Preparation of Nairobi County Wind Map as Part of the Kenya National Annex to En 1991-1-4

Onkendu Edwin Ong'ayo

CE300-0012/12

A Thesis Submitted to Pan African University Institute for Basic Sciences, Technology and Innovation in partial fulfilment for the Degree of Master of Science in Civil Engineering (Structural Option).

2014

DECLARATION

This thesis is my original work and has not been submitted to any other university for examination.

Signature:.................................. Date:...

Edwin O. Ong'ayo

This thesis has been submitted for examination with our approval as University supervisors.

Signature:.. Date:..

Prof. S. K. Mwea

Signature:... Date:..

Dr. S.O. Abuodha

ACKNOWLEDGEMENTS

My sincere thanks goes to the Almighty God for enabling me to reach this far, Pan African University for giving me the chance to study and interact with colleagues from all over Africa, my supervisors Prof. S.K. Mwea and Dr. S.O. Abuodha for their support and immense guidance in this research. Special thanks also go for Dr. Oludhe for his insight on the research subject and for giving me data without which the research would not have been successful and my family for their tireless support throughout my studies.

DEDICATION

This research is dedicated to my family especially my dear mum who has always believed in me and have always supported me as I strive to achieve my dreams.

ABSTRACT

Structural engineering education and practice in Kenya has been based on British Standards which are developed and maintained by the British Standards Institution (BSI). Given that BSI has decided to change to Structural Euro codes, the way forward for engineering design training and practice is to adopt the use of Euro codes. For Kenyan engineers to switch to the use of Eurocode 1991-1-4 on Wind loads, they is need to develop a National Annex to that code to take care of the local wind characteristics. Part of the information to be put in the annex is a wind map that enables evaluation of wind loads by Eurocode 1991-1-4

This research was carried out as an initial step in the development of the Kenyan National Annex (NA) of the EN1991-1-4 by developing a wind map illustrating the basic 50 year return period design wind speeds in Nairobi County. Hourly wind speeds were obtained from the Kenya Meteorology Department and the environmental correction factors (both terrain and altitude correction factors) determined. The combined factors were then multiplied to the hourly wind speeds and the maximum wind speeds from each storm derived. These were then subjected to extreme value analysis to come up with the basic hourly wind speeds which were then multiplied by a factor of 1.06 to get the 10-minute wind speeds from which a wind contour map was drawn. The results show that the 10-minute wind speeds within Nairobi County vary from 18m/s to 22m/s. Currently, a 3-second gust speed of 28m/s is used in the design of structures within Nairobi Country. When converted to the 10-minute wind speed using the durst curve shown in figure 2.1, it resulted to a 10 minute wind speed of 19.63m/s. This is comparable to the 10 minute wind speeds obtained from this research.

TABLE OF CONTENTS

List of Tables

List of Figures

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Euro codes are a set of harmonized technical rules developed by the European Committee for Standardization for the structural design of construction works in the European Union. They are expected to replace the existing national building codes published by the European national standard bodies like the British Standard Institution (BSI). Each country is expected to issue a national annex to the eurocodes which will need referencing for a particular country. The implication of this for countries switching to eurocodes is that the national building codes will not be updated in keeping up with new knowledge thus they will be outdated after some time. Structural engineering education and practice in Kenya and in most of the commonwealth countries has been based on British standards which are developed and maintained by the British Standards Institution (BSI). Given that BSI has decided to change to structural euro codes, the way forward for engineering design training and practice is to adopt the use of euro codes. Changing to euro codes will open international construction markets to Kenyan engineers, making competition possible in the fields of studies and construction activities. Switching will also allow keeping up with the evolution of the codes – no longer the case for BS. The attractive features of the euro codes are (Guide to the use of EN 1991-1-4-Wind Actions, 2006):

1. General Part: This part is the same for all participating countries.
2. National Annex: This part allows for development of nationally determined parameters (NDP).

The participating country undertakes definition, conception and publication of national annexes to be used in conjunction with the euro codes.

The national annexes give alternative procedures, values and recommendations for classes with notes indicating where national choice may be made. Therefore the national standard institutions e.g. Kenya Bureau of Standards (KEBS) implementing the euro codes should come up with national annexes to the various euro codes containing nationally determined parameters to be used for the design of buildings and civil engineering works to be constructed in the relevant country.

In the case of EN 1991-1-4, there are various parameters that need to be determined for each country before it can be implemented. One of the most important parameters that should be determined is the fundamental basic wind speed that will be contained in a national wind map. This fundamental basic wind velocity is a key parameter in the determination of wind loads for the design of structures. The fundamental basic wind velocity is the mean wind velocity for a 10 minute averaging period with an annual risk of being exceeded of 0.02, at a height of 10m above ground level at an area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights (Z_O = 0.05m) (Guide to the use EN 1991-1-4-Wind Actions, 2006)7.

Kenyan structural engineers currently use two documents for the determination of wind loads for the structural design of buildings i.e. CP 3: Chapter V: Part 2 and BS 6399 Part 2. Both of these documents were prepared by United Kingdom. However, CP 3: Chapter V: Part 2 uses a 3 second gust wind speed while BS 6399 Part 2 uses a mean hourly wind speed in the determination of wind loads on structures. The Kenyan wind map that shows the basic wind speeds was developed in the 1970s. This map was developed using the 3 second gust speed and has never been updated since then. Moreover, there is no document showing how the wind speeds were determined. Old structural engineers in the country say that the wind speeds were determined by British engineers based on the similarity between the wind speeds indifferent areas in Kenya and those recorded in the United Kingdom. The wind speeds for the different regions that are currently in use in Kenya are as follows:

Table 1.1: Different regions and their wind speeds in Kenya.

REGION	WIND SPEED IN M/S
Nairobi, Central and Southern Half of Eastern Province	28
Northern Half of Eastern and North Eastern Province	40
Coast Province	31
Southern Part of Rift Valley	36
Nyanza and Western Province	46

The fundamental basic wind speeds to be contained in the EN 1991-1-4 wind map are set to be different from the ones currently in use in Kenya due to the following reasons:

- The fundamental basic wind speeds in the EN 1991-1-4 wind map are based on a 10-minute mean velocity while the wind speeds currently in use were based on a 3 second gust speed.
- The fundamental basic wind speed to be used in EN 1991-1-4 are based on a reference terrain roughness which is an area with low vegetation such as grass and isolated obstacles (trees, building) with separations of at least 20 obstacle heights while the wind speeds currently in use have a reference terrain of an open situation.

Due to these differences the wind map to be used in EN 1991-1-4 is set to have different wind speeds from the ones currently in use. It is also important that Kenya develops its own wind map containing scientifically determined fundamental basic wind speeds that can be used in determination of wind loads. This will also take care of the climatic changes that have taken place in the country from the time the wind speeds currently in use were determined.

This research was carried out as an initial step in the development of the Kenyan National Annex (NA) to the EN1991-1-4 by coming up with a wind map illustrating the basic 50 year return period design wind speeds in Nairobi County. This wind map was based on historical wind records across Nairobi County and detailed the 10-min mean wind speed at an area with low vegetation such as grass and isolated obstacles (trees, building) with separations of at least 20 obstacle heights (Z_O = 0.05m) which had a probability of 0.02 of being equalled or exceeded in any one year. The map wind speed was adjusted using an altitude factor given in the United Kingdom (UK) National Annex.

1.2 Research Problem.

Kenyan structural engineers have been using the British Standards for structural design. However, the British standards are being phased out to give way to euro codes. The way forward is to switch to the euro codes. In the determination of wind loads on buildings as per EN 1991-1-4, the following steps are followed:

1. Read $V_{b,0}$ from map
2. $V_b = C_{dir} \,.\, C_{season} \,.\, C_{prob} \,.\, V_{b,0}$ ……………………………………………….$Equation$ 1
3. $q_b = \frac{1}{2\rho {V_b}^2}$ …………………………………………………………………$Equation$ 2
4. $q_b = C_e(z)q_b$ …………………………………………………………..$Equation$ 3
5. $W_e = q_b(z)C_{pe}$ …………………………………………………………$Equation$ 4
6. $F_w = C_sC_d \sum WA_{ref}$ ……………………………………………………….$Equation$ 5

Where:

$V_{b,0}$ = The fundamental basic wind speed that can be read directly from the wind map

Vb = The fundamental basic wind velocity modified to account for seasonal and directional factors

C_{dir} = The direction factor used to modify the basic wind speed to produce wind speeds with the same risk of being exceeded in any wind direction

C_{season} = The season factor used to modify the basic wind speeds with the same risk of being exceeded in any specific sub-annual period

C_{prob} = The probability factor used to modify the basic wind speed to change the risk of wind speed being exceeded.

Q_b = The basic velocity pressure derived from the basic wind velocity (q_b =0.613 V_b^2

C_sC_d = The structural factor that takes account of the effect of non-simultaneous wind action over the surfaces of the structure

$C_e(z)$ = The exposure factor that accounts for the effect of terrain, orography and building height.

We = The wind pressure acting on external building surface.

C_{pe} = Extenal pressure coefficient which is the ratio of pressure acting on the external surface to the peak velocity pressure.

F_w = The wind force acting on the overall structure or element

From the above equations used in the determination of wind loads, the basic wind speed is a key parameter in determining the wind loading on a structure at a particular location.

Therefore for Kenyan engineers to switch to the use of EN 1991-1-4 on wind loads, it is necessary to come up with a wind map containing the fundamental basic wind speeds in different localities so that the wind loads can be determined. This will enable engineers to carry out safe and economical design of structures especially high rise structures whose design is significantly affected by wind loads.

1.3 OBJECTIVES

1.3.1 General Objective

To prepare a wind map of Nairobi County to be part of the Kenyan National Annex to Eurocode 1991-1-4.

1.3.2 Specific Objectives

1. To determine altitude correction factors in Nairobi County.
2. To determine terrain correction factors in Nairobi County.
3. To determine the 10 minute mean wind velocity with an return period of 50 years

CHAPTER 2: LITERATURE REVIEW

2.1 Wind Action

Wind is defined as air in motion. It can be in any direction though in most cases the horizontal component is greater than the vertical component. It develops due to spatial differences in the atmospheric pressure. These differences are due to uneven absorption of solar radiation on the earth's surface. Wind is mainly influenced by the earth's rotation (Coriolis forces) and frictional forces especially near the earth's surface.

Wind causes pressure at points on objects in its path. The wind kinetic energy has a potential pressure called the dynamic pressure that is proportional to the square of the wind speed. This potential pressure acts at points where the objects stop the wind therefore the pressure distribution causes forces to act on the objects. Wind engineering analyses wind effects on the natural and built environment. Structural engineers focus on strong winds which can cause damage. Since structures are becoming taller and more slender, the effect of wind is becoming critical.

2.2 Wind Climate in Nairobi County.

The City of Nairobi is located between 36 50' E mid 1 18'S. The mean altitude is about 1700 metres above the mean sea level but since the city has a highly variable topography, this height ranges from 1600m (to the east) to over 1800m (to the west and northwest of the central business district (CBD).The prevailing winds are mainly in the easterly direction.

North-easterly winds prevail during the northern winter while south-easterlies are dominant during the southern winter. Computed frequency roses have shown that the surface winds at the city of Nairobi have a high frequency of easterly flow for the whole year. However, some westerlies are observed during the period June, July and August which are associated with the high pressure ridge that prevails over East Africa during the period. During this period, the winds are also observed to be more variable both in speed and direction. There is also large diurnal variability with the day-time winds being highly constant in direction than is the case with night-time conditions. (Ng'ang'a, 1992).

2.3 Wind Loads.

Wind loads need to be considered in the design of structures. This is especially so for high-rise and light weight structures. Since wind loads are usually specified as pressure due to the predicted maximum wind velocity, it is important to predict a maximum wind velocity that can be expected over the design life of structures so that the design is carried out with these wind speeds in mind. Wind loading standards provide procedures for determining the loads on specific structures in specific locations for specific conditions and needs. They start with general (neutral) conditions and move towards the specific conditions.

2.3.1 Basic Wind Speed

The basic wind speed is defined as the maximum expected wind speed at the standard height above the ground on a reference terrain over a chosen recurrence interval. This speed is established by extreme value analysis of the wind data collected from meteorological stations in a given geographical region over a period of time. (Celik, 2004, Bivona et al., 2003, Coelingh et al.,1996).The wind speeds for different regions are usually used to draw a wind speed map. The basic wind speed used in the determination of the wind load on a structure in a given location is read from this wind speed map.

EN 1991-1-4, (2005) defines the basic wind velocity as the characteristic 10 minutes mean wind velocity, irrespective of wind direction and time of year, at 10 m above ground level in open country terrain with low vegetation such as grass and isolated obstacles with separations of at least 20 obstacle heights. BS 6399-2, (1997) on the other hand defines the basic wind speed as the hourly mean wind speed with an annual risk Q of being exceeded of 0.02, (Return period of 50 years) irrespective of wind direction, at a height of 10 metres over completely flat terrain at sea level that would occur if the roughness of the terrain was uniform everywhere (including urban areas, inland lakes and the sea) and equivalent to typical open country in the United Kingdom. CP3: Chapter V: Part 2, (1972) defines the basic wind speed as the 3-second gust speed, at 10m above ground in an open situation that is likely to be exceeded on average only once in 50 years.

In the OAS/NCST/BAPE Code of Practice for Wind Loads for Structural Design, (1981) the basic wind speed is defined as the 3-second gust speed estimated to be exceeded averagely only once in 50 years at a height of 10m above the ground in an open situation. This speed is adjusted for specific cases using various parameters including averaging period, return period, ground roughness, height, topography and size of the structure in order to obtain the design wind speed for the particular cases. However, there are cases such as CUBiC, (2012) where the apparent starting point for computation is the basic wind pressure. In this case the basic wind pressure has been predetermined by the building code from the basic wind speed. The way in which standards progress from basic wind speeds to design wind speeds differ from one standard to the other. However all other things being equal, the end results should be the same which is the design wind speed.

From the definitions of basic wind speeds given in the above mentioned building codes, in coming up with basic wind speeds map, the following parameters or methodologies need to be defined: the method to be used for extreme value analysis of the wind speeds, the averaging period, the standard reference terrain, the standard height, the probability of recurrence and the method used to map the basic wind speeds.

2.3.2 Extreme Value Analysis of Wind Speeds

Wind speed is a random variable which is affected by a lot of factors such as geometric shapes, roughness, and elevations of ground surface. Therefore, the easiest and most direct means of obtaining wind speed distribution in different locations is to set up a measurement station at each location. The wind speed of short recording time is usually higher than the wind speed of long recording time. Those extreme values obtained from observed data are considerably important to engineering applications. The maximum wind pressure, i.e. extreme-value wind speed, is the major variable to be considered for structural wind resistant design.

A major question that arises in the wind speed extreme value analysis is the type of probability distribution that that is best suited for modelling the behaviour of extreme winds. Since wind speed is a probabilistic event, researchers have extensively studied the probability distribution function that better fit the extreme value of wind speed. Type 1 extreme value distribution is widely used to evaluate the design wind speed values. (Coelingh,1996).

Thom, (1960) has studied the annual extreme wind data for 141 open country stations in the United States of America (USA). Type II Extreme Value distribution was chosen to fit the annual extreme wind series to give isotachs maps for 2, 50 and 100-year mean recurrence intervals. Thom, (1968) has also developed new distributions of extreme winds in the USA for 138 stations. New maps were drawn for 2-year, 10-year, 25-year, 50-year and 100-year mean recurrence intervals. In carrying out his study, he used the Type II (Frechet) distribution. He indicated that examination of extensive non-extreme wind data showed that such data follow a log-normal distribution quite closely, which reinforces his choice of Type II distribution. Simiu et al (1975) presented a study in which a 37 year series of five minute largest yearly speeds measured at stations with good climates were subjected to the probability plot correlation coefficient test to determine the tail length parameter of the best fitting distribution of the largest values. Of the series, 72% were best modelled by Type I distribution or equivalently by the Type II distribution with $y=13$; 11% by the Type II distribution with $7<y<13$; and 17% by the Type II distribution with $2<y<7$. Simiu and Scalan, (1986) also obtained the same percentages from the analysis of 37 data sets generated by Monte-Carlo simulation from a population with a Type I distribution which indicates that in a well-behaved climate extreme wind speeds are better modelled by Type I rather than Type II distributions. Further, Simiu and Filliben, (1976) showed that Type I distribution of the largest values gives an adequate representation of extreme wind behaviour in most regions not subjected to hurricane force winds. For hurricane–prone regions he indicated that type II distribution with a small value of tail length parameter could give a better estimation of extreme wind speeds.

The ANSI A58.1-821 wind load provision is based on a wind speed contour map that was developed by Simiu et al. (1979) .The wind speeds in the map were established from the data collected at 129 meteorological stations in the USA. The analysis was done using Type I (Gumbel) distribution. He used data only for locations for which a minimum of 10 years of continuous records were available. The provisions of the National Building Code of Canada are also based on the assumption that the extreme wind speed is best modelled by the Type I distribution. From the studies carried out, it is evident that Type I (Gumbel) distribution is best suited for extreme value analysis in a hurricane free zone like Nairobi County, thus was used in this research.

2.3.3 Errors in Prediction of Wind Speeds

Errors are inherent in the process of wind speed prediction. Besides the errors associated with the quality of the data, there are sampling and modelling errors. The sampling errors are a consequence of the limited size of samples from which the distribution parameters are estimated. These errors in theory vanish as the size of the sample increases infinitely (Simiu et al., 1978).

The modelling errors are due to inadequate choice of the probabilistic model. Chi-square and K-S Test are usually performed to choose the best fitting model.

2.3.4 Averaging Period

Wind speeds are measured by the use of anemometers. These instruments vary in the way they sample the wind and in the way they report the results. One significant characteristic of mechanical anemometers is the response time. This is a function of the inertia of the system. The shortest response time for mechanical anemometers is 1-3 seconds. Many countries have adopted the 3-second gust as the averaging period for the basic wind speed. These countries include Australia, the USA (post 1995) and Barbados. The United Kingdom (UK) used the 3-second gust up to 1995 when they changed to the mean hourly wind speed.

Data averaged over relatively short intervals like 5 second average, can at times be affected by stronger than usual local turbulence, thus resulting in a distorted picture of the mean winds. Averaging over relatively long periods like 10 minutes is therefore desirable. Wind speed measured for any averaging period may be converted to another averaging period using relationships that have been determined experimentally and analytically. During the 1990s Krayer and Marshall (1992) proposed an adjusted S curve for tropical cyclone regions. The Durst curve is used for both tropical and extra-tropical cyclones. Figure 2.1 shows the Durst curve (Ratio of Probable Maximum Speed Averaged over t seconds to Hourly Mean Speed) which has been in use since the 1960s.

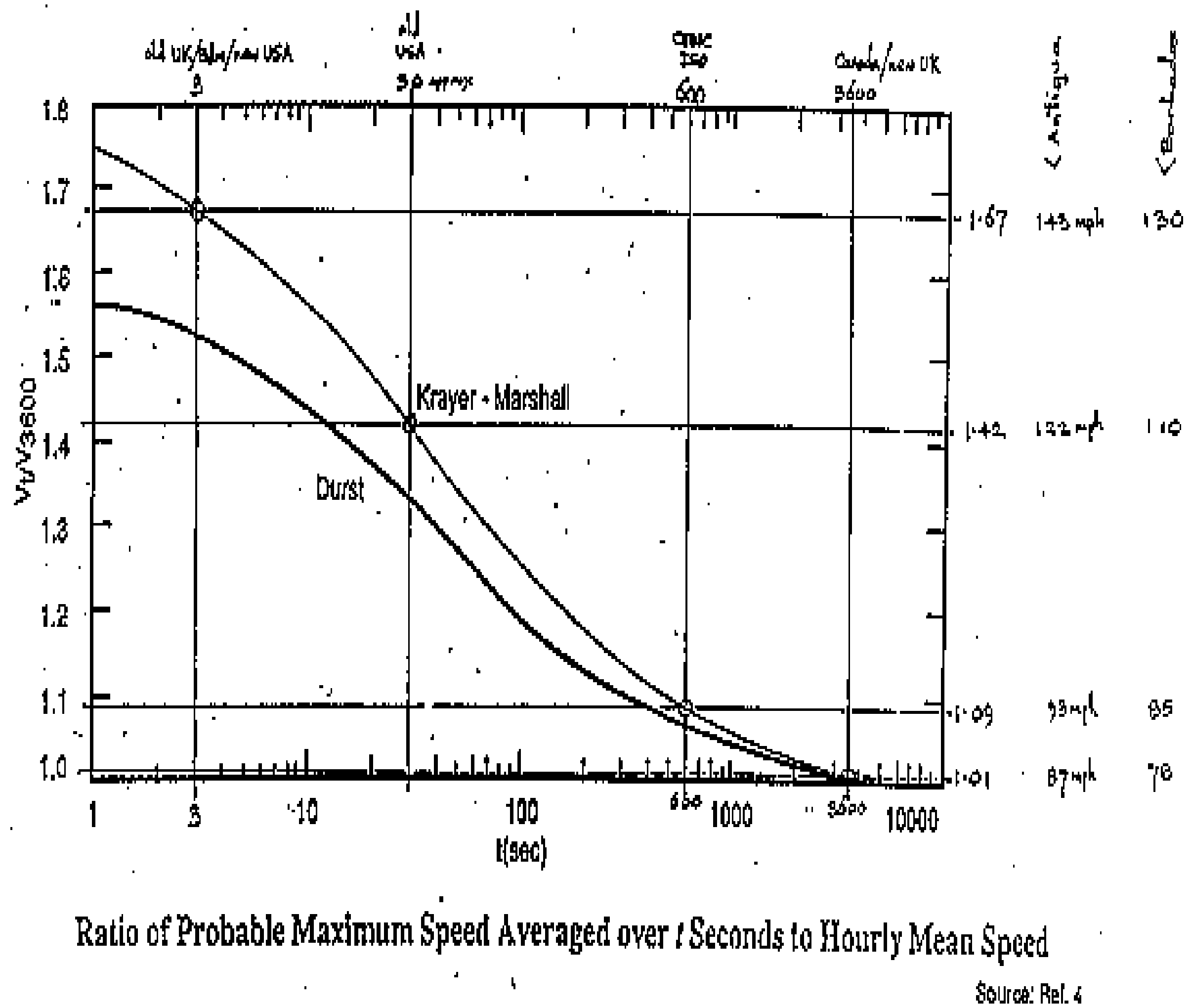


Figure 2.1. Ratio of Probable Maximum Speed Averaged over t seconds to Hourly Mean Speed

EN 1991-1-4 has adopted the use of 10 minutes as the averaging period. However, the wind speed data available in Kenya is in form of mean hourly wind speeds and mean daily wind speeds. Therefore the basic hourly wind speeds have to be converted to 10 minute wind speeds so as to be used in the EN 1991-1-4 to determine wind loads. From Figure 2.1, to convert the wind speeds from a mean hourly averaging time period to a 10-minute averaging time period, the mean hourly basic wind speeds should be multiplied by a factor of 1.06 as shown in equation 6 below.

$V_{10min} = 1.06 * V_{hourly}$ ....Equation 6

2.3.5 Return Period

Wind speeds are amenable to statistical analysis. It can be argued that historical records are not long enough for such analyses to be reliable. However, statistical analyses of historical information are usually adjusted on theoretical bases so that they can be used in determining the relative wind speeds expected to occur over different periods of time. A short return period (2 years) is usually recommended for temporary structure and for (incomplete) structures during erection.

Generally, the longer the return period chosen and the lower the probability level chosen, the more conservative will be the design wind speed. Most buildings in Nairobi County are designed for a 50 year design life. Therefore it is appropriate to determine wind speeds with a return period of 50 years. This ensures that there is a very low likelihood of the structure experiencing a higher wind load than the one determined at the design stage during its design life. The mathematical model used to determine the extreme wind speeds for a given return period, R, for a Gumbel distribution is:

$$G\left(\frac{1}{1-\frac{1}{R}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. Equation\ 7$$

Where G is the percent point (or the inverse cumulative distribution) function of the Gumbel distribution.

The Gumbel percent point function is:

$$-\ln\left(-\ln\left(\frac{1}{p}\right)\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. \ldots\ldots Equation\ 8$$

Where p is the desired quantile. From the return period, R, the desired quantile is determined. The percent point function is then applied to this quantile to determine the maximum wind speed that corresponds to the desired return interval.

2.3.5 Ground Roughness

Micrometeorological characteristics, such as terrain roughness, are very important in the determination of design wind speeds. When unaccounted for, they can lead to significant effects on wind speed estimates. A study has shown that errors can be in upwards of 40% for terrain assumptions alone using Automated Surface Observing Stations (ASOS). (Yohana et al. 2009) The roughness of the terrain over which the wind passes has two effects on the wind: speed and turbulence. Rough surfaces lead to low wind speeds but high turbulence. Ground roughness is generally affected by surface objects such as buildings (including the sizes and density of the buildings in the area) and trees. If the roughness around an anemometer changes significantly during the period of record under consideration, then the measured record should be adjusted to a common terrain roughness by using similarity model An important terrain parameter is the surface roughness parameter $Z_{O.}$ This is a measure of the retarding effect that the surface in question has on the wind speed near the ground. Table 2.1 shows the typical values for upwind fetches of comparatively uniform roughness where the general description of the terrain fits a particular terrain category. The values given in Table 2.1 are derived in the following way:

For a standard height less than 30m from the ground surface, the following equation is assumed:

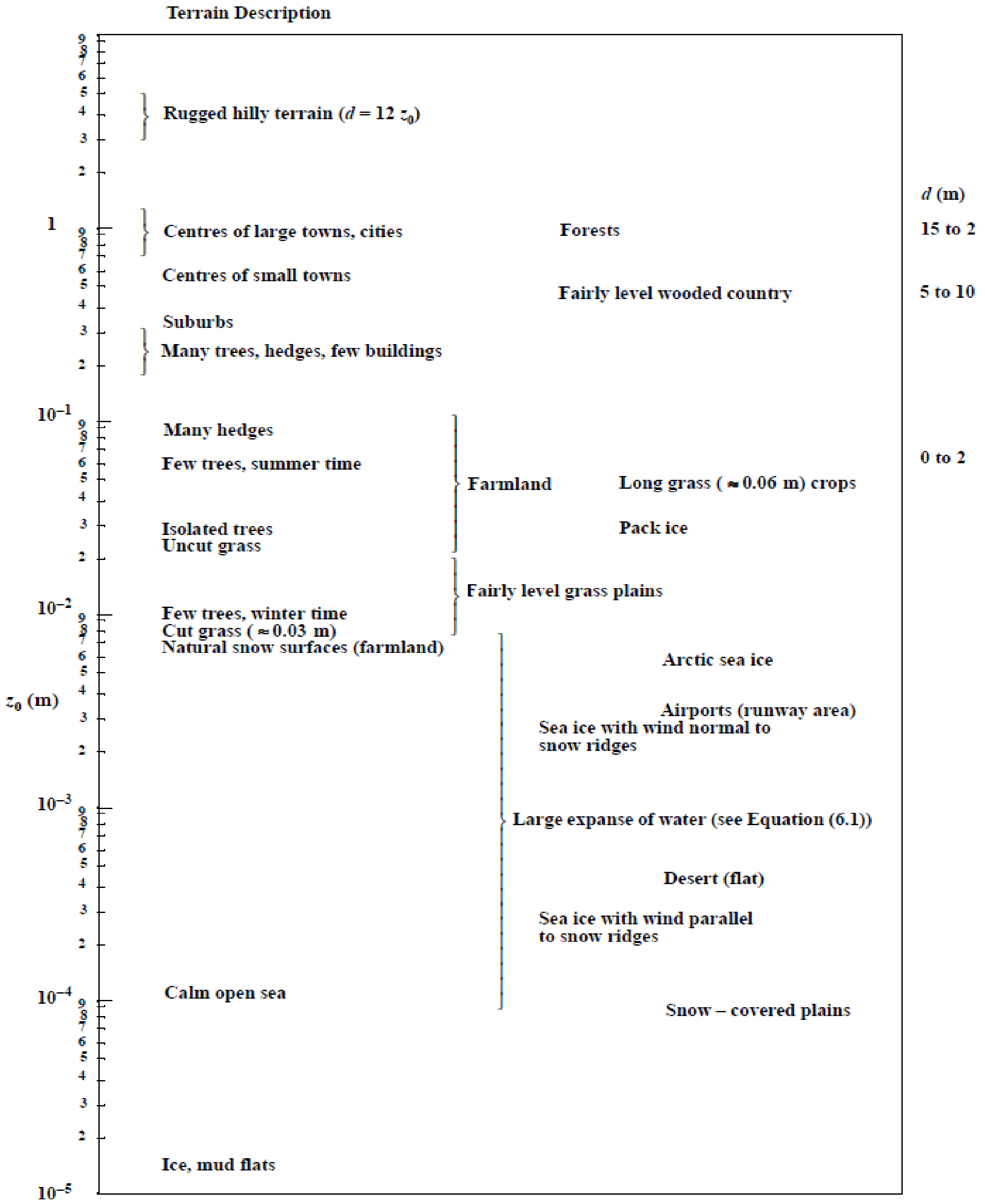
$$V_z = 2.5u_* \ln\left(\frac{z}{z_o}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..Equation\ 9$$

Equation 9 can be rearranged as follows:

$$\ln z = V_z(1/2.5u_*) + \ln z_o \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots Equation\ 10$$

Therefore if measured values of V_z (for heights less than 30m) are plotted against ln z for a given site a straight line fit to the data will give a value of ln Z_O as the intercept on the ln z axis.

Table 2.1 Values of Surface Roughness Parameter, Z_O



2.3.6 Standard Height

Ground roughness is usually combined with height above ground in wind-loading standards. Height of 10m above ground is considered to be the standard instrument height. Wind data measured at any other height should be adjusted to the standard height by wind profile power law (Masters, 2010). The wind profile power law gives the relationship between the wind speeds at a given height and those at another height. The power law is used where data at various heights must be adjusted to a standard height prior to use. The wind profile of the atmospheric boundary layer (ground surface to around 2000m above ground) is logarithmic and can be best approximated using the log wind profile equation that accounts for parameters like surface roughness and atmospheric stability. However, the wind profile power law relationship often substitutes the log wind profile when surface roughness or stability information is not available. The wind profile power law relationship is:

$$\frac{u}{u_r} = (z/z\_r\,)^{\alpha} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ Equation\ 11$$

When estimating the wind speed at a certain height x, Equation 11 is rearranged as follows:

$$u_x = u_r\left(\frac{z_x}{z_r}\right)^{\alpha} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ Equation\ 12$$

Where:

U is the wind speed in m/s at a height z in metres

U_r is the known wind speed at a reference height.

α is an empirically derived coefficient that varies dependent upon the stability of the atmosphere. For neutral stability conditions, α is approximately 1/7.

2.3.7 Isotach Map

Isotachs are lines of equal wind speed on a graph or a chart. An isotachs map is map showing isotachs in a given area. Isotachs are produced from values of basic wind speeds of the various meteorological stations within and around the area. Isotachs can be drawn using various software e.g. ARCGIS, NOVAPOINT, CIVIL 3D etc. These softwares use the following parameters to draw the isotachs: basic wind speeds, grid points (latitude and longitudes) of the meteorological stations. A good contour interval is chosen based on the difference between the highest wind speed and the lowest wind speed. If the difference is small, then a small contour interval e.g. 1m/s should be chosen while for a big difference in wind speeds, a bigger contour interval e.g. 5m/s should be adopted so as to give a good contour map. Once the basic wind speeds and the survey grid points (Latitudes and longitudes) have been input into the software and the operator has given a command to generate contours, the software will generate a triangle model in a process called triangulation. Generating a triangle model is a function that positions triangles between individual points and any break line. These triangles are defined by a mathematical process, by which the smallest triangle between three points is found. In a triangulation model, the surveyed points are bound together in a network of triangles. From the triangulation model, the software uses a mathematical process known as interpolation to come up with the basic wind speeds of points within and along the triangles. From these values, the software generates isotachs by connecting points of equal wind speeds.

2.4 CASE STUDIES

2.4.1 Basis for Wind Map in BS 6399-2

a) Derivation of Extreme Wind Information

Wind data, kept by the meteorological office of United Kingdom, were obtained from continuously recording anemographs, exposed at 10m height above the ground in an open, level terrain or, in other terrains, at a height equivalent to the standard exposure. The network of meteorological stations was comprised of about 130 stations and the data kept comprised of hourly mean wind speeds and wind directions, and the details of the maximum gust each hour.

In preparing the basic wind speed map the method used was one that involved the maximum wind speed during each storm. This approach increased the amount of data available for analysis and enabled the directional and seasonal characteristics of the UK wind climate to be examined. A storm was defined as a period of at least 10 consecutive hours with the mean wind speed greater than 5m/s. These periods were identified for 50 anemograph stations, evenly distributed over the UK (mostly having standard exposures), using their records during the period 1970 to 1980.The average number of storms each year was about 140 at most of these stations. For each storm, the maximum hourly mean wind speed blowing from each of the twelve 30^0 wind direction sectors was calculated. The extreme information needed was:

- An improved map of basic wind speeds
- Direction factors
- Seasonal factors.

Extreme wind speeds were analysed in terms of their probability of occurrence whose standard measure is the cumulative distribution function (CDF), given by the symbol P and corresponding to the annual risk of not being exceeded. Design to resist extreme wind was based on the annual risk (probability) Q that the hourly mean wind speed will be exceeded given by Q=1-P.The reciprocal of this is known as the return period. It is the mean interval between recurrences when averaged over a long period. This definition becomes invalid for periods less than 10 years. This concept of return period is not very useful and is open to misinterpretation since the period between individual recurrences varies considerably from this mean value. The concept of annual risk being less open to misinterpretation should be seen as the risk of exceeding the design wind speed in each year the structure is exposed to the wind.

b) Storm Maxima

The basic wind speed is estimated to have a risk of Q= 0.02 of being exceeded in a given year. Obtaining this speed for every station requires that all the maximum wind speeds in storms be first abstracted, irrespective of direction. The cumulative distribution function P that represents the risk of a specific value not being exceeded was determined by the method of order statistics. (BS 6399-2)

In this method the maxima are sorted into ascending order of value and assigned a rank m (m=1 for the lowest value and m=N for the highest value), then P is estimated for the storm maxima by: $P(v_s) = \frac{m}{N+1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation } 13$

c) Annual Maxima

Maxima from different storms can be regarded as statistically independent, so the CDF $P_{(V)}$ of annual maximum wind speeds is found from $P_{(V)}$ = $Pr_{(VS)}$ where r is the average annual rate of storms. The CDF of annual maxima is fitted to a Fisher-Tippet Type 1 distribution, defined by:

$$P(v) = e^{-e^{-y}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 14$$

Where: y = a (v-U)

U is the mode, 1/a is the dispersion.

Therefore:

$$y = -\ln\left[-\ln\left\{\left(\frac{m}{N+1}\right)^{r}\right\}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 15$$

And a plot of y versus V (maxima wind speeds) leads to estimates of the annual mode and dispersion. The wind speed V associated with a specific annual cumulative risk P of non-exceedance may be found from:

$$V = \left(U + \frac{\ln\left[\frac{1}{p}\right]}{a}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 16$$

d) Best Extreme Model

To obtain the dynamic pressure q, the maximum wind speed in each storm is multiplied by its square and this is multiplied by half the density of air. Extreme value theory predicts that the Fisher-Tippet Type 1 distribution should be a better fit to dynamic pressure than to wind speed.

This analysis method was repeated for every station using q as the variable. Results showed that the rate of convergence of storm maxima to the FT1 Model was quicker for the q model than the Vs model. The wind speed corresponding to the dynamic pressure having a risk of Q=0.02 of being exceeded at least once a year was used to derive the value for each station.

After that terrain and topographic corrections are made to individual station estimates to ensure that when all the values were plotted on a map, they represented a height of 10m above ground in open, level terrain at mean sea level. Finally isotachs were drawn to be a best fit to the wind speeds plotted.

2.4.2 Basis for Wind Map in Irish National Annex to EN 1991-1-4

a) Weather Station Auditing

Analysis of daily maximum gust speeds and hourly maximum speeds for period up to and including 2005 were carried out using extreme value analysis. In addition pictorial documents and historical auditing reports were accessed from Met-Eirean data archives for all the weather stations.

This information was used to evaluate:

- Changes in surroundings over time
- Changes to anemometer location
- Changes to anemometer height and type

The general procedure adopted for analysis of the hourly-mean and daily-gust wind speeds from each anemometer to derive the design wind speeds was as follows:

I. **Data Quality**: Checking the quality of measurements from each anemometer and separating inconsistent data.

II. **Exposure Correction**: Transposing wind records from each anemometer (with respect to elevation, topographic and terrain correction) so as to be consistent with open country terrain (Engineering Sciences Data Unit (ESDU)) Z_O =0.03m)

III. **Extreme Value Analysis**: Perform an extreme value analysis and assessing directionality using discrete wind records.

IV. **Design Wind Speed Map**: Carrying out a review of the predicted gust and mean wind design for each anemometer and generating contours that account for local topography.

b) Weather Stations

Wind records consisting of hourly mean wind speeds and daily gust speeds were analysed over a range of ten to sixty years. The anemometer effective height was taken as 10m. The standard instrument of measurement up to the 1990s was the Dine pressure tube anemometer before being replaced by the Vaisala or Vector rotating-cup anemometer. A trial separation of the gust and mean wind speeds by anemometer type showed small variations and thus the gust and mean data records were separated and independent analysis carried out based on the anemometer type.

c) Exposure Correction.

Wind records were corrected for topography, terrain and altitude. These correction factors were assessed for each anemometer and the factors applied to the wind records to get the design wind speeds.

d) Terrain Assessments

The atmospheric boundary layer model used in the ESDU analyses was that developed by Deaves and Harris. It takes account of varying surface roughness with fetch. Surface roughness length is characterised by a typical $Z_{O,}$ in line with the model used in ESDU. In this method the varying terrain roughness with fetch at 30^0 sectors about the origin is taken account of. A detailed survey of the terrain roughness was carried out for each anemometer using methods such as aerial topography, OSI Trail Master and satellite imagery.

The analysis was carried out for each of the twelve 30^0 sectors of wind direction to a distance in excess of 40 km from the anemometer and for each sector and patch of the terrain, a typical roughness coefficient Z_O assigned. Two terrain assessments were made, a conservative estimation and a best-guess estimation. The conservative estimation considers a rougher upwind terrain thus resulting in higher factors being applied to the wind records.

e) Topographic Assessments

Reviewing photographs and satellite imagery of the local anemometer permits the categorization of proximity effects such as mountains, cliffs etc. These regions were identified to enable categorization of the directions from which the obstructions may have affected the resulting design wind speeds.

f) Altitude Factor

The design wind speed is defined at the mean sea level. Hence, wind speeds measured at anemometers should be corrected to account for the effect of the difference in elevation of the anemometer relative to the mean sea level. Based on these elevations an altitude factor is estimated as recommended in international standards, and used in the Euro code. The altitude factor is of the form:

$$S_A = 1 + 0.001(A) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Equation } 17$$

Where A is the elevation above sea level in metres.

These correction factors i.e. topographic, terrain and altitude factors were multiplied to wind speeds measured at anemometer sites to resolve the design wind speeds for a standard open country terrain roughness and standard elevation.

g) Extreme Value Analysis Procedure

The cumulative probability function (CDF) of most wind speed measurements that have been carried out is most closely modelled by the Weibull distribution which is of the form:

$$Pv = 1 - \exp\left[-\left(\frac{V}{C}\right)^{k}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 18$$

Where "c" and "k" are empirical constants for a best fit to individual data sets.

Pv is the probability that a velocity will be less than a velocity V.

Theoretically, for a set of data conforming to a Weibull distribution, the CDF of the extremes will converge towards a Fisher-Tippet Type I distribution which is of the form:

$$P_x = \exp[-\exp(-y)] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 19$$

Reduced variate y, is given by the following equation:

$$y = -\ln[-\ln(P_x)] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 20$$

PX is the probability that an extreme value will be less than a value x in any given year.

The extreme value is equated to the square of the wind velocity to ensure a rapid convergence to the extreme value distribution. The two methods of extreme value analysis carried out in an assessment were: a modified Gumbel analysis (annual maximum data) and a Harris Independent Storms (using the maximum '2.4 x years of data' wind speeds from independent storms). These methods are valid for both daily gust and hourly mean wind speeds. The design wind speeds that resulted from the two methods of analysis were compared for consistency.

h) Analysis of Annual Maxima Data

The following procedure was used for fitting recorded annual maxima to the Type 1 Extreme Value distribution.

• Extract the largest wind speed in each calendar year of the wind record.

• Rank the series in order of smallest to largest.

• Assign each value a probability of non-exceedance, p,

$$p = \frac{m}{N+1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. Equation\ 21$$

• Form a reduced variate.

• Plot the wind speed V^2 against y and draw a line of best fit.

This probability analysis provides the design wind speeds for various return periods, with greater confidence associated with the shorter return periods events. A probability weighted least squares methodology should be adopted to account for the greater confidence in the shorter return period events. The mode and dispersion of the statistical fit is derived. This fit is called a modified Gumbel.

A minimum of 20 consecutive years of wind records is required in order to get reliable results when using a modified Gumbel analysis (Cook, 2003). One weakness of the Gumbel analysis method is that the maximum wind speeds are chosen from each calendar year as opposed to each storm year leading to a situation where yearly maximums occurring on the 31st of December and the 1st of January in the following year could both be kept as separate data. These two wind speeds could be related and associated with the same storm generating event, thus the inclusion of both wind speeds leads to a conservative estimate of the design speed.

i) Analysis of Individual Storm Data

This method of analysis makes use of wind speed maxima taken from independent storms of the same mechanism. The method has an advantage over the one which considers annual maximum data since many more wind records are available to define the mode and dispersion parameters of a distribution. This leads to greater confidence in estimating the design wind speeds. Cook (2003) said that only seven years of wind data are needed to permit a reasonable estimate of design winds. A storm separation period of 3 days was considered.

Thus the smaller values of pairs of wind records separated by 3 days or less were deleted to ensure only independent storm maxima were retained. With the exception of the calculation of the reduced variate, the procedure for analyzing the independent storm data is similar to that for the yearly maxima.

The probability that the extreme value will not be exceeded in any given year is based on the rank of the wind speed when compared to the total number of storms usually taken as 2.4 x years of data. The plotting positions are modified based on probability weighted least squares. This probability analysis provides design speeds for various return periods, with greater confidence associated with shorter return period events.

j) Errors in Analysis

There is an amount of uncertainty in the estimation and the precision of design wind speed estimates when using the methods of analysis outlined above. The estimates depend on both the length and quality of the wind records. There are cases where the recorded wind maxima fall outside confidence limits. Common reasons that account for obscure wind records include:

- The value may originate from a storm with a different mechanism.
- The event may have a smaller probability of occurrence than the analysis indicates due to the finite record length not containing other intermediate storm events which would eventually occur.
- The value could be due to a manual/rounding error.

k) Mean and Gust Wind Speeds

The use of mean speeds over gust speeds has been favoured due to the theoretical stability of measurement of mean speeds and the problems experienced when interpreting and comparing gust speed records from different anemometer and recording systems. Statistical variation and random measurement problems lead to over-prediction of extremes However, gust speeds are much less sensitive to changes of terrain roughness and site exposure and the prediction reliability is of less concern with long data records.

l) Directionality of Design Winds

Direction factors are applied to site specific design wind speed so that designers can carry out a more accurate assessment of the wind loading of a structure. Non-inclusion of direction factors in a design assessment could easily lead to over-design. Direction factors were derived by dividing every independent directional design wind speed by the maximum directional design wind speed.

m) Design Wind Map for Ireland

The mean hourly directional wind speeds from all the anemometers were converted into 10-minute mean wind speeds using a 1.06 conversion factor which has also been used in generating the wind map of the UK National Annex. The average gust factor based on 50-year wind speed predictions is calculated and a more conservative value is used to convert the design gust speeds to hourly mean design speeds. The 10-minute mean design speeds were plotted on the map of Ireland and contour lines drawn to fit. (Derivation of Irish Wind map, 2009).

CHAPTER 3: METHODOLOGY

3.0 General procedure

The general procedure that was adopted for collection and analysis of the hourly-mean wind speeds from each of the anemometers to derive design wind speeds was as follows;

- **Data Collection and Quality Check**: The data was collected and a check done on the quality of measurements for each anemometer. Inconsistent data records were removed from the data set.

- **Exposure Correction**: Wind records from each anemometer were transposed (considering elevation and terrain corrections) to be consistent with open country terrain.

- **Extreme Value Analysis**: Extreme value statistical analysis was carried out using discrete wind records.

- **Design Wind Speed Map**: The predicted mean wind speeds for each anemometer were used to generate a wind map.

3.1 Data Collection and Quality Check.

Hourly mean speeds and wind direction data that were available at all the meteorological stations within and immediately around Nairobi County were collected from Kenya Meteorological Department (KMD). The meteorological stations from which data was obtained were: Dagoretti, Wilson Airport, JKIA, Eastleigh Airbase, Kabete, Machakos, Thika and Narok Meteorological Stations. The data obtained from these meteorological stations was for periods between five years and thirteen years as shown in the Table 3.1 outlined below;

Table 3.1; Periods of data Available in Years

PERIOD OF DATA USED	
STATIONS	**Period of Data (Years)**
KABETE	From 1995 to 2000
JKIA	From 1995 to 2000, From 2005 to 2010
WILSON	From 1995 to 2000, From 2005 to 2010
DAGORETTI	From 1995 to 2000, From 2005 to 2010
EASTLEIGH	From 1995 to 2003
MACHAKOS	From 1995 to 2000
THIKA	From 1995 to 2000
NAROK	From 1995 to 2000

As seen from Table 3.1, the following wind speed data were not used in the analysis since the data was not available:

- Between the years 2001-2004 for the following stations: JKIA, Wilson and Dagoretti
- After the year 2000 for Kabete, Machakos, Thika and Narok
- After the year 2003 for Eastleigh.

The raw wind speed values obtained were then scanned for statistical outliers. An outlier is a wind speed which is three times greater than both the previous and post hourly (mean) recording (wind speeds such as these would be attributed to local thunderstorm behaviour). These outliers were removed from subsequent analysis

The hourly mean speeds that were obtained from KMD were in units of knots (nautical mile per hour) and they had been obtained at two different heights i.e. in some stations wind speed measurements were done at 2m height while in others it was done at 10m height. The wind speeds had also been obtained at different terrain (ground roughness) and at anemometers stationed at different heights above the mean sea level. Therefore, before extreme wind analysis could be carried out the wind speeds were converted to be in m/s at standard height of 10m at the standard terrain and altitude.

After removing the outliers the hourly wind speeds obtained from the Kenya Meteorological Department (KMD) were in knots (nautical mile per hour). The values were multiplied by 0.5144 to convert them to wind speeds in metres per second.

From the definition of the fundamental basic wind speed given in EN 1991-1-4, the standard instrument height is 10m. The following stations had their wind speeds measured at 10m height: Dagoretti, JKIA, Eastleigh Airbase, Wilson Airport and Narok Meteorological stations. The following stations are agro-meteorological stations i.e. stations whose measurements are mainly for agricultural purposes: Kabete, Machakos and Thika Agro-meteorological stations. Their wind speeds were measured at 2m heights. These wind speed measurements had to be adjusted using the wind profile power law so as to obtain the wind speed at 10m height.

The wind profile power law relationship is:

$$\frac{u}{u_r} = (\frac{z}{z_r})^{\alpha} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \mathit{Equation}\ 22$$

Where u is the wind speed (in m/s) at height z (in metres) and u_r is the known wind speed at a reference height z_r. The exponent (α) is an empirically derived coefficient that varies dependent upon the stability of the atmosphere. For neutral stability conditions, α is approximately 1/7 or 0.143.

In order to determine the wind speed at 10m, the relationship was rearranged to:

$$u = u_r \left(\frac{10}{2}\right)^{0.143} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \mathit{Equation}\ 23$$

The wind speed (having been already converted to m/s) were then subjected to equation 23 above to get the wind speeds at 10m height.

3.2 Determination of Exposure Corrections.

This involved correcting the wind speeds for terrain and altitude so as to obtain the wind speed values at standard terrain i.e. at an area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights ($Z_O = 0.05$m) and at the standard altitude which is the mean sea level.

3.2.1 Determination of Terrain Factors

The atmospheric boundary layer model used in the ESDU (Engineering Sciences Data Unit) analysis was used for this analysis. It was developed by Deaves and Harris and takes account of varying surface roughness with fetch. Surface roughness length is characterised by a typical Z_O, consistent with the model used in ESDU. This method takes into consideration the varying terrain roughness with fetch at 30 degree sectors about the origin of the anemometer. A survey of terrain roughness was carried out for each anemometer using satellite images from the **GOOGLE EARTH** software.

The survey was carried out for a distance of 50km in each direction from the anemometer location. This analysis was carried out for twelve sectors of wind direction from the meteorological station. For each sector, a typical roughness coefficient, Z_O, was assigned as per Table 2.1 containing the values for typical surface roughness parameter, Zo. A conservative assessment of the terrain was made. This conservative estimate considered a rougher upwind thereby resulting in higher factors being applied to the wind records.

Figures 3.1, 3.2 and 3.3 show the Google earth images which were used in determining the terrain correction factors at Dagoretti, Narok and Kabete meteorological stations respectively

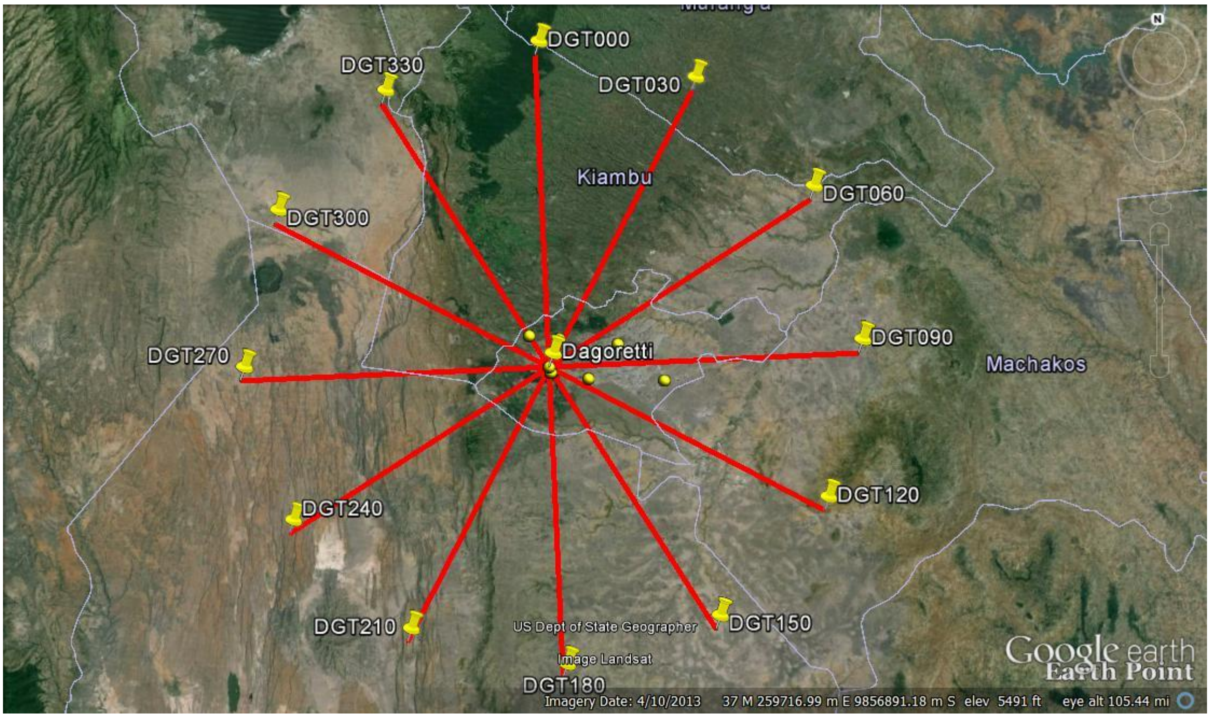


Figure 3.1. Google Earth Map of Terrain around Dagoretti Meteorological Station

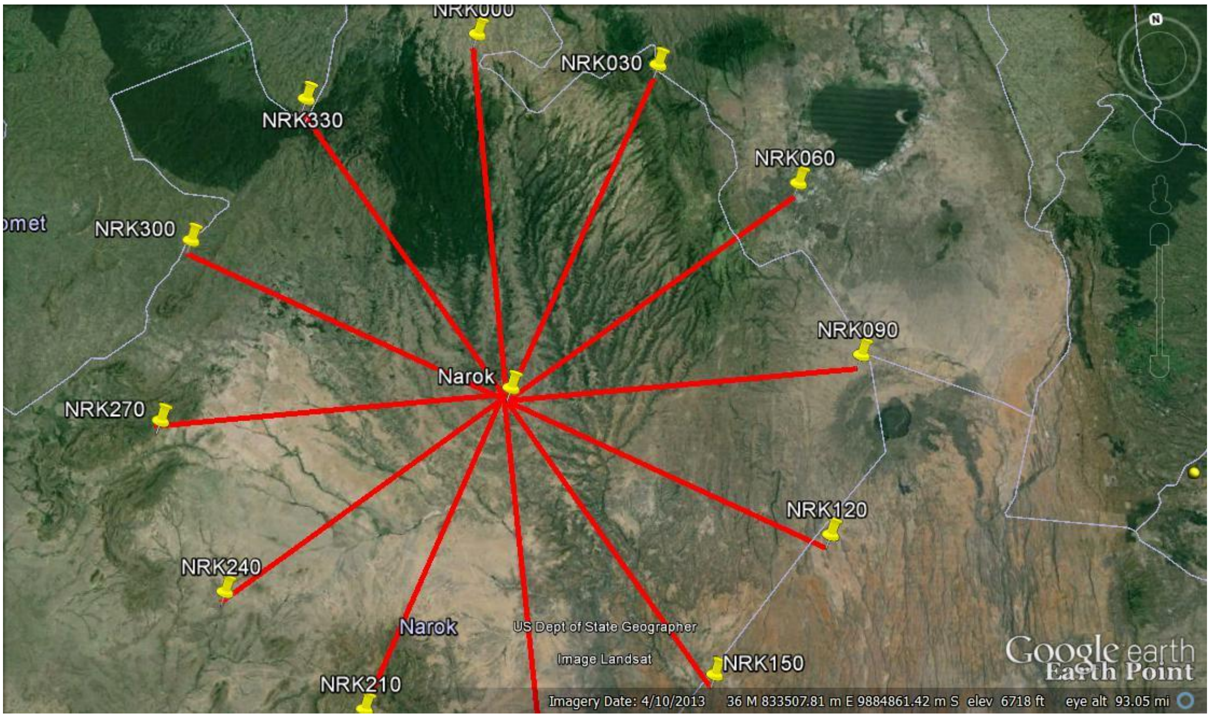


Figure 3.2 Google Earth Map of Terrain around Narok Meteorological Station

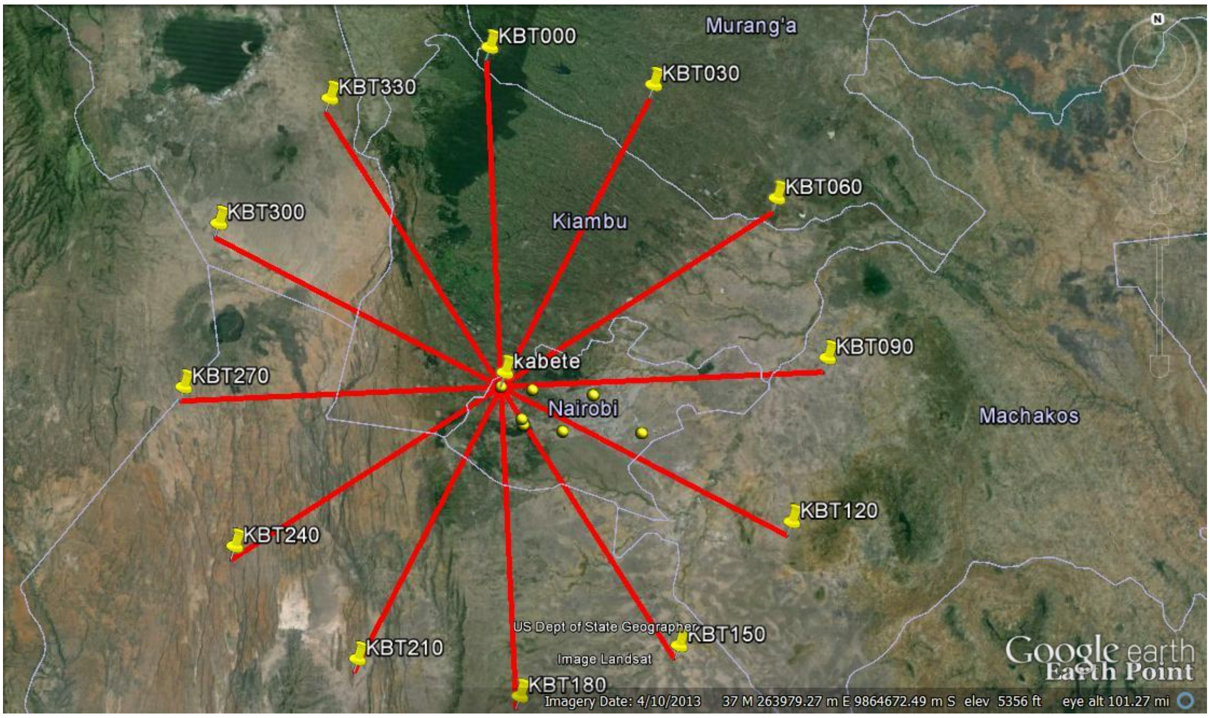


Figure 3.3. Google Earth Map of Terrain around Kabete Agro- Meteorological Station

3.2.2 Determination of Altitude Factors

Design wind speed is usually defined at an elevation of reference that is taken to be the mean sea level. Wind speeds measured at all the anemometers were transposed to the reference altitude which is the mean sea level. The elevations above sea level for each anemometer were obtained from the Kenya Meteorology Department. Based on these elevations, correction factors known as altitude factor (S_A) were estimated as recommended in International Standards and used in the Euro code.

The altitude factors were got from the following formulae as given in the United Kingdom National Annex to EN 1991-1-4:

$$S_A = 1 + 0.001(A) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . Equation\ 24$$

Where: S_A is the Altitude Correction Factor

A is the Altitude in metres.

The terrain correction factors from each meteorological station and specific direction were multiplied by the altitude correction factors from each meteorological station. This resulted in the combined correction factors for each meteorological station and direction. The combined correction factors were then multiplied by the mean hourly wind speeds from the respective meteorological stations. These wind speeds were already in m/s and at 10m heights so once they were multiplied by the terrain and altitude factors, they represent wind speeds at 10m heights, standard terrain i.e. at an area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights ($Z_O = 0.05$m) and at the standard altitude which is the mean sea level.

3.3 Extreme Value Analysis

The wind speeds at 10m heights and standard terrain and elevation were subjected to Gumbel method of analysis to obtain the basic design wind speeds. Independent storms (periods of high wind speeds) were identified from the data. A period of storm separation of three days was considered. Therefore the smaller values of pairs of wind records separated by three days or less were deleted to ensure that only independent storm maxima were retained. From each storm the maximum wind speed was extracted. The following procedure was used to fit independent storm maximum wind speeds to the Type 1 Extreme Value Distribution:

- The Largest wind speed in each independent storm in the wind record was extracted.
- The series was ranked in order from the smallest to largest.
- Each value was assigned a value of non-exceedance according to:
- $P_v = \frac{m}{N+1} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . Equation\ 25$
- The reduced variate was formed from:
- $Y = -\ln(-lnP_v) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . Equation\ 26$

The Independent storm maximum wind speeds were plotted against Y (Reduced variate) and a line of best fit drawn by means of linear regression. From the graph, u= intercept of the line, 1/a = slope of the line.

For a 50 year return period, the following equation was used to determine extreme wind speed.

$$U_r = U + \left(\frac{1}{a}\right)(-\ln(-\ln(0.98))) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation } 27$$

Where:

Ur is the 50 year return period wind speed,

U is the y-intercept of the line,

1/a is the slope of the line.

The values obtained from Equation 27 were the mean hourly wind speeds for each of the meteorological stations. However, EN 1991-1-4 uses an averaging period of 10 minutes i.e. the fundamental basic wind speed is defined in form of a 10-minute speed. Therefore the mean hourly wind speeds got were multiplied by a factor 1.06 got from Figure 2.1. to obtain the 10-minute wind speeds.

The following graphs were obtained from analysis of wind data from the stations.

DAGORETTI METEOROLOGICAL STATION

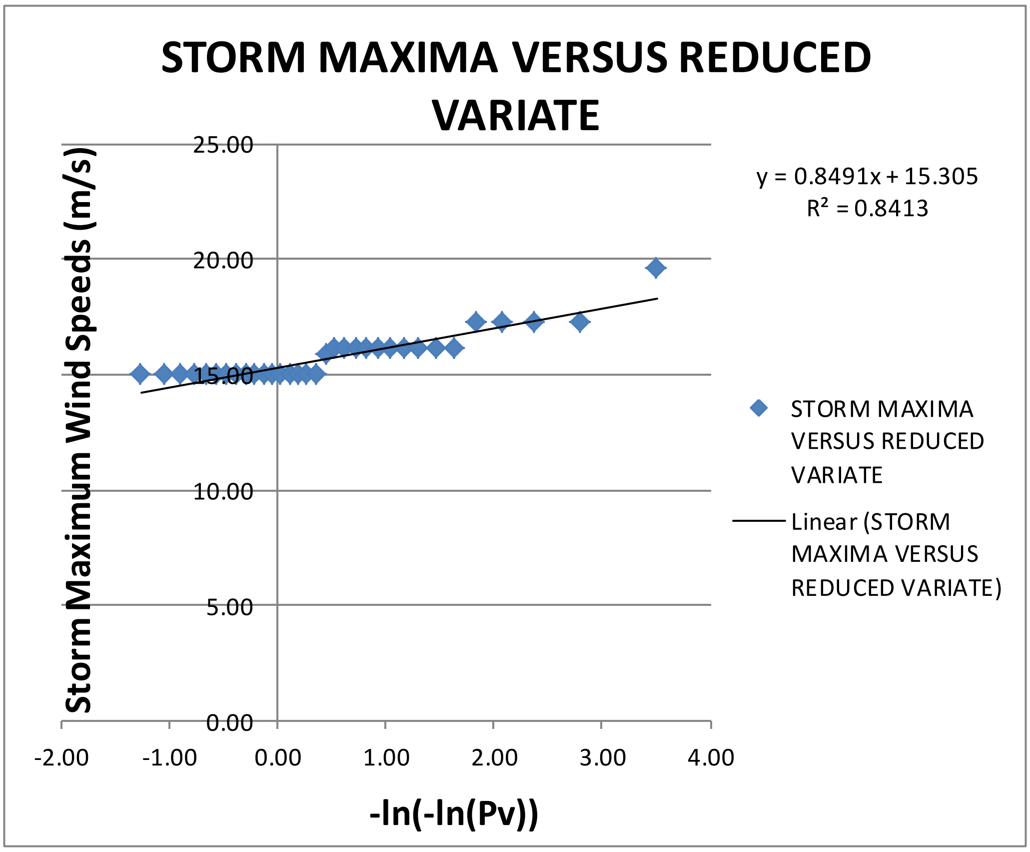


Figure 3.4: Graph of Storm Maximum Wind Speed Versus Reduced variate of Dagoretti Hourly Wind Speeds

EASTLEIGH METEOROLOGICAL STATION

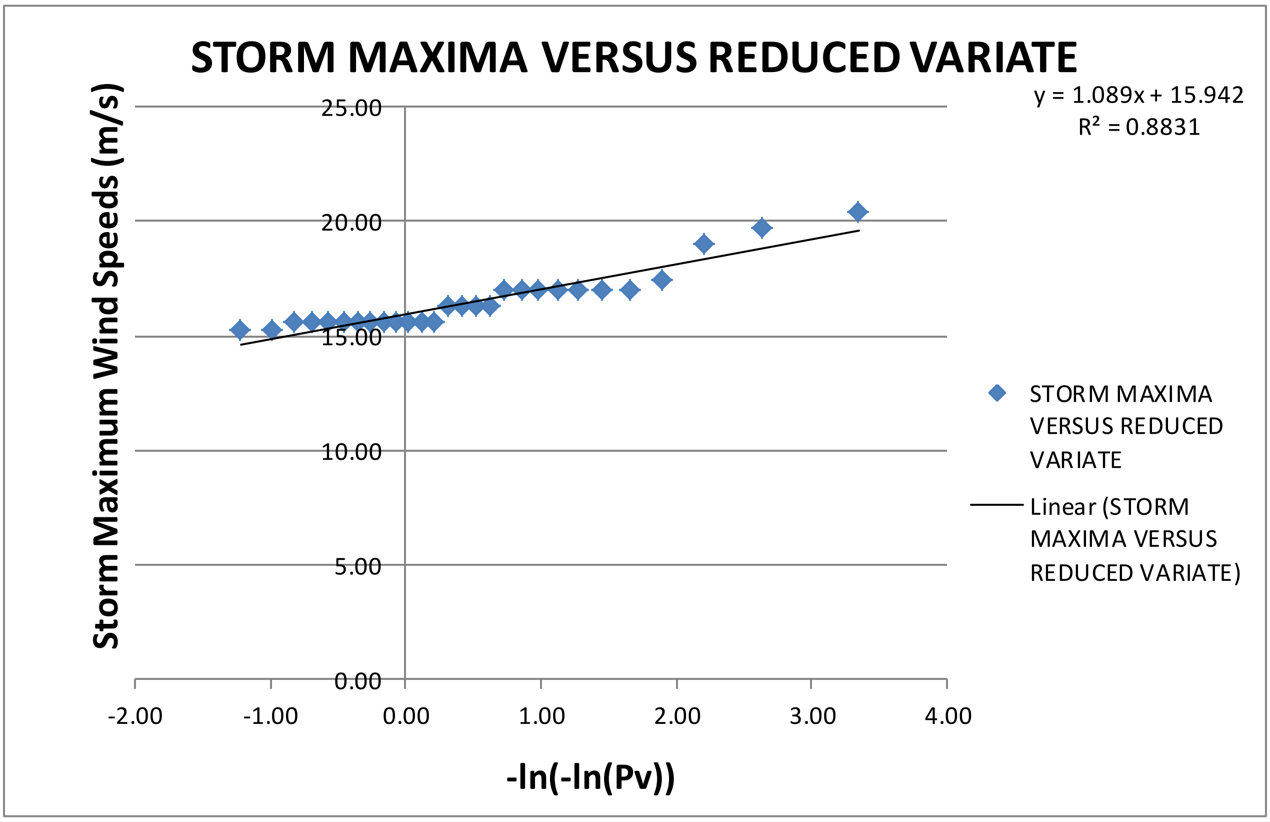


Figure 3.5: Graph of Storm Maximum Wind Speed Versus Reduced variate of Eastleigh Hourly Wind Speeds

JKIA METEOROLOGICAL STATION

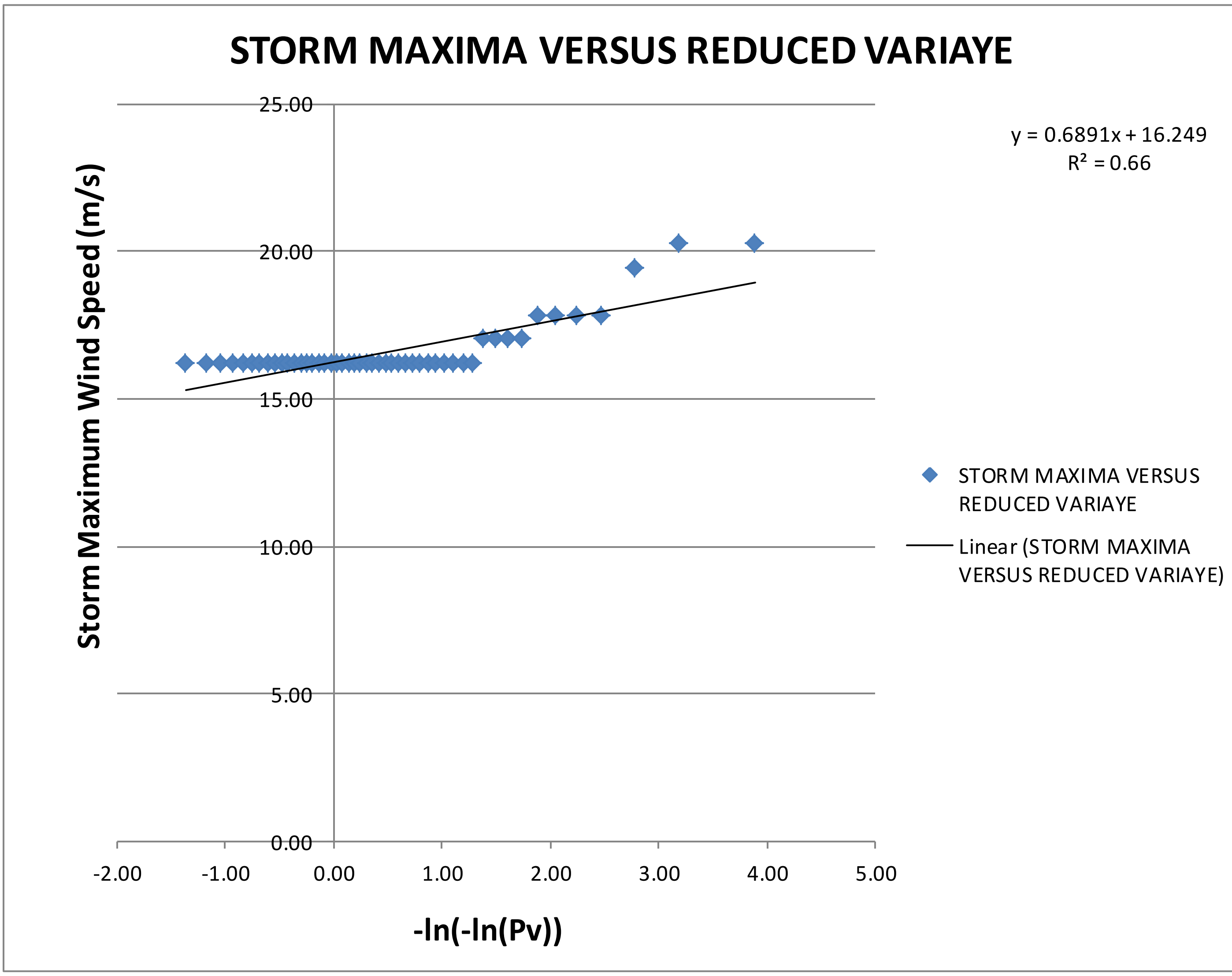


Figure 3.6: Graph of Storm Maximum Wind Speed Versus Reduced variate of JKIA Hourly Wind Speeds

KABETE METEOROLOGICAL STATION

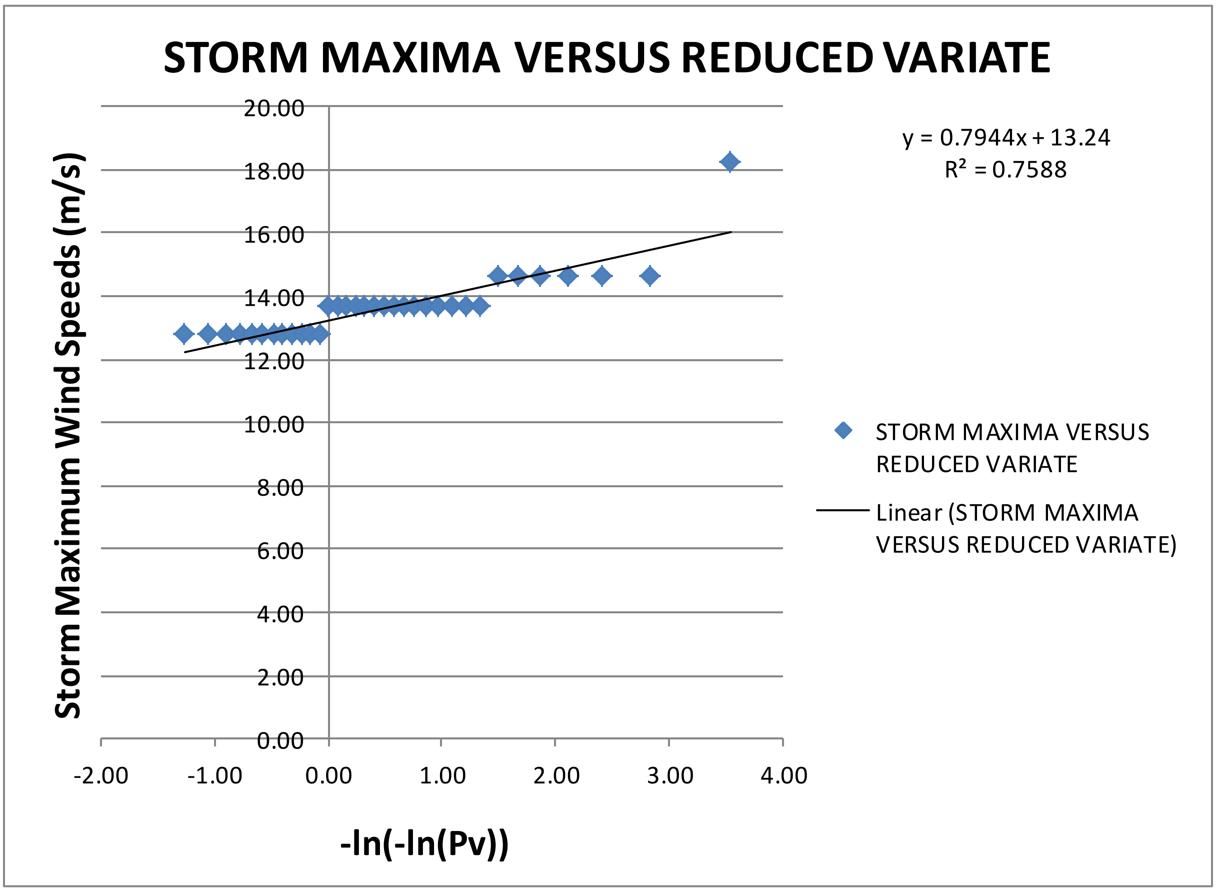


Figure 3.7: Graph of Storm Maximum Wind Speed Versus Reduced variate of Kabete Hourly Wind Speeds

MACHAKOS METEOROLOGICAL STATION

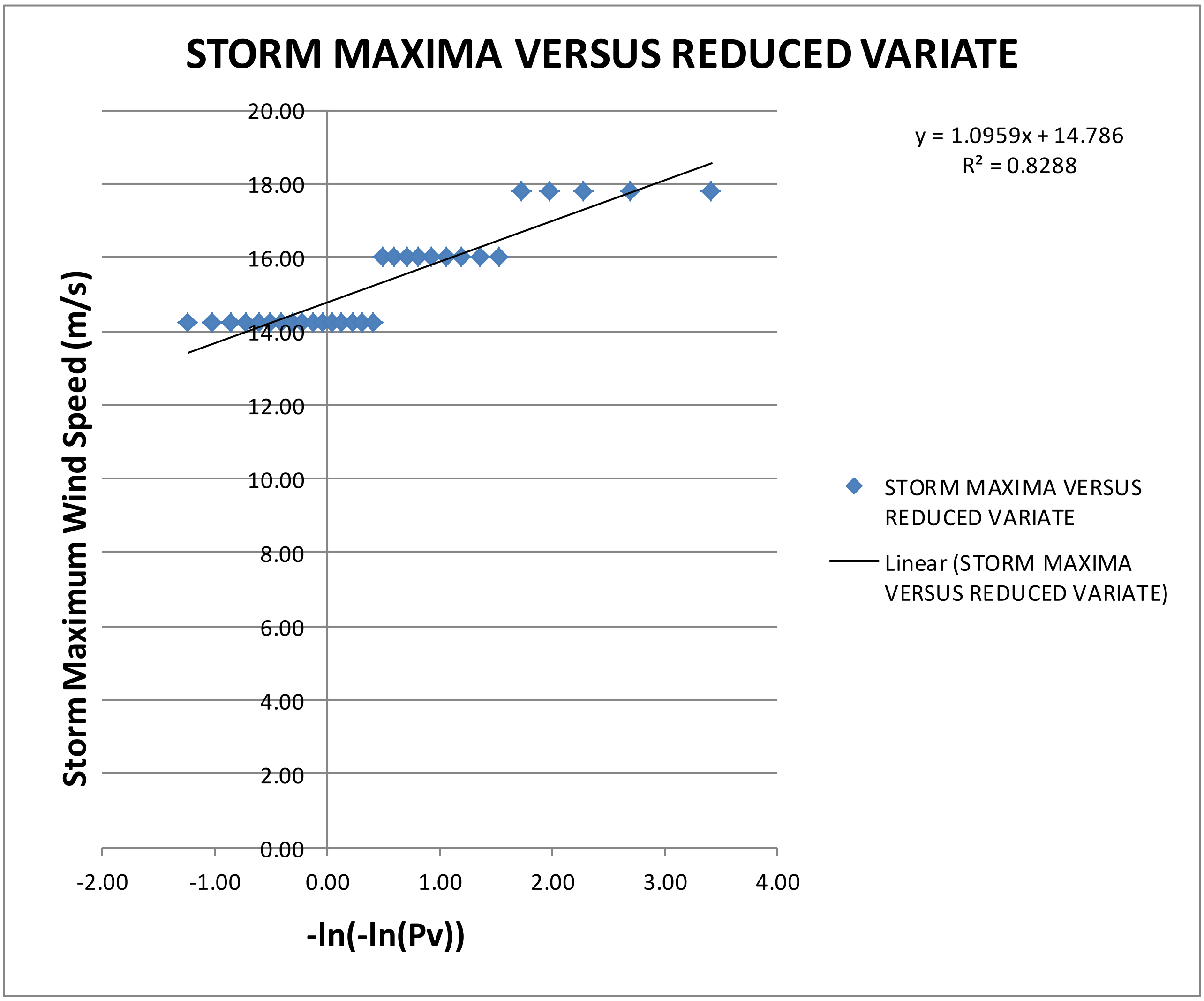


Figure 3.8: Graph of Storm Maximum Wind Speed Versus Reduced variate of Machakos Hourly Wind Speeds

NAROK METEOROLOGICAL STATION

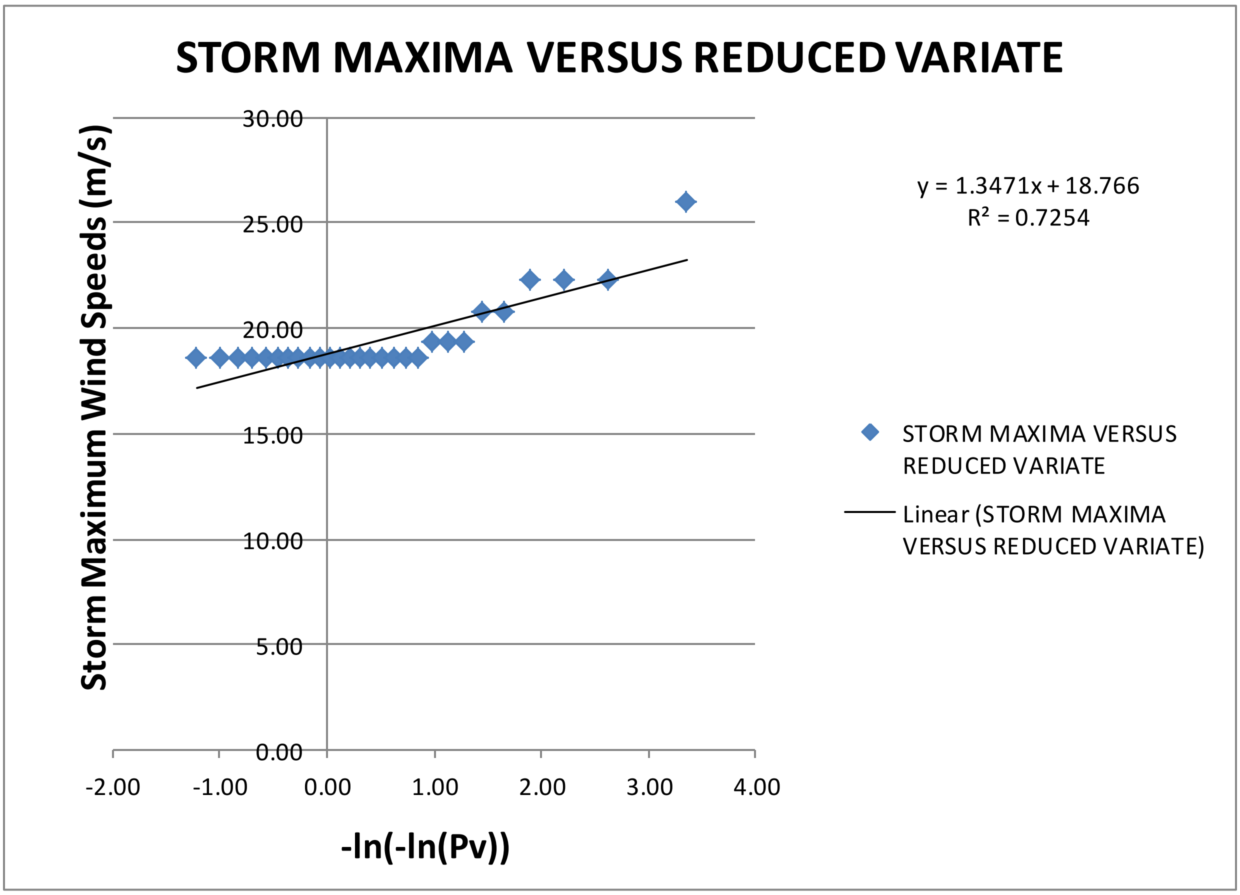


Figure 3.9: Graph of Storm Maximum Wind Speed Versus Reduced variate of Narok Hourly Wind Speeds

THIKA METEOROLOGICAL STATION

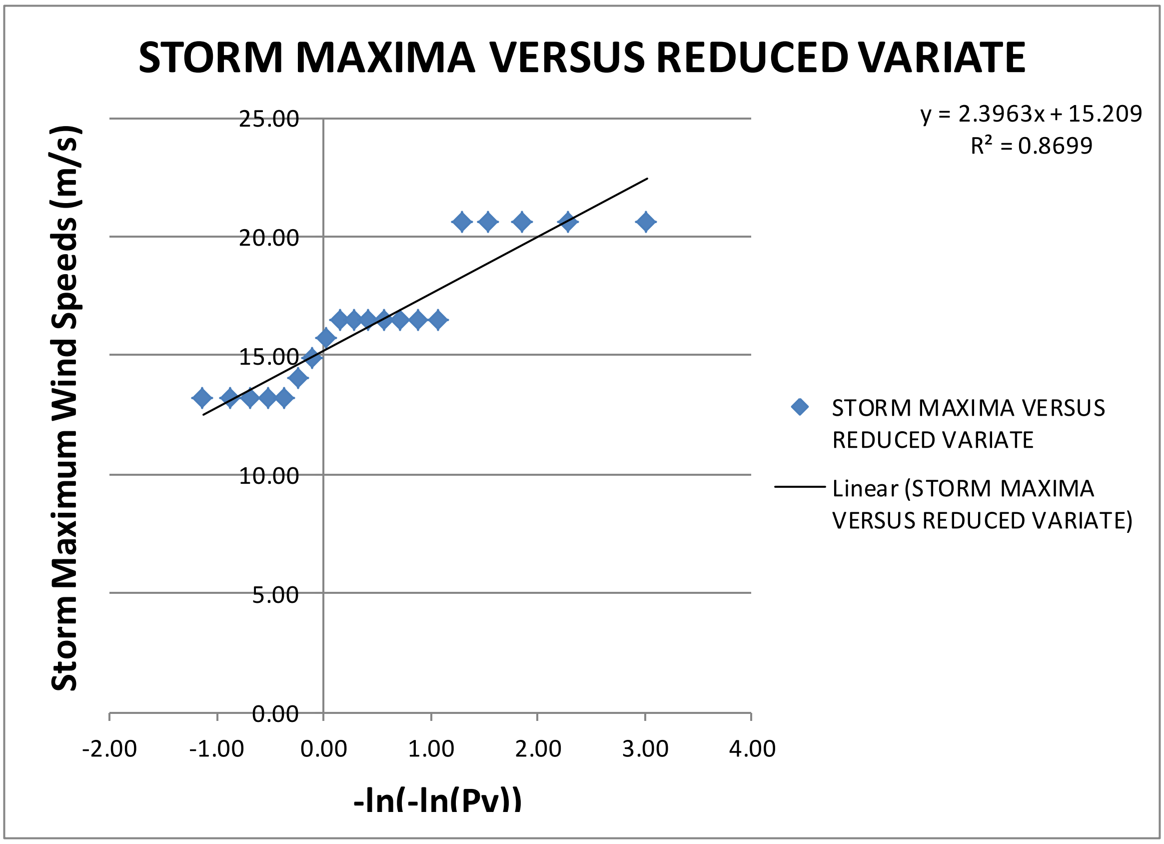


Figure 3.10: Graph of Storm Maximum Wind Speed Versus Reduced variate of Thika Hourly Wind Speeds

WILSON METEOROLOGICAL STATION

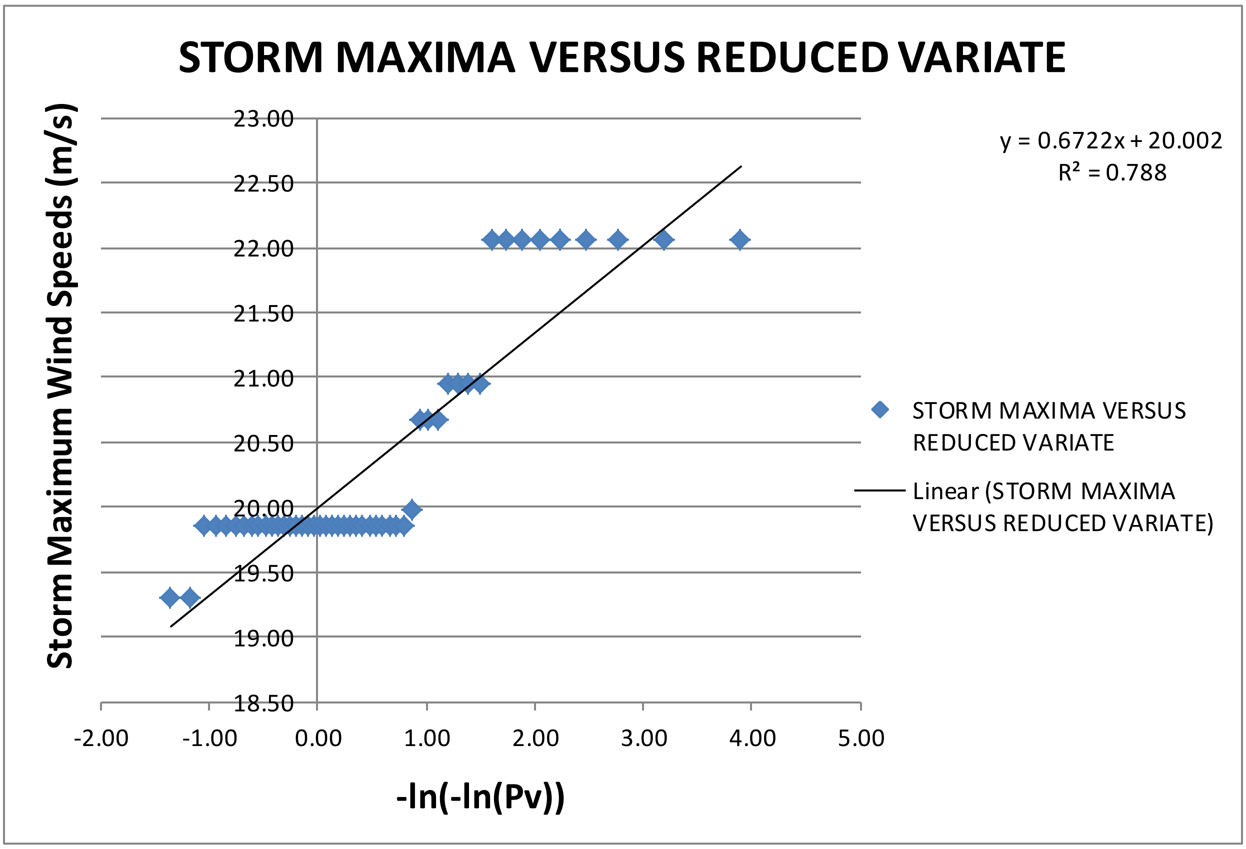


Figure 3.11: Graph of Storm Maximum Wind Speed Versus Reduced variate of Wilson Airport Hourly Wind Speeds

3.4 Drawing the Wind Speed Map

After obtaining the fundamental basic wind speeds at the meteorological stations, isotachs were drawn on the Nairobi County map. The isotachs were drawn using the NOVAPOINT software. The grid points (latitudes and longitudes) and the fundamental basic wind speeds of each of the meteorological stations were input into the software for it to generate the isotachs. The software was also instructed to generate the isotachs at an interval of 1 m/s. A map of Nairobi County was superimposed on the NOVAPOINT map to ensure that the isotachs map generated would show the boundary of Nairobi County.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Correction Factors.

These were parameters which were used to transpose the wind speeds measured at the anemometers to a reference terrain and elevation at standard height. They included the terrain correction factors and the altitude correction factors.

4.1.1 Altitude Correction Factors.

The altitude correction factors are the correction factors which transpose the recorded wind speeds to a standard height which is the mean sea level. Nairobi County and its environs generally lie in a high altitude area. Equation 17 shows that the altitude correction factors are directly proportional to the altitude therefore the altitude correction factors were high i.e. Between 2.55 at Thika and 2.89 at Narok.

From Table 4.1 all the altitude correction factor values obtained were greater than one. When these correction factors were multiplied by the raw wind speeds, the resulting wind speed at the mean sea level were higher than the wind speeds measured at the anemometers. This shows that transposition of wind speeds from a high altitude to a lower altitude results in higher wind speeds at the lower altitude. Therefore the wind speeds when transposed to the mean sea level would be higher if only the altitude correction factors were considered. Table 4.1 shows the altitude correction factors that were determined.

Table 4.1: Altitude Correction Factors.

ALTITUDE FACTORS

STATIONS	ALTITUDE	FACTORS
KABETE	1820	2.82
JKIA	1624	2.62
WILSON	1679	2.68
DAGORETTI	1798	2.80
EASTLEIGH	1640	2.64
MACHAKOS	1750	2.75
THIKA	1549	2.55
NAROK	1890	2.89

4.1.2 Terrain Correction Factors

The terrain correction factors are correction factors which transpose the recorded wind speed to the reference terrain which in this case was an area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights (Z_O = 0.05m). From Table 4.2 the correction factors obtained were all less than one. When these correction factors were multiplied by the raw wind speeds, the resulting wind speed at the reference terrain were lower than the wind speeds measured at the anemometers. This shows that transposition of wind speeds from a rougher terrain (as seen around Nairobi County) to a smoother terrain results in lower wind speeds at the smoother terrain. Therefore the wind speeds when transposed to the reference terrain would be lower if only the terrain correction factors were considered. Table 4.2 shows the terrain correction factors that were determined.

Table 4.2: Terrain correction factors.

TERRAIN FACTORS												
	DIRECTION IN DEGREES											
STATIONS	30	60	90	120	150	180	210	240	270	300	330	360
KABETE	0.5	0.5	0.5	0.8	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5
JKIA	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.5	0.8	0.8	0.6
WILSON	0.8	0.8	0.4	0.3	0.3	0.3	0.3	0.5	0.5	0.5	0.5	0.5
DAGORETTI	0.5	0.5	0.8	0.4	0.3	0.5	0.5	0.5	0.5	0.5	0.5	0.5
EASTLEIGH	0.5	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5
MACHAKOS	0.5	0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.5	0.5
THIKA	0.5	0.5	0.5	0.5	0.4	0.3	0.3	0.3	0.5	0.5	0.5	0.5
NAROK	0.5	0.5	0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.5	0.5

4.1.3 Combined Correction Factors

The altitude correction factors were multiplied by the terrain correction factors to result in the combined correction factors. The combined correction factors show the overall effect of the correction factors on the wind speed measurements. If the combined correction factors are greater than one, then the wind speeds at the reference terrain and altitude would be higher than the wind speeds measured at the anemometers. However, if the combined correction factors are less than one, then the wind speeds at the reference terrain and altitude would be lower than the wind speeds measured at the anemometers.

From Table 4.3 showing the correction factors obtained, 69.79% of the values were greater than one while30.21% of them were less than one. Therefore, generally in Nairobi County, the wind speeds at the reference terrain and elevation were greater than the measured wind speeds. Therefore from the combined correction factors, it is seen that if the extreme wind analysis is carried out without considering the correction factors then the resulting fundamental basic wind speeds would be lower than they really are. Table 4.3 shows the combined correction factors.

Table 4.3: Combined Correction Factors.

STATIONS	**WIND DIRECTION**											
	30	60	90	120	150	180	210	240	270	300	330	360
KABETE	1.41	1.41	1.41	2.26	1.13	1.41	1.41	1.41	1.41	1.41	1.41	1.41
JKIA	1.05	1.05	0.79	0.79	0.79	0.79	0.79	0.79	1.31	2.10	2.10	1.57
WILSON	2.14	2.14	1.07	0.80	0.80	0.80	0.80	1.34	1.34	1.34	1.34	1.34
DAGORETTI	1.40	1.40	2.24	1.12	0.84	1.40	1.40	1.40	1.40	1.40	1.40	1.40
EASTLEIGH	1.32	1.06	1.06	1.06	1.06	1.06	1.32	1.32	1.32	1.32	1.32	1.32
MACHAKOS	1.38	1.38	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	1.38	1.38
THIKA	1.27	1.27	1.27	1.27	1.02	0.76	0.76	0.76	1.27	1.27	1.27	1.27
NAROK	1.45	1.45	1.45	0.87	0.87	0.87	0.87	0.87	0.87	0.87	1.45	1.45

4.3 Basic Mean Hourly Wind Speeds.

The basic mean hourly wind speeds are the wind speeds that resulted from the extreme value analysis of the hourly wind speeds that had been transposed to reference terrain and elevation at standard height. The analysis is shown in Tables A1 to A8 in appendix A. Table 4.4 shows the basic mean hourly wind speeds in Nairobi County and its environs. The wind speeds vary from 16.34m/s at Kabete to 24.56m/s at Thika. Previously, the 3-second gust speeds in Nairobi County has been assumed to be 28m/s. From the durst curve in figure 2.1, the conversion factor from a mean hourly wind speed to a 3-second gust speed is 1.52. The mean hourly wind speed is obtained by dividing 28m/s by 1.52. Therefore this translates to a mean hourly wind speed of 18.42m/s which is comparable to the wind speeds obtained from the analysis.

Table 4.4: Basic Mean Hourly Design Speeds

STATIONS	Basic Hourly Mean Design Speed(m/s)
KABETE	16.34
JKIA	18.94
WILSON	22.62
DAGORETTI	18.62
EASTLEIGH	20.19
MACHAKOS	19.06
THIKA	24.56
NAROK	24.02

4.4 Basic 10 Minute Wind Speeds.

EN 1991-1-4 defines the fundamental basic wind speed in form of a 10-minute speed. Thus it proposes an averaging period of 10 minute. Therefore the mean hourly wind speeds obtained in Table 4.4 were multiplied by a factor 1.06 got from Figure 2.1. to obtain the 10-minute wind speeds shown in Table 4.5 below. From Table 4.5, the 10-minute wind speed varies from 17.32m/s to 26.03m/s. When the 3 second gust speed currently in use in Nairobi County is converted to a mean hourly wind speed using the durst curve from figure 2.1, it results in a mean hourly wind speed of 18.52m/s. When this wind speed is multiplied by the factor from figure 2.1 which is 1.06, a 10 minute wind speed of 19.63m/s is obtained. This is comparable with the 10 minute

Table 4.5: 10-Minute Design Wind Speed

STATIONS	Basic 10-min Design Speed(m/s)
KABETE	17.32
JKIA	20.08
WILSON	23.98
DAGORETTI	19.74
EASTLEIGH	21.40
MACHAKOS	20.20
THIKA	26.03
NAROK	25.46

4.5 Nairobi County Wind Speed Map

From the 10 minute wind speeds in Table 4.5, the Nairobi County wind speed map shown in Figure 4.1 was drawn. This map was drawn using software known as NOVAPOINT. To draw the map the 10 minute basic wind speeds and the grid points (longitudes and latitudes) of each of the meteorological stations were input into the software. The isotachs were drawn at an interval of 1m/s. From the wind speed map in Figure 4.1, the 10 minute wind speeds within Nairobi County vary from 18m/s to 22m/s. This is comparable to 19.63m/s which is what would have been obtained if the 3-second wind speed currently in use i.e. 28m/s would have been converted to a 10 minute wind speed using the durst curve from Figure 2.1.

It is important to note that the wind speed of short recording time is usually higher than the wind speed of long recording time. Therefore it is most probable that the wind speeds obtained from this research were affected by the period of data available. The data available ranged from 6 years to 12 years. This could have resulted in higher wind speeds. Longer recording periods would have led to more accurate results.

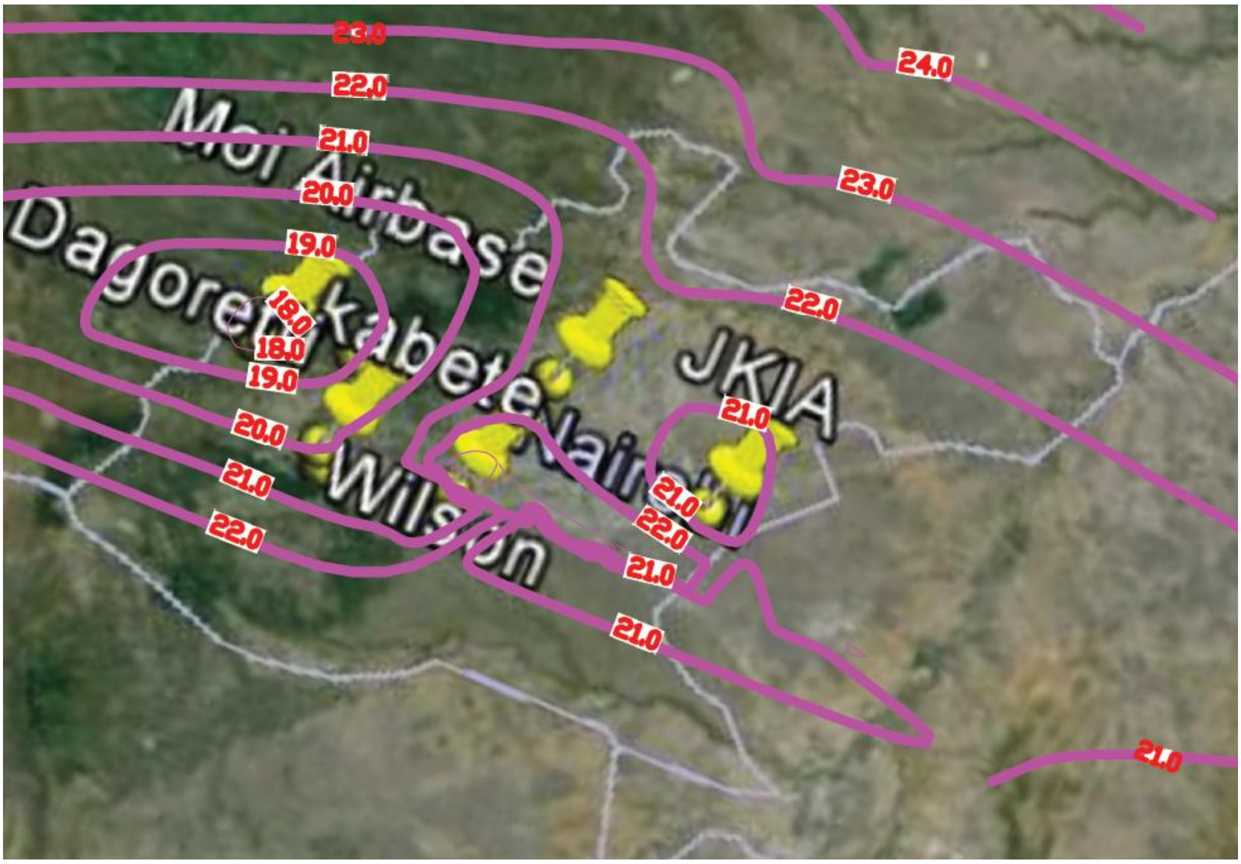


Figure 4.1: Nairobi Wind map

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. CONCLUSION

1. This research has led to the development of a Nairobi County wind speed map which can be used to determine wind loads on various structures within Nairobi County. The contour map obtained can be used with Euro code 1991-1-4 since it is based on 10-min mean wind speed at sea level (ZO = 0.03m) which has a probability of 0.02 of being exceeded in any one year.
2. The basic 10 minute mean wind speeds within Nairobi County vary from 18m/s to 22m/s.
3. The current basic 3-second gust speed used in Nairobi County is 28m/s. When converted to a 10 minute wind speed, it becomes 19.63m/s which is within the range of basic wind speeds obtained for Nairobi County.

5.2 RECOMMENDATIONS.

1. The Nairobi County Contour wind map obtained from this research should be used alongside the Euro code 1991-1-4 in determination of wind loads in Nairobi County.
2. Future research should cover the whole country so as to result in a National Wind Map.
3. Kenya Meteorological Department (KMD) should strive to have and avail hourly wind speeds for all the meteorological stations in Kenya to ensure research covering the whole country can be successfully carried out.
4. Kenya Meteorological Department (KMD) should strive to have and avail hourly wind speeds covering longer periods i.e. over 20 years since it will lead to higher accuracy of the results.

5. Kenya Meteorological Department should employ Automatic Weather Station (AWS) technology as this increase the wind data available for extreme wind analysis since more accurate data from many other locations apart from the meteorological stations can be got.

REFERENCES

Bivona S. ,Burton R., Leone C. (2003). Hourly wind speed analysis in Sicily, Renewable Energy, 28(9), pp 1371-1385.

BNS CP28- Code of Practice for Wind Loads for structural Design, (1981)

British Standard: Eurocode 1: Actions on Structures – Part1- 4: General actions – wind actions; BS EN 1991-1-4:2005, BSI, London,(2005)

BS 6399-2 Loading for Buildings-Part 2: Code of practise for wind loads, (1997)

Celik A.N. (2004). On the distributional parameters used in assessment of the suitability of wind speed probability density functions, Energy conversion and Management 45(11-12) pp 1735-1747.

Coelingh J.P, Van Wijk J.M., Holyslag A.M. (1996). Analysis of wind speed observations over North Sea. Journal of Wind Engineering & Industrial Aerodynamics, 61(1-2), pp51-69.

Cook, N.J., (2003) Extreme wind speeds in the UK.,The Structural Engineer.

CP 3 Chapter V: 1972, BSI. (1972)

Guide to the use EN 1991-1-4-Wind Actions. (2006)

Krayer W.R. and Marshall R.D., (1992). Gust Factors Applied To Hurricane Winds, Bull. Am. Meteor. Soc., 73(5), 613-617

Masters F., Vickery P., Bacon P. and Rappaport E. (2010). Towards objective, standardized intensity estimates from surface wind speed observations, Bull. American Meteorological Society, 12, 1665-1681.

Ng'ang'a, J.K.. (1992, February and May). The Climate and Meteorology of Nairobi Region, Kenya, Journal of Social Development in Africa, Volume 7, Nos. 1 and 2.

Ove Arup & Partners Ltd, Department of the Environment, Heritage and Local Government. Irish National Annex to the Wind Euro code (EN 1991-1-4), Derivation of the Wind Map, (2009).

Simiu E. and Filliben J.J. (1976, September). Probability Distributions of Extreme Wind Speeds. Journal of the Structural Division, ASCE Vol. 102, No. ST9, pp. 1861-1877.

Simiu E., Bietry J., and Filliben J.J., (1978, March). Sampling Errors in the Estimation of Extreme Winds, Journal of the Structural Division, ASCE, Vol.104, No. ST3, pp. 491-501.

Simiu E., Changery M.J. and Filliben J.J., (1979, March). Extreme Wind Speeds at 129 Stations in the Contiguous United States, NBS Building Sciences Series 118, U.S. Dept. of Commerce, National Bureau of Standards,.

Simiu, E., and Filliben, J.J., (1975). Statistical Analysis of Extreme Winds, Technical Note No. 868, national Bureau of Standards, Washington D.C.,.

The Caribbean Uniform Building Code, (2012)

Thom, H.C.S., (1960). Distribution of Extreme Winds in the United States, Journal of the Structural Division, ASCE, Vol. 86, No. ST4, , pp. 11-24.

Thom, H.C.S., (1968). New Distribution of Extreme Winds in the United States, Journal of the Structural Division, ASCE, Vol. 94, No. ST7 , pp. 1787-1801.

Yohana Noradika Maharani, Sungsu Lee and young-Kyu Lee, (2009, November 8-12) Topographic Effects on Wind Speed over various Terrains: A Case study for Korean Peninsula. The Seventh Asia-Pacific Conference on Wind Engineering, Taipei; Taiwan.

APPENDIX A

Table A.1: Table of Analysis of Dagoretti Independent Storm Maximum Wind Speeds

DAGORETTI WIND ANALYSIS					
V	m	N	Pv	-ln(Pv)	-ln(-ln(Pv))
14.97	1	33	0.03	3.53	-1.26
14.97	2	33	0.06	2.83	-1.04
14.97	3	33	0.09	2.43	-0.89
14.97	4	33	0.12	2.14	-0.76
14.97	5	33	0.15	1.92	-0.65
14.97	6	33	0.18	1.73	-0.55
14.97	7	33	0.21	1.58	-0.46
14.97	8	33	0.24	1.45	-0.37
14.97	9	33	0.26	1.33	-0.28
14.97	10	33	0.29	1.22	-0.20
14.97	11	33	0.32	1.13	-0.12
14.97	12	33	0.35	1.04	-0.04
14.97	13	33	0.38	0.96	0.04
14.97	14	33	0.41	0.89	0.12
14.97	15	33	0.44	0.82	0.20
14.97	16	33	0.47	0.75	0.28
14.97	17	33	0.50	0.69	0.37
15.83	18	33	0.53	0.64	0.45
16.12	19	33	0.56	0.58	0.54
16.12	20	33	0.59	0.53	0.63
16.12	21	33	0.62	0.48	0.73
16.12	22	33	0.65	0.44	0.83
16.12	23	33	0.68	0.39	0.94
16.12	24	33	0.71	0.35	1.05
16.12	25	33	0.74	0.31	1.18
16.12	26	33	0.76	0.27	1.32
16.12	27	33	0.79	0.23	1.47
16.12	28	33	0.82	0.19	1.64
17.27	29	33	0.85	0.16	1.84
17.27	30	33	0.88	0.13	2.08
17.27	31	33	0.91	0.09	2.38
17.27	32	33	0.94	0.06	2.80
19.57	33	33	0.97	0.03	3.51

Table A.2: Table of Analysis of Eastleigh Independent Storm Maximum Wind Speeds

EASTLEIGH WIND ANALYSIS					
V	m	N	Pv	-ln(Pv)	-ln(-ln(Pv))
15.21	1	28	0.03	3.37	-1.21
15.21	2	28	0.07	2.67	-0.98
15.62	3	28	0.10	2.27	-0.82
15.62	4	28	0.14	1.98	-0.68
15.62	5	28	0.17	1.76	-0.56
15.62	6	28	0.21	1.58	-0.45
15.62	7	28	0.24	1.42	-0.35
15.62	8	28	0.28	1.29	-0.25
15.62	9	28	0.31	1.17	-0.16
15.62	10	28	0.34	1.06	-0.06
15.62	11	28	0.38	0.97	0.03
15.62	12	28	0.41	0.88	0.13
15.62	13	28	0.45	0.80	0.22
16.30	14	28	0.48	0.73	0.32
16.30	15	28	0.52	0.66	0.42
16.30	16	28	0.55	0.59	0.52
16.30	17	28	0.59	0.53	0.63
16.98	18	28	0.62	0.48	0.74
16.98	19	28	0.66	0.42	0.86
16.98	20	28	0.69	0.37	0.99
16.98	21	28	0.72	0.32	1.13
16.98	22	28	0.76	0.28	1.29
16.98	23	28	0.79	0.23	1.46
16.98	24	28	0.83	0.19	1.66
17.38	25	28	0.86	0.15	1.91
19.01	26	28	0.90	0.11	2.21
19.69	27	28	0.93	0.07	2.64
20.37	28	28	0.97	0.04	3.35

Table A.3: Table of Analysis of JKIA Independent Storm Maximum Wind Speeds

JKIA WIND ANALYSIS					
V	m	N	Pv	-ln(Pv)	-ln(-ln(Pv))
16.20	1	35	0.02	3.91	-1.36
16.20	2	35	0.04	3.22	-1.17
16.20	3	35	0.06	2.81	-1.03
16.20	4	35	0.08	2.53	-0.93
16.20	5	35	0.10	2.30	-0.83
16.20	6	35	0.40	0.92	0.09
16.20	7	35	0.42	0.87	0.14
16.20	8	35	0.44	0.82	0.20
16.20	9	35	0.46	0.78	0.25
16.20	10	35	0.48	0.73	0.31
16.20	11	35	0.50	0.69	0.37
16.20	12	35	0.52	0.65	0.42
16.20	13	35	0.54	0.62	0.48
16.20	14	35	0.56	0.58	0.55
16.20	15	35	0.58	0.54	0.61
16.20	16	35	0.60	0.51	0.67
16.20	17	35	0.62	0.48	0.74
16.20	18	35	0.64	0.45	0.81
16.20	19	35	0.66	0.42	0.88
16.20	20	35	0.68	0.39	0.95
16.20	21	35	0.70	0.36	1.03
16.20	22	35	0.72	0.33	1.11
16.20	23	35	0.74	0.30	1.20
16.20	24	35	0.76	0.27	1.29
17.01	25	35	0.78	0.25	1.39
17.01	26	35	0.80	0.22	1.50
17.01	27	35	0.82	0.20	1.62
17.01	28	35	0.84	0.17	1.75
17.82	29	35	0.86	0.15	1.89
17.82	30	35	0.88	0.13	2.06
17.82	31	35	0.90	0.11	2.25
17.82	32	35	0.92	0.08	2.48
19.44	33	35	0.94	0.06	2.78
20.25	34	35	0.96	0.04	3.20
20.25	35	35	0.98	0.02	3.90

Table A.4: Table of Analysis of Kabete Independent Storm Maximum Wind Speeds

KABETE WIND ANALYSIS					
V	m	N	Pv	-ln(Pv)	-ln(-ln(Pv))
12.78	1	34	0.03	3.56	-1.27
12.78	2	34	0.06	2.86	-1.05
12.78	3	34	0.09	2.46	-0.90
12.78	4	34	0.11	2.17	-0.77
12.78	5	34	0.14	1.95	-0.67
12.78	6	34	0.17	1.76	-0.57
12.78	7	34	0.20	1.61	-0.48
12.78	8	34	0.23	1.48	-0.39
12.78	9	34	0.26	1.36	-0.31
12.78	10	34	0.29	1.25	-0.23
12.78	11	34	0.31	1.16	-0.15
12.78	12	34	0.34	1.07	-0.07
13.70	13	34	0.37	0.99	0.01
13.70	14	34	0.40	0.92	0.09
13.70	15	34	0.43	0.85	0.17
13.70	16	34	0.46	0.78	0.24
13.70	17	34	0.49	0.72	0.33
13.70	18	34	0.51	0.66	0.41
13.70	19	34	0.54	0.61	0.49
13.70	20	34	0.57	0.56	0.58
13.70	21	34	0.60	0.51	0.67
13.70	22	34	0.63	0.46	0.77
13.70	23	34	0.66	0.42	0.87
13.70	24	34	0.69	0.38	0.97
13.70	25	34	0.71	0.34	1.09
13.70	26	34	0.74	0.30	1.21
13.70	27	34	0.77	0.26	1.35
14.61	28	34	0.80	0.22	1.50
14.61	29	34	0.83	0.19	1.67
14.61	30	34	0.86	0.15	1.87
14.61	31	34	0.89	0.12	2.11
14.61	32	34	0.91	0.09	2.41
14.61	33	34	0.94	0.06	2.83
18.26	34	34	0.97	0.03	3.54

Table A.5: Table of Analysis of Machakos Independent Storm Maximum Wind Speeds.

MACHAKOS WIND ANALYSIS					
V	m	N	Pv	-ln(Pv)	-ln(-ln(Pv))
14.25	1	30	0.03	3.43	-1.23
14.25	2	30	0.06	2.74	-1.01
14.25	3	30	0.10	2.34	-0.85
14.25	4	30	0.13	2.05	-0.72
14.25	5	30	0.16	1.82	-0.60
14.25	6	30	0.19	1.64	-0.50
14.25	7	30	0.23	1.49	-0.40
14.25	8	30	0.26	1.35	-0.30
14.25	9	30	0.29	1.24	-0.21
14.25	10	30	0.32	1.13	-0.12
14.25	11	30	0.35	1.04	-0.04
14.25	12	30	0.39	0.95	0.05
14.25	13	30	0.42	0.87	0.14
14.25	14	30	0.45	0.79	0.23
14.25	15	30	0.48	0.73	0.32
14.25	16	30	0.52	0.66	0.41
16.03	17	30	0.55	0.60	0.51
16.03	18	30	0.58	0.54	0.61
16.03	19	30	0.61	0.49	0.71
16.03	20	30	0.65	0.44	0.82
16.03	21	30	0.68	0.39	0.94
16.03	22	30	0.71	0.34	1.07
16.03	23	30	0.74	0.30	1.21
16.03	24	30	0.77	0.26	1.36
16.03	25	30	0.81	0.22	1.54
17.81	26	30	0.84	0.18	1.74
17.81	27	30	0.87	0.14	1.98
17.81	28	30	0.90	0.10	2.28
17.81	29	30	0.94	0.07	2.71
17.81	30	30	0.97	0.03	3.42

Table A.6: Table of Analysis of Narok Independent Storm Maximum Wind Speeds.

NAROK WIND ANALYSIS					
V	m	N	Pv	-ln(Pv)	-ln(-ln(Pv))
18.58	1	28	0.03	3.37	-1.21
18.58	2	28	0.07	2.67	-0.98
18.58	3	28	0.10	2.27	-0.82
18.58	4	28	0.14	1.98	-0.68
18.58	5	28	0.17	1.76	-0.56
18.58	6	28	0.21	1.58	-0.45
18.58	7	28	0.24	1.42	-0.35
18.58	8	28	0.28	1.29	-0.25
18.58	9	28	0.31	1.17	-0.16
18.58	10	28	0.34	1.06	-0.06
18.58	11	28	0.38	0.97	0.03
18.58	12	28	0.41	0.88	0.13
18.58	13	28	0.45	0.80	0.22
18.58	14	28	0.48	0.73	0.32
18.58	15	28	0.52	0.66	0.42
18.58	16	28	0.55	0.59	0.52
18.58	17	28	0.59	0.53	0.63
18.58	18	28	0.62	0.48	0.74
18.58	19	28	0.66	0.42	0.86
19.33	20	28	0.69	0.37	0.99
19.33	21	28	0.72	0.32	1.13
19.33	22	28	0.76	0.28	1.29
20.81	23	28	0.79	0.23	1.46
20.81	24	28	0.83	0.19	1.66
22.30	25	28	0.86	0.15	1.91
22.30	26	28	0.90	0.11	2.21
22.30	27	28	0.93	0.07	2.64
26.02	28	28	0.97	0.04	3.35

Table A.7: Table of Analysis of Thika Independent Storm Maximum Wind Speeds.

THIKA WIND ANALYSIS					
V	m	N	Pv	-ln(Pv)	-ln(-ln(Pv))
13.20	1	20	0.05	3.04	-1.11
13.20	2	20	0.10	2.35	-0.86
13.20	3	20	0.14	1.95	-0.67
13.20	4	20	0.19	1.66	-0.51
13.20	5	20	0.24	1.44	-0.36
14.03	6	20	0.29	1.25	-0.23
14.85	7	20	0.33	1.10	-0.09
15.68	8	20	0.38	0.97	0.04
16.51	9	20	0.43	0.85	0.17
16.51	10	20	0.48	0.74	0.30
16.51	11	20	0.52	0.65	0.44
16.51	12	20	0.57	0.56	0.58
16.51	13	20	0.62	0.48	0.73
16.51	14	20	0.67	0.41	0.90
16.51	15	20	0.71	0.34	1.09
20.63	16	20	0.76	0.27	1.30
20.63	17	20	0.81	0.21	1.55
20.63	18	20	0.86	0.15	1.87
20.63	19	20	0.90	0.10	2.30
20.63	20	20	0.95	0.05	3.02

Table A.8: Table of Analysis of Wilson Independent Storm Maximum Wind Speeds.

WILSON WIND ANALYSIS					
V	m	N	Pv	-ln(Pv)	-ln(-ln(Pv))
19.29	1	35	0.02	3.91	-1.36
19.29	2	35	0.04	3.22	-1.17
19.84	3	35	0.06	2.81	-1.03
19.84	4	35	0.08	2.53	-0.93
19.84	5	35	0.10	2.30	-0.83
19.84	6	35	0.12	2.12	-0.75
19.84	7	35	0.14	1.97	-0.68
19.84	8	35	0.16	1.83	-0.61
19.84	9	35	0.46	0.78	0.25
19.84	10	35	0.48	0.73	0.31
19.84	11	35	0.50	0.69	0.37
19.84	12	35	0.52	0.65	0.42
19.84	13	35	0.54	0.62	0.48
19.84	14	35	0.56	0.58	0.55
19.84	15	35	0.58	0.54	0.61
19.84	16	35	0.60	0.51	0.67
19.84	17	35	0.62	0.48	0.74
19.84	18	35	0.64	0.45	0.81
19.98	19	35	0.66	0.42	0.88
20.67	20	35	0.68	0.39	0.95
20.67	21	35	0.70	0.36	1.03
20.67	22	35	0.72	0.33	1.11
20.95	23	35	0.74	0.30	1.20
20.95	24	35	0.76	0.27	1.29
20.95	25	35	0.78	0.25	1.39
20.95	26	35	0.80	0.22	1.50
22.05	27	35	0.82	0.20	1.62
22.05	28	35	0.84	0.17	1.75
22.05	29	35	0.86	0.15	1.89
22.05	30	35	0.88	0.13	2.06
22.05	31	35	0.90	0.11	2.25
22.05	32	35	0.92	0.08	2.48
22.05	33	35	0.94	0.06	2.78
22.05	34	35	0.96	0.04	3.20
22.05	35	35	0.98	0.02	3.90