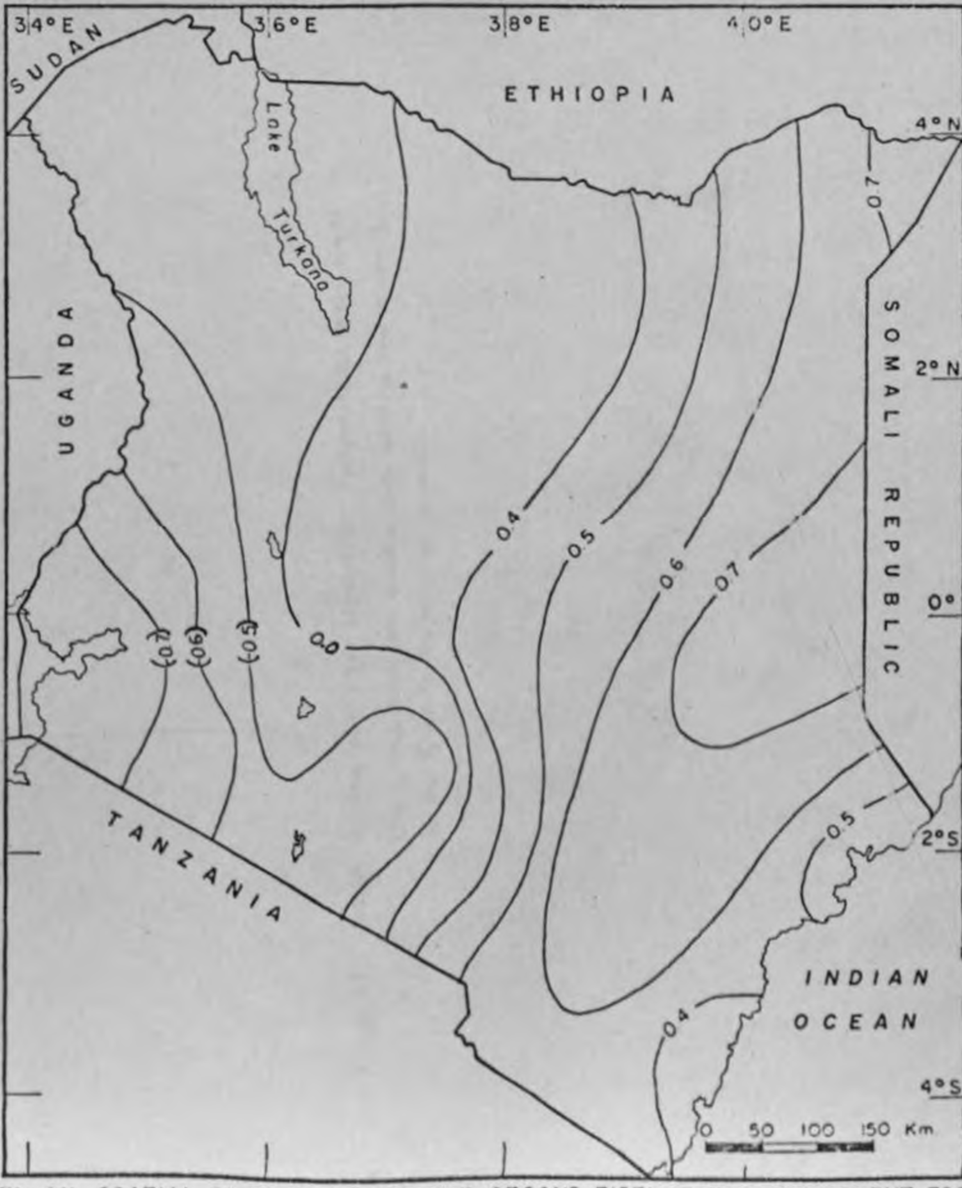


Fig.21b SPATIAL DISTRIBUTION OF THE SECOND EIGENVECTOR COMPONENT FOR MEAN WINDS.

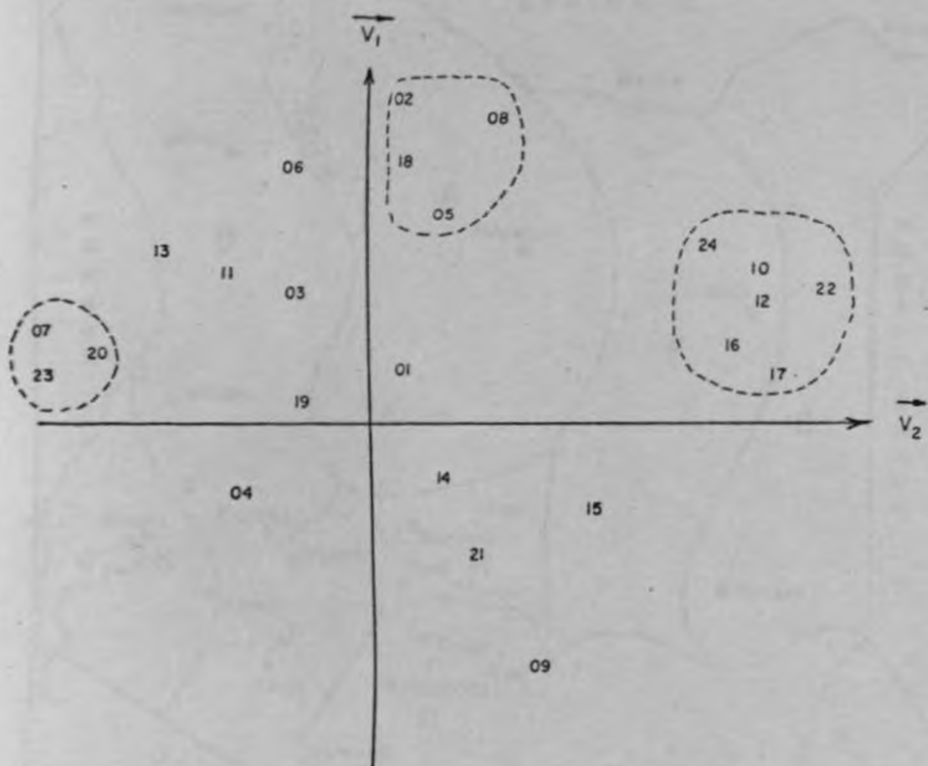


Figure 22: Scatter diagram of the two eigenvector components for mean winds (The numbers plotted refer to station code number as given in table I). $\overrightarrow{V_1}$ and $\overrightarrow{V_2}$ are the first and second eigenvector.

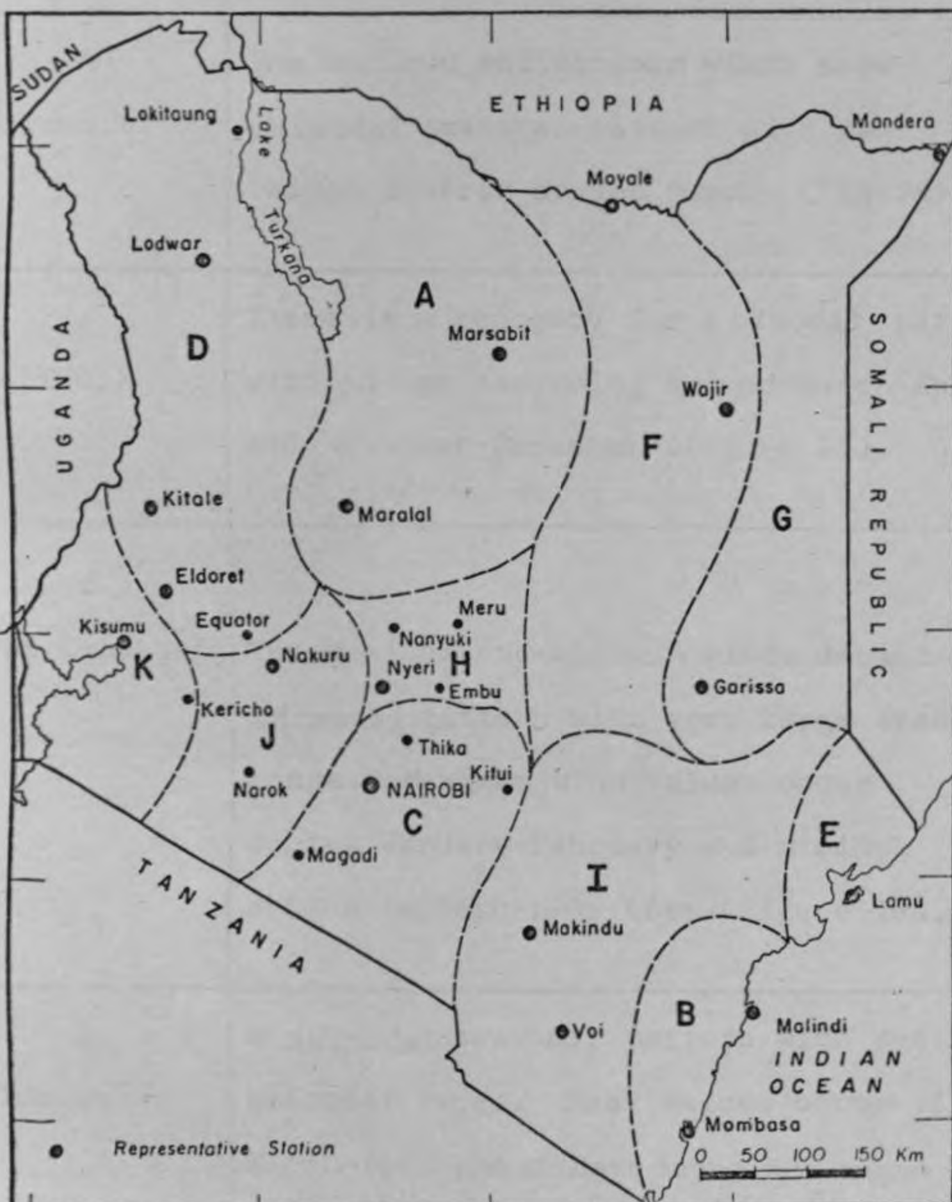


Fig. 23 HOMOGENEOUS REGIONAL GROUPS.

TABLE 7 - CHARACTERISTICS OF THE MONTHLY VARIATIONS OF THE WIND SPEEDS AT THE VARIOUS REGIONS.

Region (representative station)	Temporal Characteristics of the Mean Monthly Variations of the Wind Speeds
A (Marsabit)	The maximum and minimum winds show unimodal seasonal pattern with peak values centred around March (Fig.24).
B (Malindi)	There is a tendency for a bimodal pattern with minima occurring around March-April and November-December (Figure 25).
C (NRB Embakasi)	The maximum and minimum winds depict a unimodal pattern with very large seasonal range. Maximum wind values occur during January-February and minimum around September-October (Figure 26a, b)
D (Eldoret)	A unimodal seasonal pattern with small seasonal range. Peak values occur in March-April and minimum during July-August (Figure 27).

TABLE 7 - CONT'D

Region	Temporal Characteristics of the Mean Monthly Variations of the Wind Speeds
E (Lamu)	A tendency for a unimodal seasonal distribution with maxima and minima during June-August and March-April respectively (Figure 28).
F (Moyale)	A bimodal pattern with July and December-January peaks for the maximum winds while the minimum winds had peaks during January and September-October (Figure 29).
G (Garissa)	The pattern is unimodal with maximum and minimum occurring during August-September and January-March respectively (Figure 30).
H (Nyeri)	A unimodal distribution with maximum during April-May (Figure (31).
I (Makindu)	Has very small seasonal range and the wind speeds are generally low. (Figure 32)
J (Nakuru)	Unimodal patterns for the maximum winds and bimodal seasonal distribution for the minimum winds with maxima of the (max and min) winds occurring at different months (Figure 33).

TABLE 7 - CONT'D

Region	Temporal Characteristics of the Mean Monthly Variations of the Wind Speeds.
K (Kisumu)	Basically, this is a unimodal distribution. The maximum winds decrease between February and August then remains constant. The minimum winds show slight seasonal changes (Figure 34).

REGION 'A'

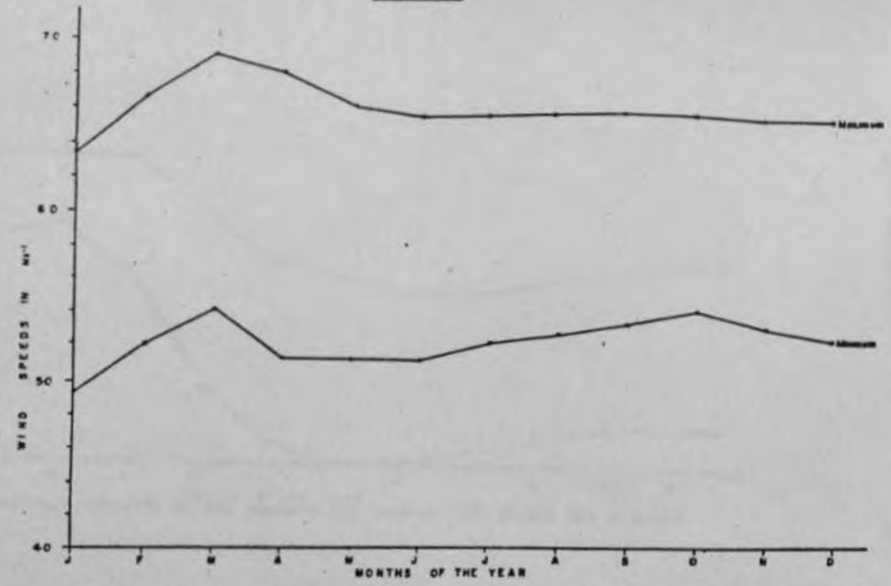
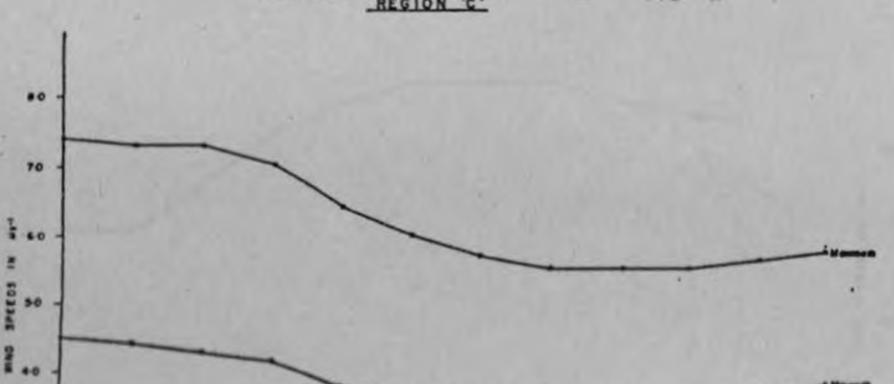


Fig. 24: MEAN MONTHLY VARIATION OF MAXIMUM AND MINIMUM WIND SPEEDS FOR MARSABIT

REGION 'C'



MEAN MONTHLY VARIATION OF THE MAXIMUM AND MINIMUM WIND SPEEDS FOR NAIROBI EMBAKASI

REGION 'B'

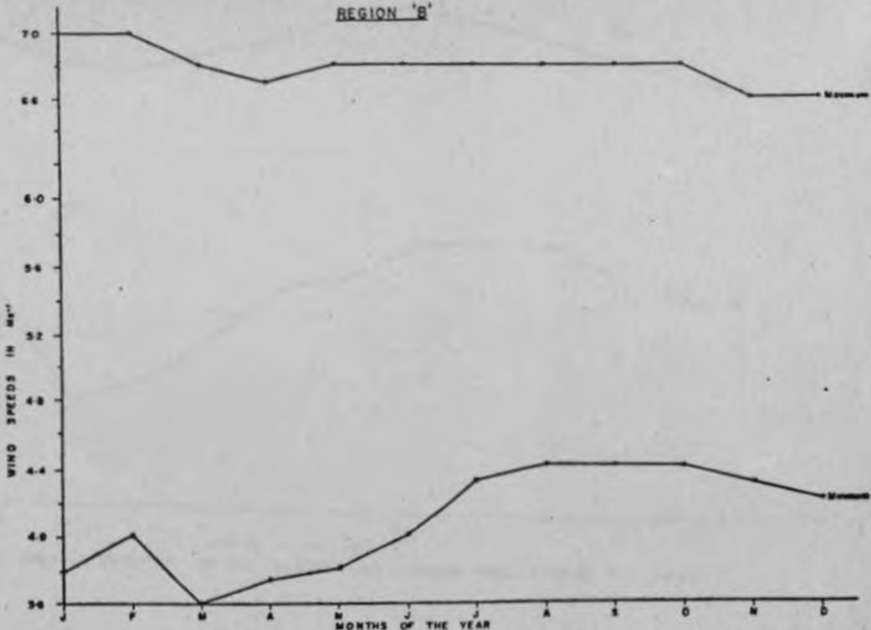


Fig. 25: MEAN MONTHLY VARIATION OF THE MAXIMUM AND MINIMUM WIND SPEEDS FOR MALINDI

REGION 'C'

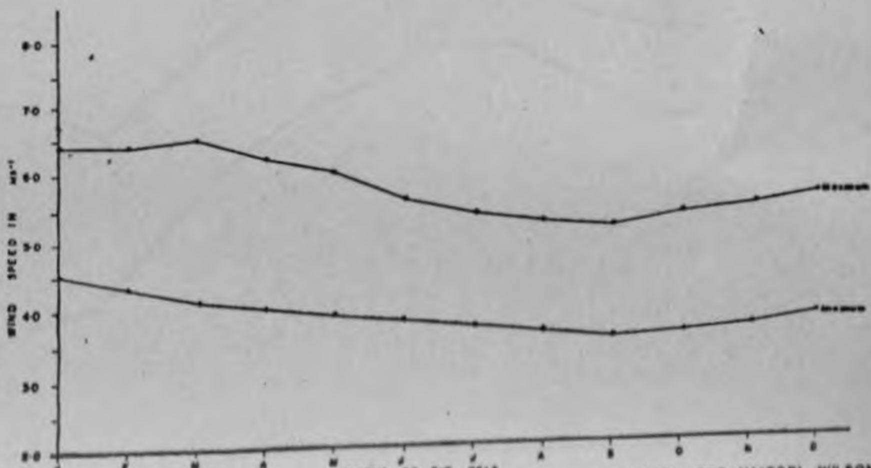


Fig. 26b: MEAN MONTHLY VARIATION OF THE MAXIMUM AND MINIMUM WIND SPEEDS FOR NAIROBI WILSON

REGION 'E'

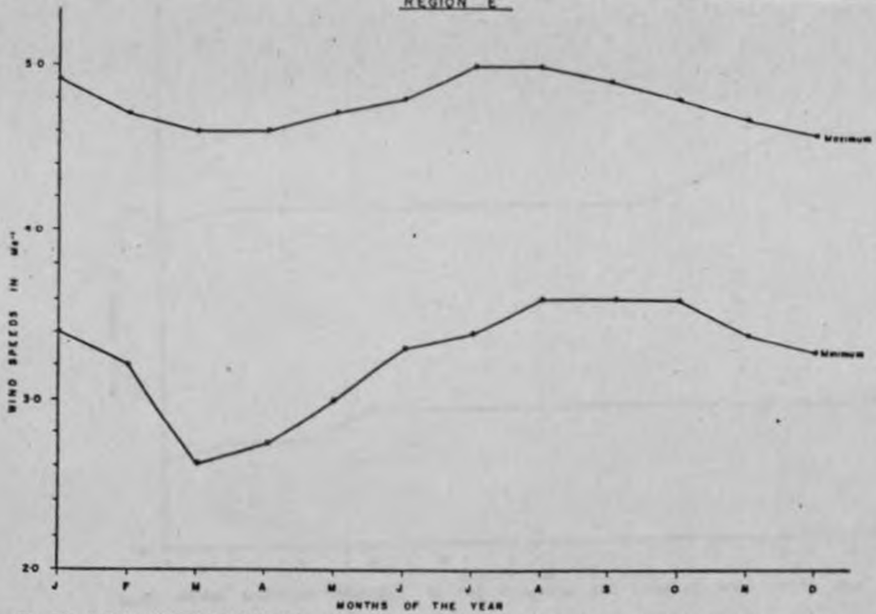


Fig. 28: MEAN MONTHLY VARIATION OF THE MAXIMUM AND MINIMUM WIND SPEEDS FOR LAMU

REGION 'G'

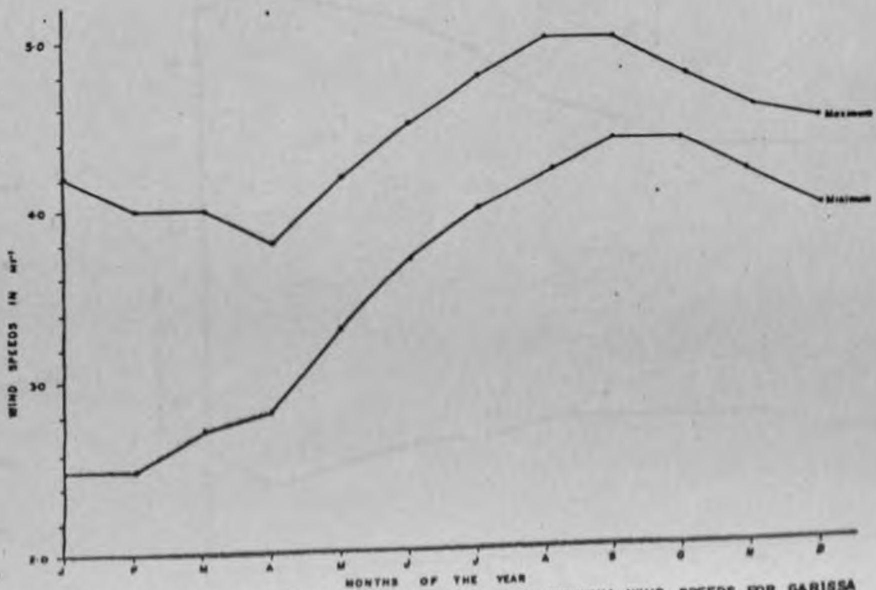


Fig. 30: MEAN MONTHLY VARIATION OF THE MAXIMUM AND MINIMUM WIND SPEEDS FOR GARISSA

REGION 'D'

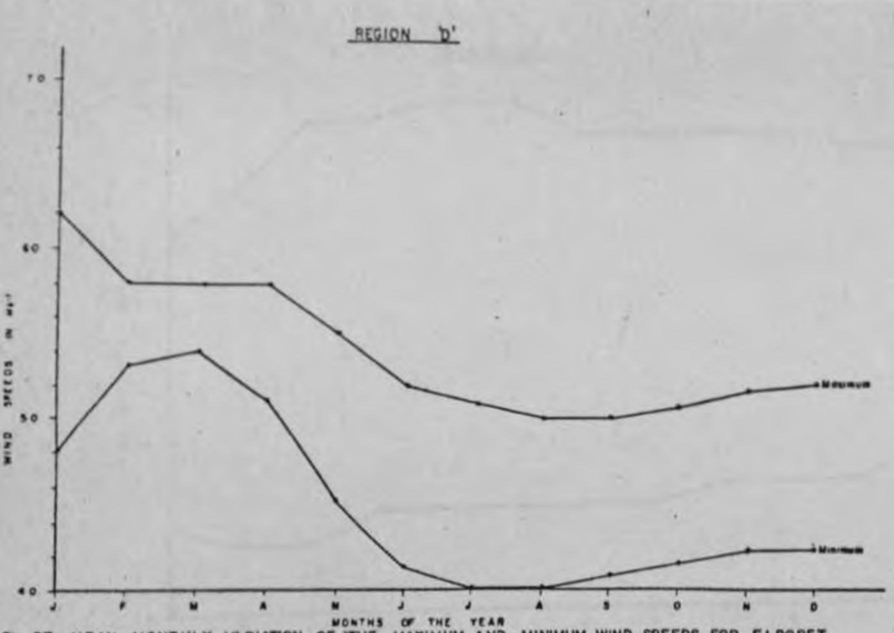
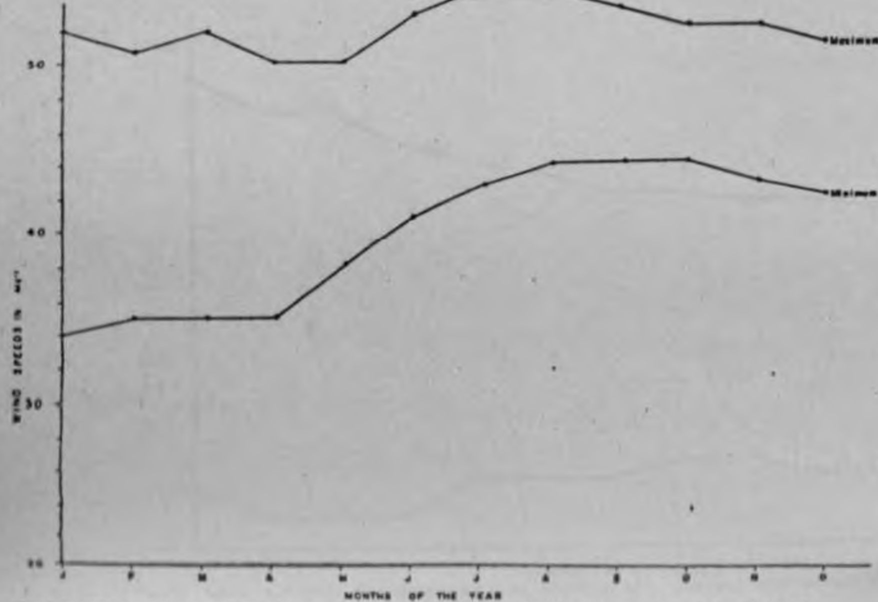


Fig. 27: MEAN MONTHLY VARIATION OF THE MAXIMUM AND MINIMUM WIND SPEEDS FOR ELDORET

REGION 'F'



[illegible] MEAN MONTHLY VARIATION OF THE MAXIMUM AND MINIMUM WIND SPEEDS FOR MOYALE

REGION 'H'

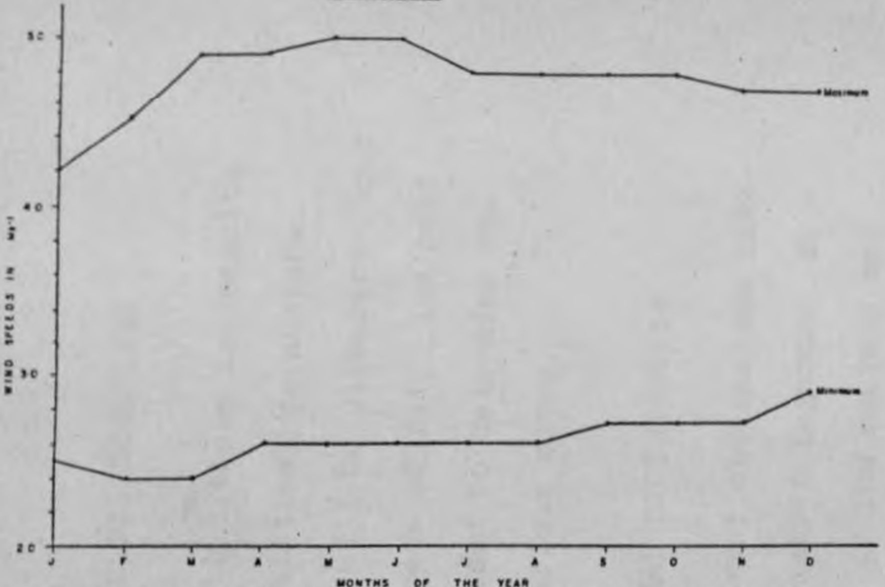


Fig.31: MEAN MONTHLY VARIATION OF THE MAXIMUM AND MINIMUM WIND SPEEDS FOR NYERI

REGION 'J'

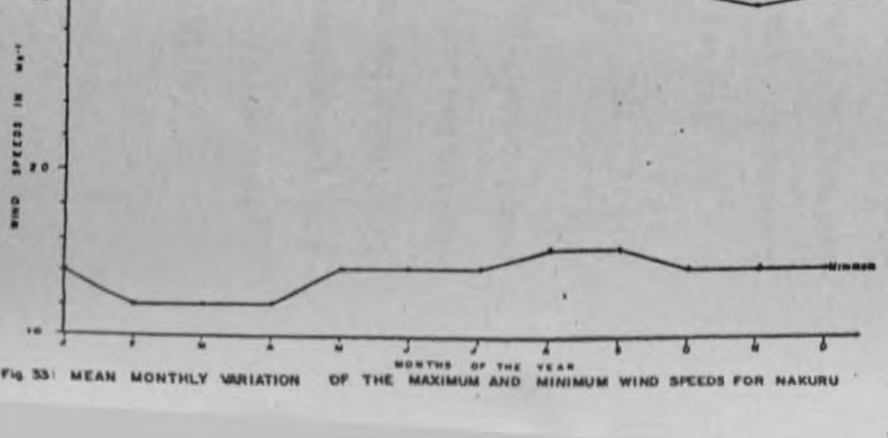


Fig. 33: MEAN MONTHLY VARIATION OF THE MAXIMUM AND MINIMUM WIND SPEEDS FOR NAKURU

REGION 'I'

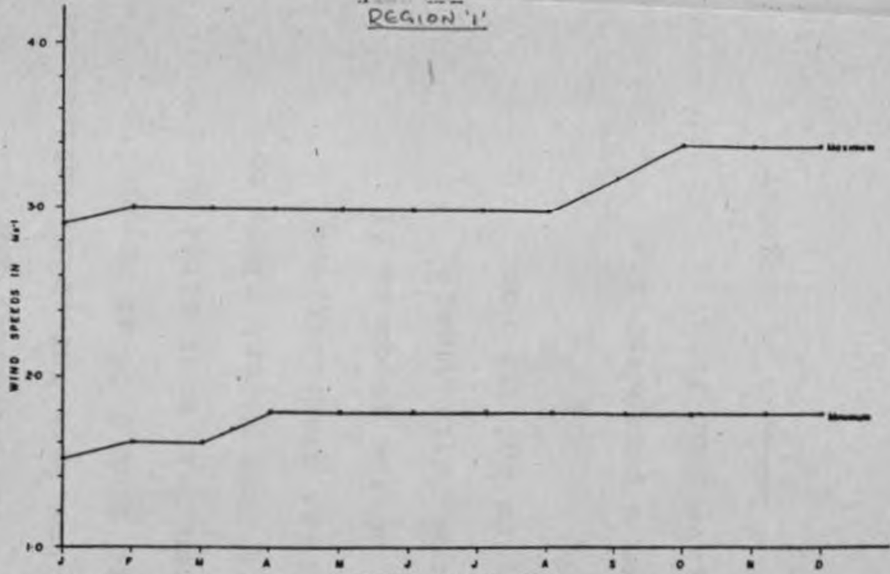


Fig. 32: MEAN MONTHLY VARIATION OF THE MAXIMUM AND MINIMUM WIND SPEED FOR MAKINDU

REGION 'K'

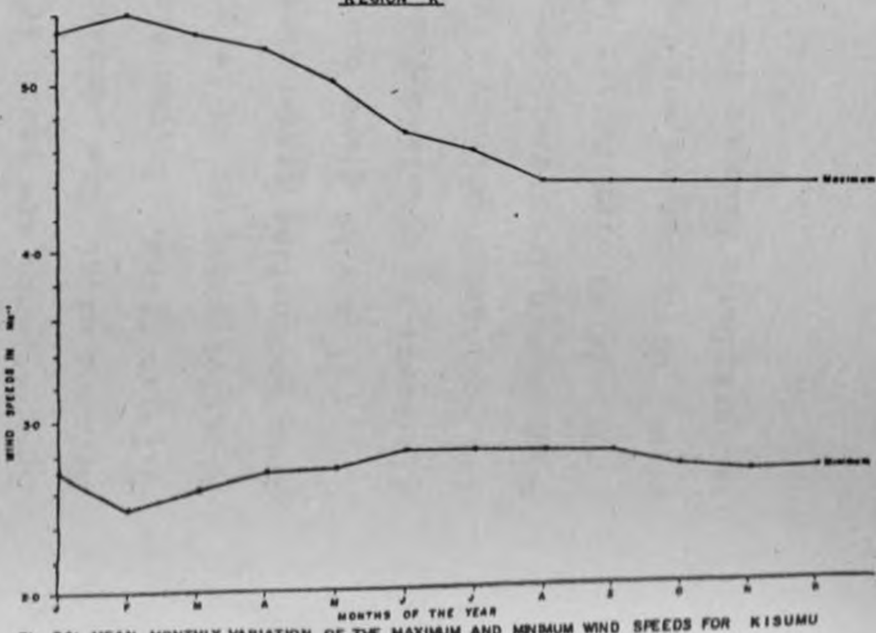


Fig. 34: MEAN MONTHLY VARIATION OF THE MAXIMUM AND MINIMUM WIND SPEEDS FOR KISUMU

3.3 RESULTS FROM THE FITTED DISTRIBUTIONS

In this section, we will discuss the results obtained with the various statistical parameters. The parameter of these models will be discussed first followed by the tests of goodness of fit. The best distribution will finally be used to determine the wind power potential at the various sites.

3.3.1 THE 2-PARAMETER LOGNORMAL DISTRIBUTION

Tables 8-10 give the moment and maximum likelihood estimates for the 2 parameter Lognormal distribution for the mean as well as the maximum and minimum wind speeds.

In table 8, we see that the ML estimates for the variance are small at most sites like Marsabit, Malindi, Mandera e.t.c. The variance ranged from 0.04 at Moyale to 0.24 at Thika. It can also be seen that most sites have negative skewness while some sites have values close to zero indicating tendencies for normal distributions

Table 11 gives the results of the goodness of fit tests as obtained from the three tests namely, the Kolmogorov-Smirnov, the Chisquare and the root mean square (residual) error tests.

At 5% significant level, the 2 parameter lognormal distribution was found to give poor fits at two stations; Eldoret and Lamu. The maximum Kolmogorov deviations at these sites were 0.12 and 0.13 respectively. A possible explantion to this lack of good fit could be attributed to the skewness of the distribution which were largely negative at these sites. This implies that most of the wind speed observations at these two sites fell below the actual mean value giving large negatively skewed distribution.

The root mean square (residual) error test showed that the 2 parameter Lognormal was not a good fit at 5 stations namely Malindi, Kisumu, Eldoret, Lamu and Narok. A value of ($\varepsilon^2 < 0.002$) was considered to be a good fit.

The χ^2 test indicated poor fit at 5% significant level at 8 stations as underlined in the table. The worst fits were obtained at Lamu, Malindi, Makindu and Eldoret.

In general, the 2 parameter lognormal distribution appears to be a relatively good distribution for modelling the surface wind speeds since it was able to fit 22 sites (K-S test).

3.3.2 THE 3 PARAMETER LOGNORMAL DISTRIBUTION

Table 12-14 give the three computed parameters for the 3 parameter Lognormal distribution. The tables indicate that no convergence could be reached after 25 iterations at six stations. These stations included all the coastal stations of Malindi, Mombasa and Lamu together with Eldoret and Narok.

Table 15 gives the results of goodness of fit for the various tests used. The Kolmogorov-Smirnov test indicated that the critical values were exceeded at two stations namely Thika and Nairobi Embakasi while the root mean square (residual) test gave good fits at 10 stations. The worst fits were again obtained with Eldoret and Lamu records.

The χ^2 - test indicated poor fits at four sites namely, Thika, Nairobi Embakasi and Lamu.

We may conclude that the 2 and 3 parameters Lognormal distribution gave fairly good fits at a number of stations. These distributions cannot however, be used to describe the wind characteristics over some parts of Kenya.

3.3.3 THE PEARSON AND LOGPEARSON III DISTRIBUTION

The parameter estimates for the Pearson and Log Pearson distributionsare given in Tables 16 and 17 respectively. It can be observed from these tables that the distributions were rather poor at a number of stations. No convergence could be obtained at 10 stations namely, Malindi, Lamu, Wajir, Eldoret, Meru, Kitale, Narok, Garissa, Nakuru and Nairobi-Dagoretti.

In general, only the distribution parameters of 14 stations could be estimated with both the

TABLE 8 - THE LOGNORMAL 2 PARAMETER ESTIMATES FOR THE MEAN WIND SPEEDS.

Station Name	Method of Moments			Method of Maximum Likelihood		
	Mean (μ)	Variance (σ^2)	Skew (γ)	Mean (μ)	Variance (σ^2)	Skew (γ)
Nyeri	3.62	1.74	0.45	1.22	0.15	-0.34
Marsabit	5.92	2.28	0.92	1.75	0.06	0.13
Malindi	5.39	2.20	0.04	1.64	0.09	-0.42
Mombasa	5.48	2.72	0.06	1.66	0.10	-0.43
Lodwar	5.91	1.76	1.19	1.31	0.10	0.33
Moyale	4.23	0.71	0.51	1.42	0.04	0.03
Mandera	4.89	1.91	0.41	1.55	0.08	-0.15
Maralal	5.75	1.62	0.55	1.72	0.05	-0.17
Kericho	4.11	1.92	0.21	1.35	0.14	-0.64
Kisumu	3.54	1.72	0.64	1.20	0.13	0.17
Wajir	4.65	1.37	-0.04	1.50	0.07	-0.49
Eldoret	4.70	1.87	-0.30	1.50	0.11	-0.86
Meru	3.73	1.22	0.46	1.27	0.09	-0.11
Kitale	2.94	0.49	0.22	1.05	0.06	-0.04
Thika	3.24	2.73	1.06	1.06	0.24	0.20
NRB Wilson	4.62	1.96	0.26	1.48	0.10	-0.39
NRB Embakasi	4.70	2.58	0.68	1.49	0.11	0.14
Makindu	2.43	0.88	0.64	0.81	0.14	0.20
Lamu	4.00	1.70	-0.37	1.32	0.16	-1.30
Voi	3.69	0.94	0.22	1.27	0.08	-0.42
Narok	2.80	1.16	-0.18	1.09	0.16	-1.15
NRB Dagoretti	3.76	1.38	0.56	1.14	0.13	-0.16
Garissa	4.28	2.52	0.66	1.39	0.14	0.03
Nakuru	2.19	0.10	1.10	0.69	0.19	0.14

TABLE 9 - THE LOGNORMAL 2 PARAMETER ESTIMATES FOR MAXIMUM WIND SPEEDS.

Station Name	Method of Moments			Method of Maximum Likelihoo		
	Mean of (μ)	Variance (σ^2)	Skew (γ)	Mean (μ)	Variance (σ^2)	Skew (γ)
Nyeri	4.72	0.79	0.66	1.53	0.03	0.14
Marsabit	6.55	2.32	0.98	1.86	0.05	0.53
Malindi	6.57	0.78	0.09	1.87	0.02	-0.43
Mombasa	6.87	0.76	0.65	1.92	0.02	0.31
Lodwar	4.45	1.96	1.09	1.45	0.08	0.46
Moyale	4.57	0.57	0.64	1.51	0.03	0.21
Mandera	5.13	1.90	0.41	1.60	0.07	-0.07
Maralal	6.21	1.36	0.73	1.81	0.03	0.22
Kericho	4.52	1.83	0.29	1.46	0.10	-0.23
Kisumu	4.64	0.86	0.53	1.52	0.04	-0.06
Wajir	5.17	0.85	0.13	1.63	0.03	-0.34
Eldoret	5.24	1.07	0.03	1.64	0.04	-0.40
Meru	4.44	0.96	0.14	1.47	0.05	-0.30
Kitale	3.54	0.16	0.04	1.26	0.01	-0.28
Thika	4.48	2.11	0.84	1.45	0.10	0.19
NRB Wilson	5.49	1.61	-0.24	1.67	0.06	-0.50
NRB Embakasi	5.74	2.37	0.02	1.71	0.08	-0.34
Makindu	3.16	0.58	-0.07	1.12	0.07	-0.55
Lamu	4.71	0.88	0.11	1.53	0.04	-0.42
Voi	4.01	0.68	0.35	1.37	0.04	-0.21
Narok	3.90	0.82	-0.85	1.33	0.08	-1.61
NRB Dagoretti	4.06	1.16	1.08	1.37	0.07	-0.24
Garissa	4.51	2.99	0.69	1.44	0.14	0.08
Nakuru	2.96	0.70	1.38	1.05	0.07	0.53

TABLE 10 - THE LOGNORMAL 2 PARAMETER ESTIMATES FOR MINIMUM WIND SPEEDS.

Station Name	Method of Moments			Method of Maximum Likelihoo		
	Mean (μ)	Variance (σ^2)	Skew (γ_1)	Mean (μ)	Variance (σ^2)	Skew (γ_1)
Nyeri	2.52	0.27	-0.45	1.02	0.02	0.21
Marsabit	5.29	1.47	0.74	1.41	0.05	0.51
Mombasa	4.21	0.82	0.42	1.43	0.03	-0.48
Lodwar	4.09	0.79	0.34	1.61	0.02	0.28
Moyale	3.36	0.98	1.05	1.32	0.08	-0.44
Mandera	3.88	0.62	0.84	1.18	0.03	0.42
Maralal	4.65	1.82	0.42	1.73	0.07	0.22
Malindi	5.29	1.47	0.74	1.22	0.03	0.29
Kericho	3.70	1.69	0.11	0.98	0.09	0.34
Kisumu	2.43	0.12	0.10	1.11	0.04	-0.41
Wajir	4.14	1.37	0.37	1.60	0.06	-0.23
Eldoret	4.16	2.12	0.06	1.48	0.01	0.46
Meru	3.01	0.46	0.13	1.14	0.06	0.12
Kitale	2.34	0.09	0.49	1.09	0.04	0.88
Thika	2.00	0.27	0.92	1.03	0.05	0.69
NRB Wilson	3.76	0.82	-0.18	1.22	0.02	0.71
NRB Embakasi	3.66	0.64	0.27	1.38	0.06	0.33
Makindu	1.69	0.11	1.02	1.41	0.01	-0.14
Lamu	3.29	1.57	-0.22	1.01	0.02	0.32
Voi	3.36	0.99	1.55	1.28	0.08	0.97
Narok	2.51	0.67	-1.06	1.44	0.11	-0.44
NRB Dagoretti	2.59	0.53	0.23	1.01	0.13	-0.24
Garissa	4.04	1.98	0.38	1.28	0.04	0.78
Nakuru	1.42	0.11	0.62	1.81	0.01	0.57

TABLE 11 - THE 2 PARAMETER LOGNORMAL TESTS OF GOODNESS-OF-FIT.

Station Name	K-S Deviations at 0.05 S.L	Residual Error (ε^2)	(χ^2)
Nyeri	0.06	0.001	3.22
Marsabit	0.03	0.0004	3.01
Mombasa	0.09	0.002	14.82
Malindi	0.09	0.003	27.46
Lodwar	0.04	0.0006	0.514
Moyale	0.02	0.0002	3.63
Mandera	0.03	0.0005	8.64
Maralal	0.007	0.00002	5.38
Kericho	0.08	0.001	8.04
Kisumu	0.04	0.003	19.26
Wajir	0.09	0.002	17.19
Eldoret	0.12	0.004	22.15
Meru	0.03	0.0004	8.92
Kitale	0.05	0.002	5.79
Thika	0.06	0.001	5.48
NRB Wilson	0.06	0.0006	5.93
NRB Embakasi	0.06	0.001	9.40
Makindu	0.07	0.002	26.55
Lamu	0.13	0.063	52.45
Voi	0.02	0.0002	1.48
Narok	0.07	0.003	18.17
NRB Dagoretti	0.03	0.0003	5.58
Garissa	0.05	0.001	6.65
Nakuru	0.04	0.0008	8.43

TABLE 12 - THE LOGNORMAL 3 PARAMETER ESTIMATES BY MAXIMUM LIKELIHOOD PROCEDURE FOR MEAN WIND SPEEDS.

Station Name	Method of Maximum Likelihood			
	(μ) Mean $\ell n(x-x_o)$	(σ^2) Var $\ell n(x-x_o)$	Skew (γ) $\ell n(x-x_o)$	Lower Bound (x_o)
Nyeri	1.58	0.07	-9.38×10^{-4}	1.40
Marsabit	1.66	0.07	9.13×10^{-4}	0.45
Malindi	-	-	-	-
Mombasa	-	-	-	-
Lodwar	1.04	0.17	0.0032	0.82
Moyale	1.29	0.05	-0.00041	0.50
Mandera	1.72	0.06	-0.00071	-0.88
Maralal	1.99	0.03	5.9×10^{-4}	-1.69
Kericho	2.52	0.01	-3.0×10^{-4}	-0.84
Kisumu	0.67	0.37	-0.035	1.22
Wajir	-	-	-	-
Eldoret	-	-	-	-
Meru	1.34	0.08	-0.0016	-0.25
Kitale	0.64	0.13	-0.0078	0.93
Thika	0.78	0.40	-0.024	0.60
NRB Wilson	2.15	0.03	-0.0014	-4.13
NRB Embakasi	1.17	0.21	-0.0094	1.14
Makindu	0.40	0.32	-0.019	0.70
Lamu	-	-	-	-
Voi	1.21	0.01	-0.015	0.82
Narok	-	-	-	-
NRB Dagoretti	1.27	0.10	-2.71×10^{-4}	-4.84
Garissa	1.13	0.23	-0.0022	0.42
Nakuru	0.29	0.42	-0.052	0.57

TABLE 13 - THE LOGNORMAL 3 PARAMETER ESTIMATES BY MAXIMUM LIKELIHOOD PROCEDURE FOR MAXIMUM WINDS.

Station Name	Mean (μ)	Variance (σ^2)	Skew (γ_1)	Location parameter x_0
Nyeri	1.24	0.07	-0.00027	1.14
Marsabit	1.08	0.21	-0.0012	3.29
Malindi	-	-	-	-
Lodwar	0.75	0.32	-0.015	1.97
Moyale	1.07	0.06	-0.00028	1.58
Mandera	-	-	-	-
Maralal	1.41	0.07	-0.0003	1.96
Kericho	1.88	0.04	-0.0005	-2.15
Kisumu	1.62	0.03	1.58×10^{-5}	-0.48
Wajir	2.90	0.003	6.8×10^{-7}	-0.001
Eldoret	-	-	-	-
Mombasa	0.98	0.10	-0.002	4.07
Meru	2.54	0.006	-0.000008	-8.25
Kitale	-	-	-	-
Thika	1.10	0.22	-0.01	1.37
NRB Wilson	-	-	-	-
NRB Embakasi	-	-	-	-
Makindu	-	-	-	-
Lamu	-	-	-	-
Voi	1.77	0.02	-1.24×10^{-5}	-1.89
Narok	-	-	-	-
NRB Dagoretti	1.86	0.03	-0.0002	2.42
Garissa	1.12	0.26	-0.02	1.02
Nakuru	0.58	0.16	0.004	1.01

TABLE 14 - THE LOGNORMAL 3 PARAMETER ESTIMATES BY MAXIMUM LIKELIHOOD PROCEDURE FOR MINIMUM WINDS

Station Name	Mean (μ)	Variance (σ^2)	Skew (γ_1)	Location parameter (x_o)
Nyeri	-	-	-	-
Marsabit	1.74	0.04	0.0002	-0.52
Mombasa	1.54	0.04	-0.0002	-0.55
Lodwar	0.93	0.13	0.002	0.66
Moyale	0.67	0.14	-0.002	1.79
Mandera	1.66	0.06	-0.008	-0.76
Maralal	1.74	0.04	0.0002	-0.52
Malindi	2.86	0.006	-0.000008	-0.001
Kericho	1.89	0.02	-0.0002	-0.03
Kisumu	-	-	-	-
Wajir	1.16	0.13	-0.004	0.76
Eldoret	2.89	0.006	-0.00002	-0.001
Meru	1.38	0.03	-0.0003	-0.01
Kitale	-	-	-	-
Thika	0.77	0.06	0.0006	0.21
NRB Wilson	-	-	-	-
NRB Embakasi	1.56	0 03	0.0002	0.27
Makindu	0.33	0.05	0.001	-
Lamu	-	-	-0.0007	-0.22
Voi	1.24	0.08		-
Narok	-	-	-	-
NRB Dagoretti	1.25	0.04	-0.0006	0..98
Garissa	1.22	0.16	-0.009	0.39
Nakuru	0.24	0.06	-0.001	0.11

TABLE 15 - TESTING THE GOODNESS OF FIT OF THE 3 PARAMETER LOGNORMAL DISTRIBUTION.

Station Name	K-S Deviation at 0.05 S.L.	Residual Error (ε^2)	(χ^2)
Nyeri	0.09	0.002	12.92
Marsabit	0.03	0.0003	3.01
Mombasa	-	-	-
Malindi	-	-	-
Lodwar	0.02	0.0002	0.51
Moyale	0.02	0.0002	3.64
Mandera	0.03	0.0005	8.64
Maralal	0.02	0.00009	5.37
Kericho	0.03	0.0003	3.43
Kisumu	0.09	0.002	22.59
Wajir	-	-	-
Eldoret	-	-	-
Meru	0.03	0.0004	8.92
Kitale	0.07	0.002	16.47
Thika	0.15	0.003	39.75
NRB Wilson	0.06	0.0009	9.49
NRB Embakasi	0.15	0.003	29.17
Makindu	0.07	0.002	18.46
Lamu	-	-	-
Voi	0.03	0.0002	1.48
Narok	-	-	-
NRB Dagoretti	0.02	0.0002	5.58
Garissa	0.08	0.002	4.13
Nakuru	0.10	0.002	12.74

TABLE 16 - PARAMETER ESTIMATES FOR THE PEARSON III DISTRIBUTION BY MAXIMUM LIKELIHOOD PROCEDURE FOR MEAN WINDS.

Station Name	Mean (μ)	Variance (σ^2)	Skew (γ_1)	Alpha (α)	Beta (β)	Gamma (x_0)
Nyeri	3.62	1.78	0.76	0.51	6.93	0.10
Marsabi	5.92	2.18	0.69	0.51	8.47	1.62
Malindi	5.39	2.21	0.04	-	-	-
Mombasa	5.48	2.72	0.23	0.19	76.70	-0.89
Ladwar	3.91	1.63	0.98	0.63	4.15	1.31
Moyale	4.22	0.72	0.69	0.29	8.39	1.76
Mandera	4.89	1.96	0.72	0.51	7.65	1.02
Maralal	5.75	1.60	0.47	0.30	18.14	0.37
Kericho	4.11	1.93	0.37	0.29	28.69	-3.33
Kisumu	3.54	1.86	1.33	0.91	2.26	1.48
Wajir	4.65	1.37	-0.04	-	-	-
Eldoret	4.70	1.87	-0.31	-	-	-
Meru	3.73	1.22	0.49	-	-	-
Kitale	2.94	0.49	0.23	-	-	-
Thika	3.24	2.79	1.45	1.21	1.81	0.94
NRB Wilson	4.62	1.99	0.52	0.37	14.68	-0.78
NRB Embakasi	4.70	2.73	1.12	0.97	2.91	1.88
Makindu	2.43	0.94	1.30	0.63	2.36	0.94
Lamu	4.01	1.69	-0.38	-	-	-
Voi	3.68	0.94	0.36	0.18	30.57	-1.68
Narok	3.22	1.16	-0.19	-	-	-
NRB Dagoretti	3.33	1.38	0.60	-	-	-
Garissa	4.27	2.53	0.70	-	-	-
Nakuru	2.19	0.99	1.18	-	-	-

TABLE 17 - PARAMETER ESTIMATES FOR THE LOG-PEARSON III DISTRIBUTION BY MAXIMUM LIKELIHOOD PROCEDURE FOR MEAN WIND SPEEDS

Station Name	Mean (μ)	Variance (σ^2)	Skew (γ_1)	Alpha (α)	Beta (β)	Gamma (x_o)
Nyeri	3.62	1.78	0.76	0.51	6.93	0.1
Marsabit	5.92	2.18	0.69	0.51	8.47	1.62
Malindi	5.39	2.21	0.04	-	-	-
Mombasa	5.48	2.72	0.23	-	-	-
Lodwar	5.91	1.63	0.98	0.63	4.15	1.31
Moyale	4.22	0.72	0.69	0.29	8.39	1.76
Mandera	4.89	1.96	0.72	0.51	7.65	1.02
Maralal	5.75	1.60	0.47	0.30	18.14	0.37
Kericho	4.11	1.93	0.37	0.29	28.69	-3.33
Kisumu	3.54	1.86	1.33	0.91	2.26	1.48
Wajir	4.65	1.37	-0.04	-	-	-
Eldoret	4.70	1.87	-0.31	-	-	-
Meru	3.73	1.22	0.49	-	-	-
Kitale	2.94	0.49	0.23	-	-	-
Thika	2.24	2.79	1.45	1.21	1.81	0.4
NRB Wilson	4.62	1.99	0.52	0.37	14.68	-0.78
NRB Embakasi	4.70	2.73	1.12	0.97	2.91	1.88
Makindu	2.43	0.94	1.30	0.63	2.36	0.94
Lamu	4.01	1.69	-0.38	-	-	-
Voi	3.68	0.94	0.36	0.18	30.57	-1.68
Narok	3.22	1.16	-0.19	-	-	-
NRB Dagoretti	3.33	1.38	0.60	-	-	-
Garissa	4.27	2.53	0.70	-	-	-
Nakuru	2.19	0.99	1.18	-	-	-

Pearson III and the Log Pearson III Distributions. It may be concluded that the statistical distribution of the winds at many Kenyan sites do not generally conform to the Pearson III and Log Pearson III distributions.

3.3.4 THE 3 PARAMETER WEIBULL DISTRIBUTION

Since the 2 parameter Weibull model can be inferred from the 3 parameter Weibull distribution (Table 2), only the results for the 3-parameter weibull distribution will be discussed here.

The parameters for the Weibull 3 parameter distribution are given in Table 18. It can be observed from this table that a number of sites have positively skewed Weibull distribution. It can be seen as well that all sites had positive location parameter (x_o) while the shape parameter (β) takes a mean value of about 2.20. The scale parameter (α) varies in accordance with the mean wind speeds. Higher mean wind speeds tend to give larger values for the scale parameter (α). Both the shape and scale parameter varied significantly from site to site.

Table 19 gives the results of goodness of fit for the 3 parameter Weibull distribution. The Kolmogorov-Smirnov test showed that the maximum deviation was never exceeded at all the sites at 5% significant level implying good fits. Likewise the root mean square (residual) errors gave smaller values of (ε^2) at all stations showing good fits of the 3 parameter Weibull distribution. Similar results were also obtained with the χ^2 - test.

We may therefore conclude that the 2 parameter lognormal and the 3 parameter Weibull distributions fitted wind data best at many Kenyan sites. The three parameter Weibull distribution however, fitted best the wind speed data from all sites. This distribution will therefore be used in the next section to determine the wind power potential at the various sites.

3.4 WIND POWER POTENTIAL AS DERIVED FROM THE THREE PARAMETER WEIBULL DISTRIBUTION.

Table 20 gives the corrected mean air density at the various stations as computed from equation (56). It can be seen that station at low altitudes have higher mean air densities than the ones at higher altitudes which is to be expected since density decreases with increasing height.

Table 21 and figure 35 give the mean wind power density at 10m above the ground as derived from the weibull model assumming a horizontal open terrain as given in equation (62). It was observed that the patterns of the mean wind power density closely resemble those of the mean wind speeds. Sites with higher mean wind speeds (Marsabit, Maralal, Malindi, Mombasa, Nairobi Embakasi and Mandera) were also the sites with greater values of mean wind power density.

Marsabit showed the highest wind power (Table 21) (184.4 W/m^2) followed by Maralal (159.7 W/m^2) while Malindi and Mombasa had nearly equal wind power densities (110.0 W/m^2). Areas with moderate wind power potentials included Nairobi Embakasi (80.3 W/m^2), Mandera (76.1 W/m^2) and Garissa (75.5 W/m^2).

Low wind power areas included Makindu, Narok, Kitale and Nakuru (less than 20.0 W/m^2)

In general, the magnitudes of these wind power densities as computed from the 3 parameter Weibull distribution were relatively higher as compared to those obtained by Chipeta (1976). His highest magnitudes were of the order of 100.0 W/m^2. The relatively low wind powers as obtained by Chipeta (1976) could have been as a result of the errors inherent in using the wind speed data (cubed) from the frequency tables.

Some examples of the seasonal characteristics of the wind power are given in figures 36-39. The sites included Marsabit (Region A), Malindi (Region B), Garissa (Region G) and Kisumu (Region K). It was noted that although there were large variations in the seasonal characteristics of the surface wind powers at many locations, substantial powers were available around the Marsabit/Maralal region throughout the year. The seasonal patterns of the wind power were found to closely resemble the seasonal characteristics of the winds which were presented in figures 24-34 and table 7.

The frequency distribution of the winds obtained using the 3 parameter Weibull distributions at some sites are presented in figures 40 and 41. These Weibull frequency curves for the wind speeds may be used to determine the best wind powered generator at the various locations as briefly described in the next section.

3.4.1 USE OF THE WEIBULL FREQUUENCY DISTRIBUTION CURVES

Using equation (20), it was possible to draw the Weibull frequency distribution curves for the various regions. Some examples of these curves are given in figures 40 and 41. The curves give the frequencies of the wind speeds at the various regions.

The frequency curves have been subdivided into three sections, namely low (I), medium (II) and high (III) wind categories. Section I are for wind speeds less than 3.6 ms^{-1} while section II are for the winds lying between 3.6 ms^{-1} and 8.0ms^{-1}. Section III are for the wind speeds greater than 8.0ms^{-1} but less than 26.8ms^{-1}.

The value 3.6ms^{-1} used here is the cut-in wind speed for wind powered generators which may be similar to that of NASA 100kw plumbrook aerogenerator unit. This is the minimum wind speed for such a generator to start operating (Hennessey, 1977). The value 8.0ms^{-1} is the rated wind speed at which the maximum possible power (100kw) is generated while wind speeds greater than 26.8ms^{-1} are described as furling speeds whereby a wind generator has to be shut down due to possible breakages.

Wind powered generators normally work best at region II as shaded in the figures. Variations in both the shape parameter (β) and the meanwind speeds affect the percentage of the wind speed cubed and therefore the power density represented by these three sections. Section I will definately have low values of the cube of the wind speed ($< 3.6^3$) while section II will have intermediate levels between (3.6^3) and (8.0^3).

The scale and shape parameter for the various curves have been indicated in each of the frequency curves by the symbols (α) and (β) respectively. A closer look at these curves depict positive skewness at many locations. The high variations in the skewness and peakedness patterns in these curves indicate high variations in the characteristics of the wind speeds and hence the total wind powers at the various location. Generally sites with low values of shape parameter and higher mean wind speeds do have highest total mean wind power density (Justus and Hargrave (1978).

From these curves, it may be concluded that the potential sites for wind powered generators (small or medium output) appear to be centred around Marsabit, Malindi Eldoret and Moyale regions. Other regions with significant potentials appear to be around Nairobi Embakasi and Wajir regions. These potential sites can in general be also recognised by their respective location parameters x_o (Table 18). Sites with relatively larger values of (x_o) seem to be also the sites with reasonable potentialities with respect to the cut-in velocity (3.6 ms^{-1}).

The cumulative frequency curves for Marsabit, Malindi Eldoret and Moyale regions are presented in figure 42. These curves show the percentage of time the wind speeds are greater than a certain given value. For example, Marsabit region which had the highest wind power potential (table 21) indicated that at least 95% of the time the wind speeds exceeded say 3.6 ms^{-1}. These cumulative curves are therefore important in the evaluation of the seasonal power expectation at any site.

TABLE 18 - THE WEIBULL 3 PARAMETER ESTIMATES FOR MEAN WIND SPEEDS BY METHOD OF MAXIMUM LIKELIHOOD PROCEDURE.

Station Name	Mean (μ)	Variance (σ^2)	Skew (γ_1)	Beta (β) shape	Alpha (α) scale	Gamma (x_o) location
Nyeri	3.62	1.72	-4.13	2.26	3.98	0.82
Marsabit	5.92	2.34	-5.03	2.43	6.36	2.43
Malindi	5.39	2.19	0.47	2.27	5.80	2.22
Mombasa	5.48	2.61	-5.94	2.60	6.00	1.57
Lodwar	3.91	1.75	0.60	2.05	4.24	1.31
Moyale	4.22	0.71	0.41	2.39	4.47	2.34
Mandera	4.89	1.88	-4.48	2.33	5.28	1.88
Maralal	5.74	1.68	-7.44	2.86	6.16	2.32
Kericho	4.11	1.88	-6.57	2.71	4.54	0.66
Kisumu	3.54	1.71	0.92	1.65	3.78	1.44
Wajir	4.66	1.31	-8.93	3.09	5.04	1.42
Eldoret	4.70	1.86	0.29	3.10	5.23	1.51
Meru	3.73	1.21	0.93	1.63	3.93	1.98
Kitale	2.94	0.49	1.34	1.30	3.01	2.04
Thika	3.24	2.71	1.20	1.40	3.46	0.96
NRB Wilson	4.62	1.93	-4.85	2.40	5.02	1.50
NRB Embakasi	4.70	2.57	0.76	1.82	5.05	1.88
Makindu	2.42	0.87	0.96	1.60	2.60	0.97
Lamu	4.00	1.68	0.11	4.44	4.44	0.24
Voi	3.68	0.93	0.18	4.00	4.00	1.05
Narok	3.22	1.12	0.44	3.65	3.65	2.95
NRB Dagoretti	3.32	1.42	1.38	3.56	3.56	1.35
Garissa	4.27	2.51	1.10	4.52	4.52	1.98
Nakuru	2.19	0.99	1.54	2.26	2.26	1.01

TABLE 19 - TESTING THE GOODNESS OF FIT OF THE WEIBULL 3 PARAMETER MODEL.

Station Name	K-S Deviations at 0.05 S.L	Residual Error (ε^2)	(χ^2) Values at 0.05 S.L.
Nyeri	0.06	0.0009	3.22
Marsabit	0.06	0.001	3.01
Malindi	0.07	0.001	3.59
Mombasa	0.06	0.001	3.99
Lodwar	0.06	0.001	3.51
Moyale	0.002	0.00009	5.37
Mandera	0.04	0.0003	3.98
Maralal	0.03	0.0004	3.63
Kericho	0.03	0.0002	3.43
Kisumu	0.06	0.001	3.67
Wajir	0.05	0.001	3.71
Eldoret	0.04	0.0007	3.19
Meru	0.04	0.0003	3.00
Kitale	0.05	0.0004	7.16
Thika	0.05	0.00009	5.93
NRB Wilson	0.05	0.00008	3.10
NRB Embakasi	0.07	0.0002	6.45
Makindu	0.05	0.001	3.69
Lamu	0.06	0.001	1.48
Voi	0.03	0.0003	3.41
Naroki	0.04	0.0002	5.61
NRB Dagoretti	0.02	0.001	3.01
Garissa	0.06	0.0002	4.13
Nakuru	0.08	0.001	3.15

TABLE 2o - CORRECTIONS FOR MEAN AIR DENSITY AT VARIOUS STATIONS.

Station Name	Barometric Pressure (mb)	Mean air temperature (°C)	Height above M.S.L (M)	Corrected mean air density kg/m³
Nyeri	826.0	31.4	1829	0.95
Marsabit	867.0	30.2	1345	1.01
Mombasa	1008.1	37.3	16	1.14
Malindi	954.4	39.8	566	1.07
Lodwar	901.1	39.0	1113	1.00
Moyale	988.9	40.3	331	1.11
Mandera	795.3	30.1	2133	0.92
Maralal	1011.5	35.5	3	1.15
Kericho	785.6	28.1	1982	0.92
Kisumu	887.3	36.9	1146	1.01
Wajir	993.1	39.5	244	1.12
Eldoret	796.0	29.7	2084	0.92
Meru	901.1	30.0	1555	0.98
Kitale	817	32.8	1829	0.94
Thika	902.2	33.3	1549	0.98
NRB Wilson	835.7	31.5	1891	0.96
NRB Embakasi	841.1	32.2	1891	0.97
Makindu	904.7	36.1	1000	1.03
Lamu	1012.3	36.4	9	1.13
Voi	953.8	37.3	560	1.08
Narok	815.3	32.7	1890	0.94
NRB Dagoretti	823.5	30.6	1891	0.95
Garissa	997.7	41.4	128	1.11
Nakuru	814.3	31.7	1851	0.94

TABLE 21 - MEAN SURFACE POWER DENSITY ESTIMATES IN W/m^2.

Station Name	Surface Power Density in W/m^2
Nyeri	34.9
Marsabit	184.4
Malindi	111.5
Mombasa	113.0
Lodwar	60.6
Moyale	60.0
Mandera	76.1
Maralal	159.7
Kericho	44.3
Kisumu	38.2
Wajir	68.0
Eldoret	58.8
Meru	37.9
Kitale	15.2
Thika	35.1
Nairobi Wilson	64.9
Nairobi Embakasi	80.3
Makindu	12.7
Voi	35.1
Lamu	44.3
Narok	20.0
Nairobi Dagoretti	28.9
Garissa	75.5
Nakuru	10.2

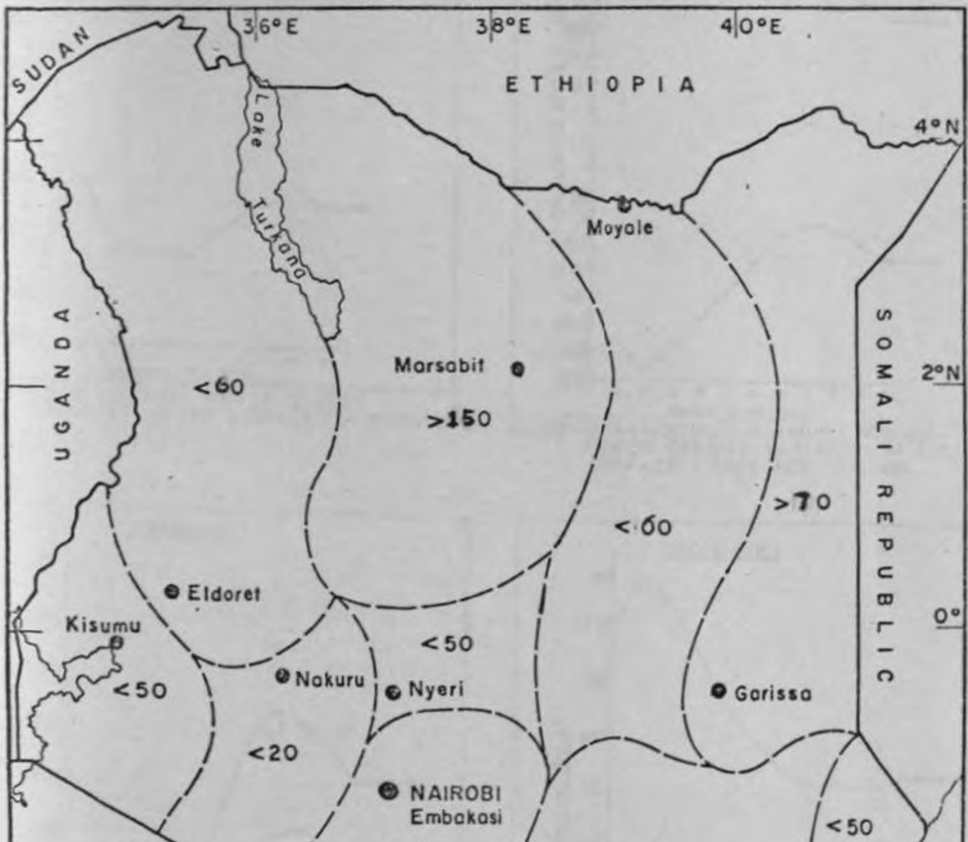


Fig. 35.- SPATIAL DISTRIBUTION OF THE MEAN SURFACE (10m) WIND POWER DENSITY IN W/m² ASSUMING A HORIZONTAL OPEN TERRAIN.

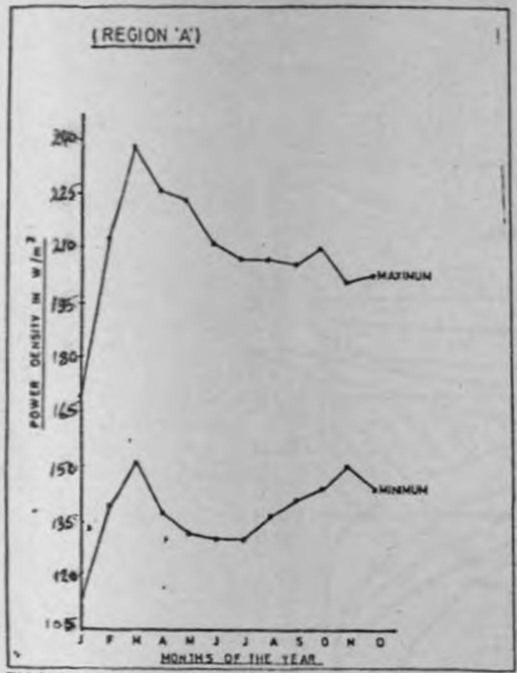


FIG.36.—MEAN MONTHLY POWER DENSITY VARIATION AT THE SURFACE FOR MARSABIT

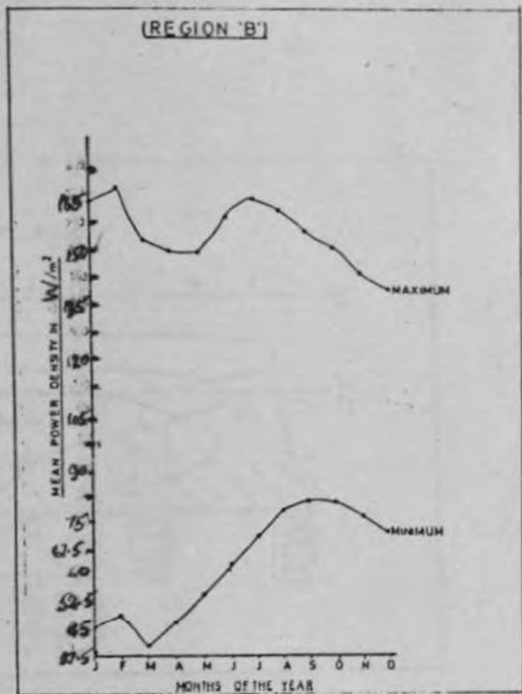


FIG.37.—MEAN MONTHLY MAXIMUM & MINIMUM POWER DENSITY VARIATION AT THE SURFACE LEVEL FOR MALINDI

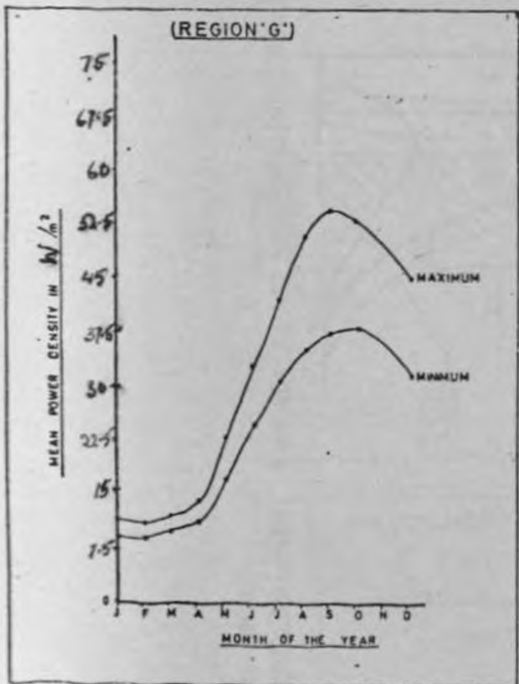


FIG.38.— MEAN MONTHLY MAXIMUM & MINIMUM POWER DENSITY VARIATION AT THE SURFACE FOR GARISSA

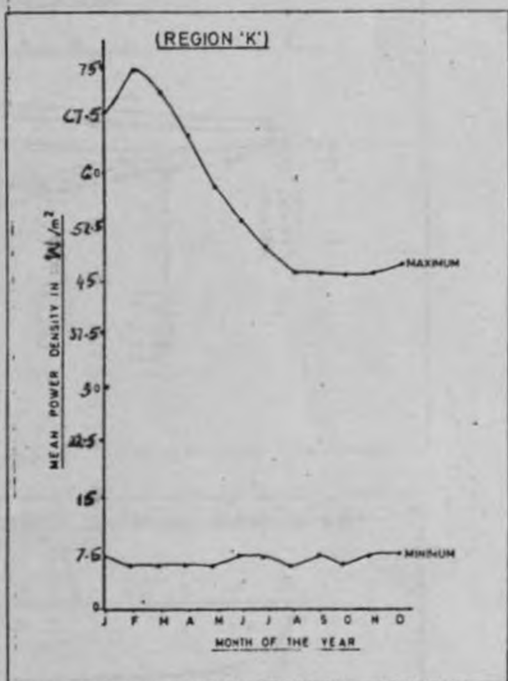


FIG39.—MEAN MONTHLY MAXIMUM & MINIMUM POWER DENSITY VARIATION AT THE SURFACE FOR KISUMU

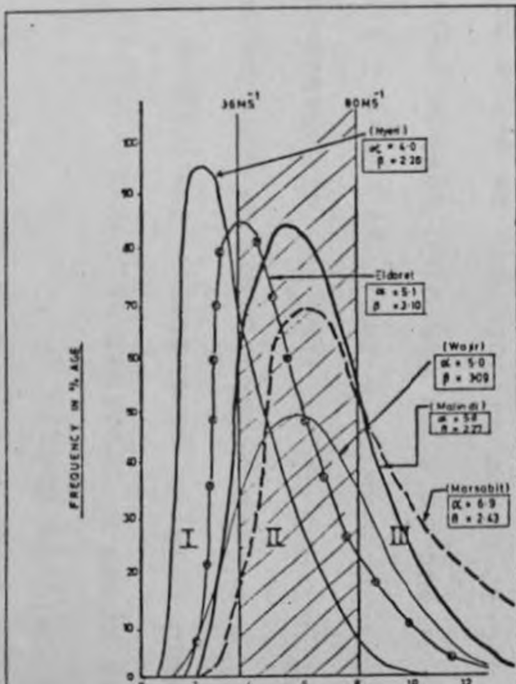


FIG 40 :— THE WEIBULL-3 FREQUENCY CURVES FOR SOME STATIONS

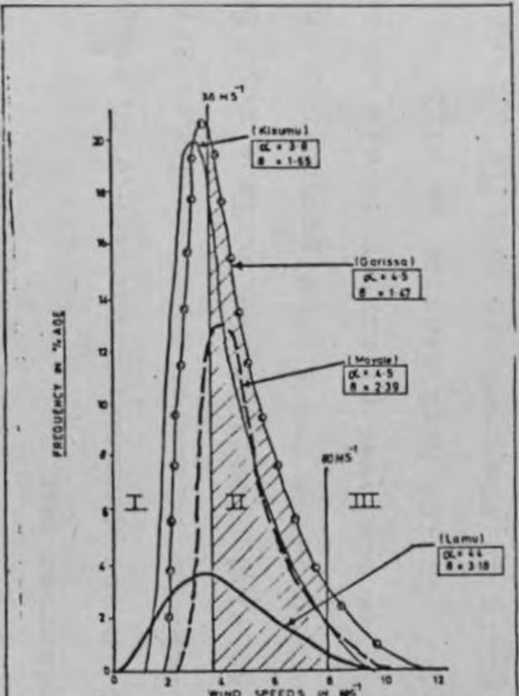


FIG 41. —WEIBULL-3 FREQUENCY CURVES FOR SOME STATIONS

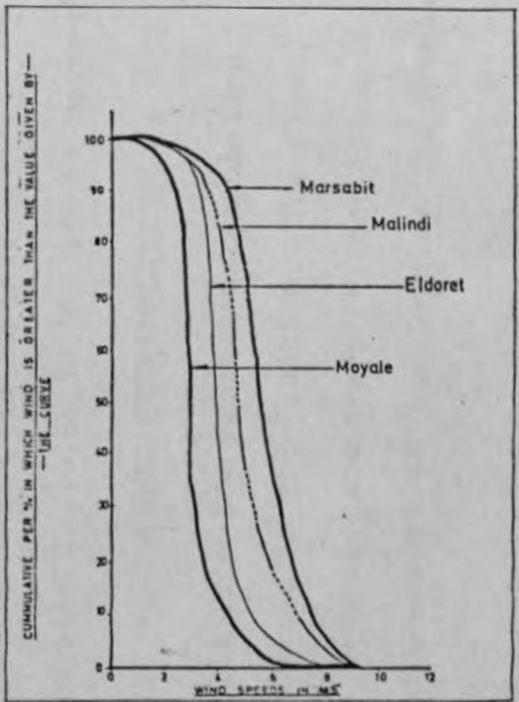


FIG 42. —THE CUMMULATIVE FREQUENCY CURVES FOR THE WEIBULL - 3

The results in general indicated that regions around Marsabit, Maralal, Malindi and Mombasa have good potentialities for wind powered generators of medium and small output units.

Figure 43 shows a hypothetical power output curve for any wind powered generator. The figure indicates that the cut-in velocity here is approximately at $4.2ms^{-1}$ while the cut-out is at $18ms^{-1}$. The maximum power output at mean wind speeds of $6.8ms^{-1}$ is about 2 kw while the rated power output is 4 kw for wind speeds greater than $10ms^{-1}$. Similar power outputs can be achieved at many locations in Kenya once proper siting for the wind generators are carried out.

The wind speeds generally increase with height due to the general reduction in the frictional effects. Thus although the wind speeds at the surface may be less than the cut-in value for a wind generator, the cut-in values may be achieved at higher levels above the surface (10m). In the next section we will describe the results of the vertical profile of the wind power as obtained from the various methods. The levels used here were 15,20,25,30,50, and 75 meters.

3.5 RESULTS OF WIND POWER EXTRAPOLATION

The results from the various extrapolation methods are presented in this section. The first method used the Weibull parameters (α) and (β) to extrapolate wind power at various levels. The levels used were 15,20,25,30, and 50 and 75 meters.

Table 22 gives the results of the wind powers at the various levels using the weibull extrapolation formulae. It was observed that the mean wind power density increased substantially with height. The vertical profile of the wind power for some sites are shown in figure 44. It was evident from the gradient patterns that the level between 25-30 meters could be the optimum level for wind power generations in Kenya before the cost-benefit factors are considered.

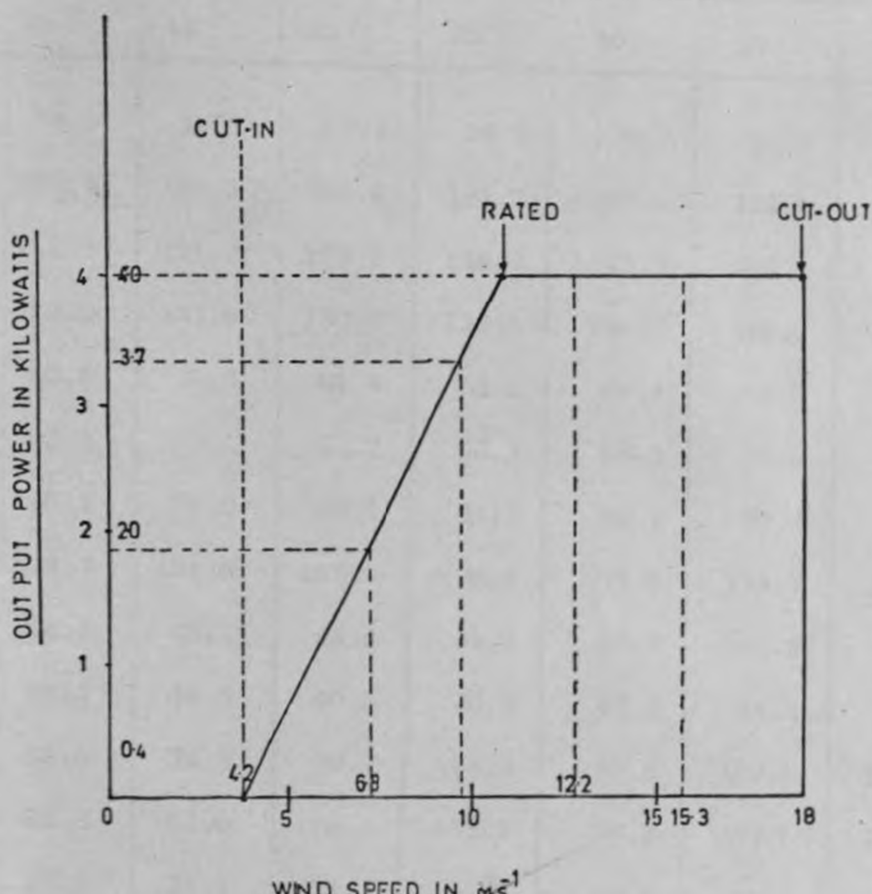
The second method was based on the power law. In this case $\alpha = 1/7$ was used to estimate the wind speeds at the various levels given above. The estimated wind speeds were then used to compute the power densities by cubing them directly and multiplying the results by half the mean air density.

Table 23 gives the wind power densities at the various levels as obtained by this method. It was observed from the table that the power increased substantially with height. The method indicated that the higher the level, the greater is the power. Relatively low values of the wind power were obtained at levels below 25m. The results at heigher levels seemed to be comparable to those obtained from the Weibull method. The results of this second method however, may not be realistic due to the assumption made in the computations of the wind power.

One such assumption was the use of a constant value ($\alpha = {}^{1}/_{7}$) being assumed to apply at all the sites which cannot be the case. Other factors like stability conditions are not incorporated in the power law equation which might as well be a drawback to the results obtained with this method.

The last method attempted was based on the logarithmic power law (equation (65)). Table 24 gives the power estimates at the various levels using this method. It was evident from the table that the method over-estimated the wind power at all the levels. However, the spatial distribution of the wind powers were identical to those observed with the first two methods (Figure 45). Some of the weakness of this method were discussed under methodology.

Comparing the values obtained from the three methods, one may consider the estimates from the 3 parameter Weibull distribution to be more realistic.



SOURCE– W.M.O. TECHNICAL NOTE NR 173 (1981)

FIG.43.— HYPOTHETICAL OUTPUT POWER CURVE FOR ANY WIND POWERED GENERATOR

Table 22 - Mean Wind Power Densities at Various Heights above the Ground Using the Weibull Extrapolation Formulae. All Values in W/m^2

Station Code	Height in Meters above surface						
	10	15	20	25	30	50	75
1	34.9	36.0	37.2	38.5	39.7	44.3	48.8
2	184.4	185.3	188.6	195.5	205.1	212.1	222.0
3	111.5	121.2	129.5	136.8	143.3	165.3	187.1
4	113.0	122.6	130.7	138.0	144.6	166.0	188.2
5	60.6	61.5	62.4	63.2	64.3	64.6	75.8
6	60.0	60.1	61.7	63.5	65.5	72.6	80.3
7	76.1	79.0	82.1	85.3	88.3	99.0	110.3
8	159.7	161.6	165.7	170.4	175.2	193.7	213.8
9	44.3	46.7	49.4	51.8	53.9	61.5	69.2
10.	38.2	38.5	40.3	40.9	42.5	44.0	48.3
11	68.0	74.3	79.7	84.3	88.5	102.5	116.2
12	58.8	63.0	70.7	75.2	79.3	92.6	105.5
13	37.9	38.9	39.7	41.0	42.4	47.3	52.5
14	15.2	16.1	17.0	17.9	18.6	21.2	23.8
15	35.1	35.3	35.7	36.2	36.8	38.1	41.5
16	64.9	68.7	72.3	75.6	78.7	89.4	100.2
17	80.3	83.6	84.5	86.1	87.0	95.0	104.8
18	12.7	12.8	13.0	13.1	13.7	14.6	16.1
19	35.1	37.4	39.4	41.3	43.1	49.0	55.1
20	44.3	49.3	53.4	57.0	60.1	70.3	80.1
21	20.0	22.1	23.9	25.4	26.7	31.1	35.3
22	28.9	29.2	29.9	30.7	31.5	34.7	38.3
23.	75.5	75.8	77.1	77.3	82.2	86.2	94.4
24	10.2	10.3	10.4	10.5	10.8	11.6	12.4

TABLE 23 - MEAN POWER DENSITY ESTIMATES AT VARIOUS HEIGHTS AS OBTAINED USING THE 1/7TH POWER LAW. ALL VALUES ARE IN W/m^2

Station Code	Height in Meters					
	10	15	20	25	30	50	75
1	36.0	40.0	43.0	44.3	48.0	59.7	71.0
2	156.1	173.6	195.4	204.9	220.1	275.8	328.1
3	127.3	142.9	155.8	175.8	176.7	236.6	281.5
4	127.0	142.7	155.5	173.1	176.4	232.9	277.1
5	50.0	53.9	55.6	58.7	62.4	78.9	94.0
6	62.4	66.7	74.6	82.2	105.5	110.6	131.6
7	73.7	81.7	89.2	105.5	125.6	142.0	168.9
8	135.7	149.9	167.7	215.2	233.6	289.6	344.6
9	49.5	55.1	59.7	62.4	67.2	83.9	100.0
10	36.2	39.1	41.8	43.6	46.3	58.7	69.8
11	83.0	93.0	101.2	111.1	114.4	149.5	117.9
12	78.3	80.6	87.7	94.3	107.6	126.9	151.0
13	38.7	42.4	45.5	49.8	50.8	67.2	79.7
14	18.6	20.4	22.3	23.5	26.6	31.6	37.6
15	30.8	31.8	32.1	32.8	35.7	44.2	52.6
16	68.9	76.7	83.2	93.7	105.7	126.1	150.0
17	75.8	81.4	90.9	97.1	115.2	130.7	155.5
18	12.1	13.7	14.0	14.4	17.6	19.4	23.1
19	63.0	64.5	70.3	71.6	85.7	96.3	114.6
20	41.5	45.9	49.8	53.1	55.6	71.5	85.1
21	32.5	35.1	37.8	46.1	53.2	62.0	73.8
22	29.8	32.3	34.5	35.1	38.2	47.2	56.2
23	64.8	70.5	75.6	85.7	105.3	115.3	137.2
24	9.1	9.8	10.1	10.7	11.2	13.0	15.5

TABLE 24 - MEAN WIND POWER DENSITY ESTIMATES AT 15, 20,25,30,50 AND 75m AS EXTRAPOATED BY THE LOGARITHMIC POWER FORMULA. ALL VALUES ARE IN W/m^2.

Station Code	Height in m						
	10	15	20	25	30	50	75
1	36.6	52.5	60.2	66.7	72.3	89.7	105
2	156.1	205.4	235.9	260.9	282.9	351.2	412.6
3	127.3	179.2	205.6	227.7	246.9	306.4	359.9
4	127.0	182.1	210.0	232.6	252.2	313.0	367.7
5	50.0	53.3	57.7	63.6	69.3	86.1	101.1
6	62.4	76.6	87.8	97.3	105.5	130.9	153.8
7	73.7	109.4	125.6	139.1	150.8	187.2	219.9
8	135.7	265.7	205.7	216.4	283.4	351.8	413.2
9	49.5	70.1	80.5	89.1	96.6	119.9	140.9
10	36.2	52.4	60.1	66.6	72.1	89.6	105.2
11	83.0	109.7	125.8	139.4	151.1	187.5	220.3
12	78.3	98.9	113.4	125.6	136.2	169.0	198.6
13	38.7	42.4	48.6	53.8	58.4	72.4	85.1
14	18.6	22.8	26.2	29.0	31.5	39.0	45.9
15	30.8	51.9	59.6	66.0	71.5	88.8	104.3
16	68.9	79.8	91.5	101.3	109.8	136.4	160.2
17	75.8	111.2	127.5	141.3	153.2	190.1	223.3
18	12.1	17.8	20.4	22.7	24.6	30.5	35.8
19	63.0	79.2	90.8	100.6	109.1	135.4	159.1
20	41.5	53.5	61.3	67.9	73.7	91.4	107.4
21	32.5	46.4	53.2	58.9	63.9	79.3	93.2
22	29.8	40.8	46.8	51.9	56.2	69.8	82.0
23	64.8	103.2	118.3	131.1	142.1	176.4	207.2
24	9.1	13.8	15.9	17.5	19.0	23.5	27.7

- 112 -

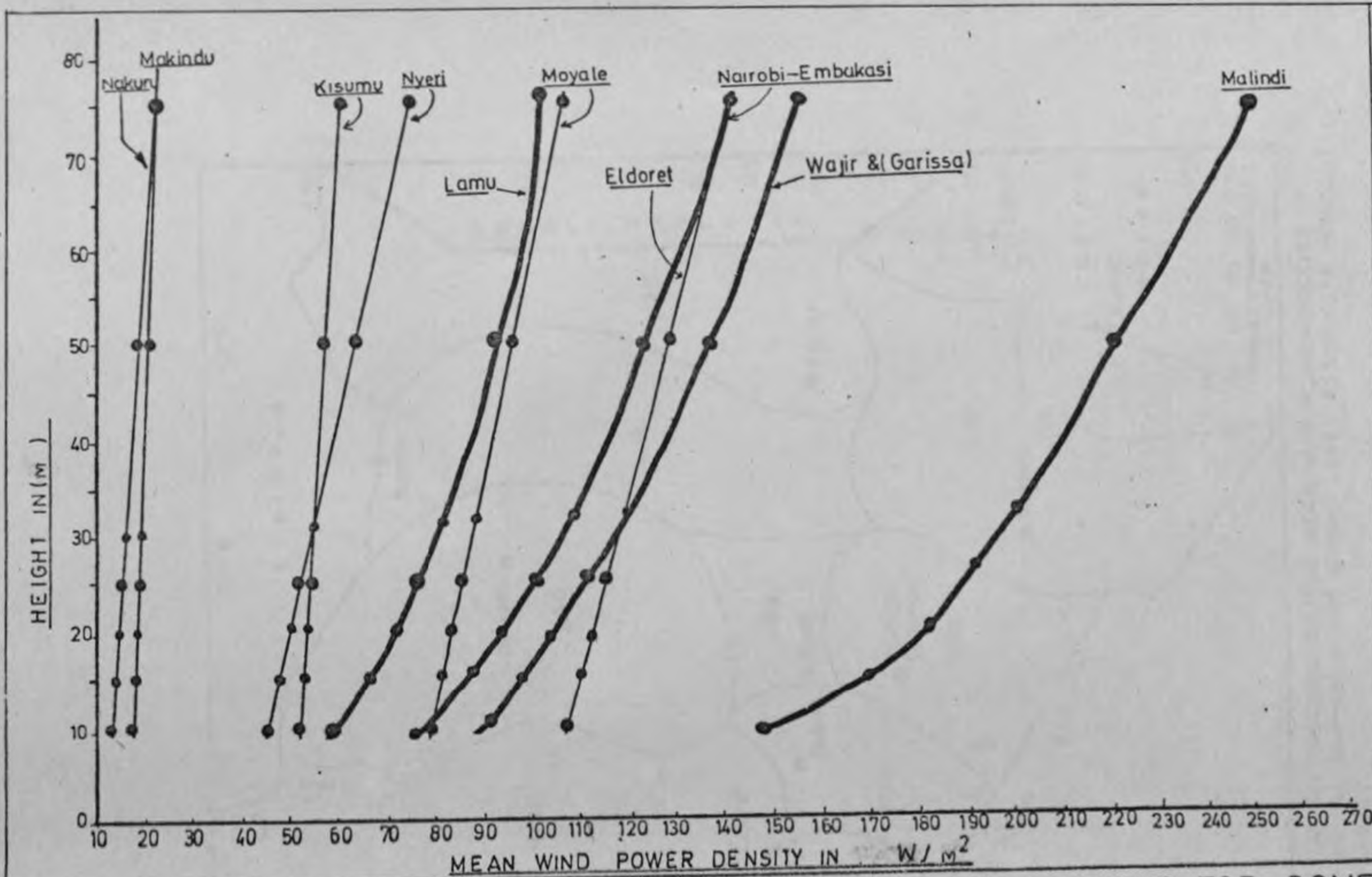


FIG.44:— VARIATION OF MEAN WIND POWER DENSITY WITH HEIGHT FOR SOME-STATIONS

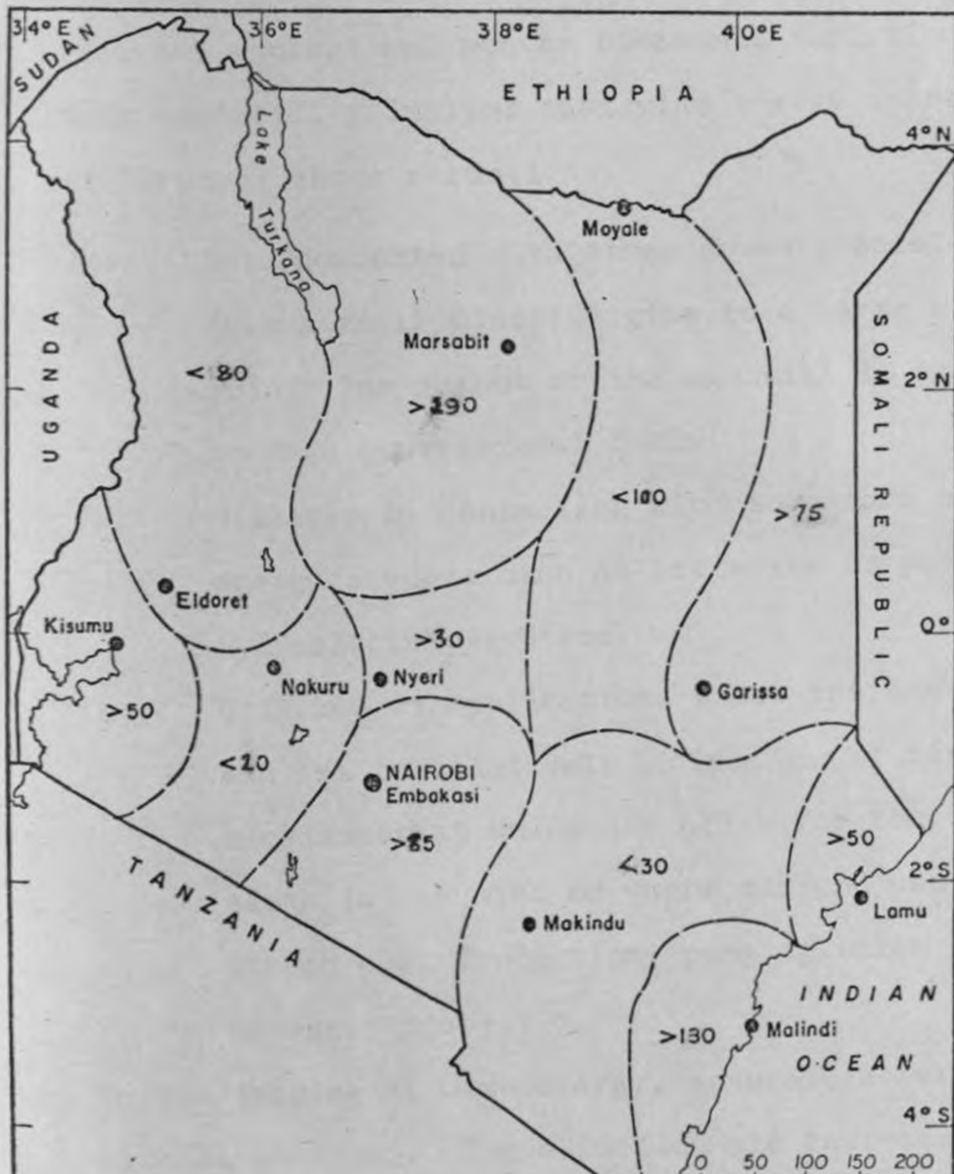


Fig 45.-SPATIAL DISTRIBUTION OF THE MEAN WIND POWER DENSITY IN W/m^2 AT 25m ABOVE THE GROUND LEVEL ASSUMING A HORIZONTAL OPEN TERRAIN.

3.6 WIND ENERGY UTILIZATION IN KENYA

It is evident from the study that the wind energy resource is quite variable both in time and space. The variability with time occurs during intervals of seconds (gusts), minutes (power variation), hours (diurnal cycles) and months (seasonal variation). This variability implies that wind energy is best utilized in three situations.

(a) Interconnected with other power plants, ranging from a small diesel engine to a large utility grid. The output of the windmill is then used to save convectional fuels.

(b) Utilized in connection with some form of energy storage such as batteries or pumped hydroelectric systems.

(c) Utilized in applications where the energy end use is relatively indipendent of time, has a time constant which can allow for the flactuations in the wind or where the end use can be stored e.g. irrigation, pumping water for domestic use e.t.c.

In the tapping of wind energy, several factors should also be stressed. These include the fact that:-

(a) Some wind generators can be constructed in various sizes ranging from a few watts to megawatts.

(b) Practical and effective wind systems can be constructed across a wide spectrum of materials and technological levels ranging from individual craftsman to advanced technological designs.

(c) The wind power can be utilized for a wide variety of purposes including electricity, direct pumping, direct mechanical work (griding, extracting oils) and direct heating.

(d) The cost-benefit factors. The cost of maintenance, operations e.t.c. should be lower than the benefits.

Small windmills with direct mechanical drive to a water pump are locally available here in Kenya. These are also easier and cheaper to manufacture. Multibladed and sail windmills of improved designs can similarly be built locally. A number of such windmills are already operating in pilot projects at various parts of Kenya.

Wind turbines (10-1000kw) are now becoming available commercially. These machines are in size range suitable for supplying power to small islands, isolated communities, irrigation schemes and so on.

The study has indicated that Kenya certainly has some potential sites for wind power utilization. These sites with maximum potentials include Marsabit, Maralal, Malindi, Mombasa, Nairobi Embakasi as well Eldoret and Garissa regions. While the variability of wind, even in relatively favourable sites, require that a diesel engine be retained as a back up, wind turbines promise to be economical as fuel savers on imported fuels. The cost of running such generators must, however, be evaluated before hand.

CHAPTER FOUR

4.0 SUMMARY AND CONCLUSION

The statistical characteristics of the wind power in Kenya were investigated in this study with the data consisting of daily maximum, minimum and mean wind speed values from 24 sites in Kenya.

The first part of the study used the method of Principal Component Analysis to determine the spatial similarities in the wind characteristics over Kenya. The results from PCA indicated that the method was able to describe the spatial patterns of the winds by some few uncorrected factors (eigenvectors). Eleven homogeneous wind categories could be delineated from the spatial patterns of the dominant eigenvectors. Detailed characteristics of the winds within the eleven regions were then investigated.

The second part of the study fitted several statistical distribution to the wind speed data. The fitted models included the Lognormal 2 and 3 parameter distributions, the Pearson III and the Logpearson III distributions, as well as the Weibull 2 and 3 parameter distributions. It was noted that the Lognormal with two parameter distribution and the 2 and 3 parameter Weibull distribution fitted the data well at many stations. The 3 parameter Weibull distribution was, however, the best distribution since it fitted the data well at all of the locations considered. The model was subsequently used to estimate the wind power potential at the various homogeneous sites.

It was observed from the Weibull estimations that the maximum wind power were located around Marsabit/Maralal regions as well as along the coastal strip of Kenya. Substantial power were also obtained around Nairobi and Garissa. The seasonal variability of wind power at various locations indicated that the total wind powers closely resemble the seasonal patterns of the wind speeds.

Finally, the variations of the wind power with height were examined at the various locations. The best vertical wind power profile were obtained using the three parameter Weibull distribution. These results generally indicated that the optimum level for wind power generation was approximately between 25-30m above the ground level. The cost and benefit factors were however, not considered here.

In conclusion, it was observed from the study that the wind power potential is quite promising over many parts of Kenya especially at the small and medium scale output levels. The large scale levels are however, abundant over many coastal parts and the Marsabit/Maralal regions.

CHAPTER FIVE

5.0 SUGGESTIONS FOR FUTURE RESEARCH WORK

A lot of work still remains uncovered before statisfactory conclusion can be said about the exact wind power potentials of a site. The values as obtained from the results of this study are only estimates spread over a large geographical area. Many more stations are required over such larger areas.

Detailed study are still required at those sites which depict greater wind power potentials by examining detailed characteristics of the local factors which influence the wind. These include topography, nature of surface. Vertical characteristics of the wind power may not be realistic at many sites since they did not take into account the surface roughness, atmospheric stability, and other atmospheric factor that may influence the wind. These may be updated when the parameters required are available.

A multivariate extension of the Weibull distribution might as well be tried to see whether this can improve the fit.

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5.2 REFERENCES

Asnani, G.C. and Kinuthia, J.H., 1979: Diurnal variation of precipitation in East Africa. Kenya Met. Dept. Memo No.8.

_____ 1984: A newly found jet in North Kenya (Turkana Channel) 1st International Conference on Southern Meteorology Jul. 31-Aug. 6, Sao Jose Dos Campus, Brazil, American Met. Soc. 377-380.

Anyamba, E.K., 1984: On the monthly mean lower tropospheric circulation and the anomalous circulation during the 1961/62 Flood in East Africa. M.Sc. Thesis. Dept. of Met. University of Nairobi.

Beck, J.V. and Arnold, K.J., 1977: Parameter Estimation in Engineering and Science A publication by John Wiley and Sons, New York.

Burry, V.K., 1976: Statistical Models in Applied Sciences. John Wiley and Sons Publication, New York, 277-436.

Carruthers, N., 1943: Variation in wind velocity near the ground. Quart. of R. Soc. 69, 278.

Chipeta, G.B., 1976: Wind power potential in Kenya. M.Sc. Thesis Dept. of Met. University of Nairobi.

Child, D. 1978: Essentials of Factor Analysis. Holt, Rinehart and Winston Billing and Sons Publication, London.

Craddock, 1973: Problems and prospects for Eigen-factor analysis in Meteorology. Statist., 22, 133-145.

Daniels, P.A., Ramage, S.C., Schroeder, T.A. and Thompson, N.J., 1977 Oahu wind power survey. First report. Dept. of Met. University of Hawaii.

Daniels, P.A. and Oshiro, N.E. 1980: Detailed wind surveys of Kaluku Oahu. Dept. of Met. University of Hawaii.

Davenport, A.G., 1963: The relationship of wind structure to wind loading. Proc. Conf. Wind Effects on Structures, Nat. Phy. Lab., London, England, 19-82.

Deacon, E.L. 1949: Vertical diffusion in the lowest layers of the atmosphere. Quart.J.R. Met. Soc. 75, 89-103.

De Marrais, G.A. 1959: Wind speed profiles at Brookhaven National Laboratory. J.App.Met.Vol.16, 181-190.

Doran, J.C. and Verholek, M.G., 1978: A note on the vertical extrapolation formula for Weibull velocity distribution parameters. J.Appl. Met.17, 410-412.

Dyer, T.G.J., 1977: The assignment of rainfall stations into nomogeneous groups on application of principal component analysis. Quart. J.R. Met. Sco. 103, 1005-1013.

E.A.M.D., 1961: Frequencies of surface wind speed and direction, East African Met. Dept. Nairobi.

Fraenkel, P. 1979: The Power Guide. A catalogue of small scale power equipment. Intermediate Technology Publication, London, 43-56.

Golding, E.W., 1955: The generation of electricity by the wind Power. Spon's electrical engineering series, London.

Gregory, S. 1975: On the delineation of regional patterns of recent climatic flactuations. Weather, 30, 276-287.

Harman, H.H., 1967: Modern Factor Analysis. University of Chicago Press.

Hennessey, J.P. 1977: Some aspects of wind power statistics. J. Appl. Met. 16, 119-128.

Justus, C.G., Hargrave, W.R. and Ali, Y, 1976; Nationwide Assessment of Potential output from wind powered generators. J. Appl. Met. 15, 613-678.

Justus, C.G., and Michael, A.G., 1976: Height variation of wind speed and wind distribution stations. Geophys. Res. Lett., 3, 261-264.

Justus, C.G., Hargrave, W.R. and Amir., M.G., 1978: Methods of estimating wind speed frequency distribution. J. Appl. Met. 18, 913-920.

Kaiser, H.F., 1958: The varimax criterion for analytic rotation in factor Analysis. Psychromatrica, 23, 187-200.

Kite, G.W., 1977: Frequency and Risk analyses in hydrology. Water Resources Publication, Fort Collins, Colorado, U.S.A.

Mage, D.T., 1979: Comment on frequency distribution of wind speed near the surface. J.Appl. Met. 18, 1089-1091.

Norman, O.E., 1981: Hawaii wind power. Department of Meteorology, University of Hawaii.

North, G.R., Bell,T.L. and R.F. Cahalan, 1982: Sampling errors in the estimation of Empirical orthogonal functions. Mon. Wea. Rev. 110, 699-706.

Ogallo, L.J., 1980: Regional classification of East African rainfall groups using the method of principal component analysis. Statistical Climat. Development in Atmo. Sci., 13, 255-265, Elsevier.

Phillips, 1967: Modern School Atlas. George Phillips and Sons Ltd., London sixth edition.

Putnam, P.C., 1948: Power from the wind. Van Nostrand Rewnhold Company, New York.

Stanton, E.T., and Brett, C.A., 1983: The characteritics of wind velocity that favour the fitting of a Weibull distribution in wind speed analysis. J.Appl. Met. 23, 125-134.

Stewart, D.A., and Essenwanger, 1978: Frequency distribution of wind speed near the surface. J. Appl. Met. 17, 1633-1642.

Skibin, D. 1984: Comment "On the evaluation of wind power from short wind record." J.Appl. Met., 23, 1477-1479.

Tackle E.,S. and Brown J.M. 1978: Note on the use of Weibull statistics, to characterise wind speed data. J. Appl. Met., 17, 556-559.

Van der Auwera, L.F. de Meyer and L.M. Malet, 1980: The use of the Weibull model for estimating mean wind power densities. J. Appl. Met., 19, 819-825.

Wallace, J.E. and Gutzler, D.G., 1981: Teleconnections in the geopotential height field during the northern hemisphere winter. Mon. Wea. Rev. 109, 784-812.

Walsh, J.E. and Mostek, A. 1980: A quantitative analysis of meteorological patterns over United States, 1900-1977.
Mon. Wea. Rev. 108, 615-630.

W.M.O., 1964: Sites for wind power installation
W.M.O. Tech. Note No.63.

W.M.O. 1954: Energy from the wind. Assessment of suitable winds and sites.
W.M.O. Tech. Note. NO.4.

W.M.O., 1981: Meteorological aspects of the utilisation of wind as an energy source.
W.M.O. Tech. Note No. 173.