"Some Aspects of Solar Radiation Over Delhi".

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CERTIFICATE

Certified that the work embodied in this dissertation titled **"SOME ASPECTS OF SOLAR RADIATION OVER DELHI"** has been carried out in the School of Environmental Sciences, Jawaharlal Nehru University, New Delhi. This work is original and has not been submitted in part or full for any other degree or diploma in this or any other university.

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CHAPTER I

INTRODUCTION

The source of energy to drive the gigantic atmospheric engine and for all biological activity in the lower layers of the atmosphere and top layers of soil can be traced to sun. Therefore, it is essential to understand the radiation climatology of a place in order to characterise it physically. The physical characterisation includes the type of life forms and socio-geographic factors of a place. The response of the atmosphere to this solar radiation depends on a number of factors including the earth's rotation, disstance from the sun, magnetic field and chemical composition of the atmosphere.

The sun is 4.0 billion years old as an ordinary celestial body. But despite this ordinary feature, it has a tremendous influence on earth's life due to unique characterstics. It is 300,000 times closer to earth than the next nearest star. The sun is about 1.5 $x10^8$ km away from the earth and is the sole source of energy to earth. The sun is a gaseous sphere of radius 6.96×10^5 km and mass approximately 1.99×10^{35} kg. It consists of mainly hydrogen and helium plus some of heavier elements i.e. iron, silicon and carbon. The temperature of the sun is 5×10^6 °k at the centre to 5800^{o}k at the surface. The density varies from 150 g cm^{-3} at the centre to 10^{-7} g cm^{-3} at the surface. The source of the sun's energy is believed to be generated by fusion process of converting four hydrogen atoms to one helium atom.

This reaction takes place in the deep interior of the sun with very high temperature. The energy released is due to the mass difference that occurs when four hydrogen atoms combine to form one helium atom and energy is released obeying Einstein's mass-energy relationship

$$E = mc^2$$

Where E is the released energy and m is the mass defect and c is the velocity of light. This energy released travels in the form of electromagnetic radiation to reach the earth where it is conventionally known as solar radiation.

Electromagnetic radiation emitted by the sun encompasses γ-ray, X-rays, ultra violet rays, light, heat, radio waves. Most important of these radiations for meteorological purposes are the thermal radiation which includes the heat and light waves.

Electromagnetic radiation is classified by its wave length (λ). The thermal range encompasses the wave length ranging 0.2 - 1000 μm. The visible spectrum having range of 0.39 to 0.77 μm. The ultravoilet includes 0.001 to 0.4 μm and the infra-red (thermal) radiation lies within 0.77 and 1000 μm.

Another subdivision of thermal radiation is short wave and long wave. They are divided some what arbitrarily. In solar energy terminology, any radiation within 3 to 4 μm is considered to be short wave and any radiation of wave length greater than 4 μm is considered as long wave.

The temperature of a body is an indicator of which type of wavelength (λ), the body emitts. A black body is that which radiates and absorbs all wavelength. So a black body is a standard body with which all real body's performance is compared with. Since both emitter sun and absorber and re-emitter earth will be compared with the black body, it is desirable to go through the fundamentals of the black body radiation. The basic three laws of black body radiation are

(a) Plank'sLaw: It relates the hemispherical spectral emissive power with the wavelength (λ) and temperature (T) by the following relation.

$$e_{b\lambda} = \frac{C_1}{\lambda^5 \, [\exp(C_2/\lambda T) \; - 1]}$$

Where $e_{b\lambda}$ is the spectral emissive power of a black body in $wm^2 \, \mu m^{-1}$ and C_1 is the first radiation constant (3.74×10^{o} $w\mu m^4$ m^{-2}) C_2 is the second radiation constant 1.388×10^4 $\mu \overset{\circ}{m} k$).
is the wavelength (μm) and T is the temperature in ^{o}k.

b) Stefan - Blotzmann's Law : It states that emissive power of a black body is proportional to the fourth power of temperature (T)

$$eb = \sigma T^4$$

Where σ = Stephan - Blotzmann's constant

$$= 5.6697 \times 10^{-8} \; wm^2 K^{-4}$$

c) Wein's Displacement Law : It states that the product of maximum wavelength emitted and its temperature is a constant.

$$\lambda_{max} T = \text{Constant}$$

$$= 2897.8 \; \mu m \; K.$$

The radiation obeying these three basic laws reaches the top of the earth's atmosphere. So the first frontier of the study now comes into play.

The distribution of electromagnetic radiation emitted by the sun as a function of the wavelength on the top of the atmosphere is called the Solar Spectrum. The solar constant is the rate of total solar energy at all wavelengths incident on a unit area exposed normal to rays of the sun at one astronomical unit (Iqbal, 1983). It is not exactly a constant but it changes slightly by a few tenths of percent over a period of years. It is in the true sense should be called "Solar Factor".

From the beginning of this century solar constant is being computed from the ground based spectral measurements and then extrapolated to their predicted value at the top of the atmosphere by taking into account the depletion in the atmosphere.

More recently, high altitude measurement is carried out with the help of aircraft, balloons and space-probes. The value of constant from the high altitude measurements varies from 1338 to 1368 wm^{-2}. The NASA value of solar constant (NASA, 1970) is based on a weighted average of several values and is

$$isc = 1353 \ wm^{-2}$$

Frolich and Colleagues [Frolich and Brusa, 1981] examined eight solar constant measurements and recommended the revised value

$$isc = 1367 \ wm^{-2}$$

Measurements of these type will continue for many years. Although no significant change is expected in the solar constant but there is some change of its spectral distribution. This radiation that enters the earth's atmosphere forms the basis of the present study.

Solar radiation comming from the sun is attenuated by the earth's atmosphere and it classified broadly by two types (1) Atmosphere without clouds (2) Atmosphere with clouds.

The standard earth's atmosphere consists mainly of nitrogen and oxygen. Clear dry air contains about 70% nitrogen, 21% oxygen, 1% argon and 0.33% carbon-dioxide, by volume. In addition, earth's atmosphere contains water vapour and particulate matter (aerosols, such as soot, dust, water vapour and ice crystals. They are the key factors to produce diffuse radiation from the radiation reaching at the top of the atmosphere. The total atmospheric matter near the earth according to the radiation climatology is classified into three parts (1) dry air molecules. (2) Water Vapour (3) Aerosols. The solar radiation entering into atmosphere is attenuated and diffused by each of these groups. Hence only some portion of radiation gets diffused and rest reaches the earth as direct radiation.

The air molecules, aerosols and water vapour deplete solar radiation by the process known as scattering. Scattering that occurs in the atmosphere is generally of two kinds (1) Rayleigh (2) Mie scattering. Mie scattering takes place when the particle size is in order of the wavelength of incident radiation. Rayleigh scattering occurs when the particle size is smaller than one tenth of the wavelength of light. Rayleigh's solution, in other words, forms one individual case of Mie theory. Rayleigh scattering is applied to the scattering of air molecules which is based on the assumption that particles are spherical, and their diameter is less than 0.2μ. The particle scattered is also independent of one another. Mie scattering is applied to the water vapour and dust particles. Although the size of water molecules are comparable to that of dry air molecules but as they coagulate, they form bigger molecules. Also because of humidity, the size of the particles of hygroscopic nature will grow as a result of condensation of water vapour. Hence the water vapour plays a significant role in Mie scattering. Scattering and absorption in specific bands by different aerosols, water vapour and prominent gases leads to the attenuation of solar radiation. They also diffuse to a large extent and thus create two types of radiation. One the beam or direct radiation and second diffuse radiation. These form the basis of this study which relates them with the pollution parameters like dust,aerosols and sunshine duration.

Solar and terrestrial radiation data are also needed for various purposes. The requirement is generally three fold (1) in engineering design of the collector and storage system (2) to evaluate the collector's efficiency or solar energy system calibration and (3) in research and for short and long term predictions of solar radiation.

The engineering purpose of collector and storage system requires the solar radiation data to select the suitable site among several locations and for designing the most efficient collector and storage system. Radiation climatological data will provide the radiation potential for a site.

The storage system requires information about the persistence of solar radiation greater than the threshold value. The network data should be supplemented by site specific data and actual measurements at the site will be required. It is essential for the design engineer to have predictions of future energy.

To find the collector's efficiency, meteorological parameters required in addition to global radiation, diffuse radiation are the long wave radiation ($L\uparrow$ and $L\downarrow$), temperature (T), wind speed, humidity (h), turbidity (β), cloud amount (N), sunshine duration (S) and the precipitation (P). The frequency distribution of radiation and the spectral distribution are also necessary.

Large amount of data has been collected by many National Meteorological services since IGY in 1957 when global observations of different components of short and long wave radiations were tabulated at a large number of stations in the world. Based on these data and other values from different meteorological parameters, radiation maps of global, diffuse and extra-terrestrial radiation have been prepared on global and national scale.

Sunshine: A study of the distribution of sunshine duration over the Indian peninsula shows that the eastern states comprising West Bengal, Tripura, Assam and Sikkim has a mean daily sunshine between 6.0 to 7.0 hours. The southern peninsula is having sunshine between 7.0 and 8.0 hours. The central peninsula is having 8 hrs sunshine. Western India is having hours of sunshine ranging from 8.5 to 10.0 hours. The northern India is having sunshine between 6.5 and 8.5 hours. The central India is having a range between 7.5 and 8.5 hours. In a year, the north-west central zone receives 3300-3700 hours of bright sunshine and central peninsula receives 2900 hours of bright sunshine.

During cold season, December to March, the highest duration is observed over central India and least over the north and northwest because of the passage of winter disturbances and decrease in length of the day with latitude. With the change of season the region of clear sky and maximum sunshine shifts from the central to northern part. With the onset of monsoon in June, over the peninsula, the duration is highest over the north western part.

With the withdrawal of monsoon over the peninsula skies become clear in the north and central portion and by November, skies clear again over central India.

Global Solar Radiation (H): Since cloudiness is the main parameter influencing the sunshine and radiation, the distribution of sunshine is expected to be similar to that of sunshine. Eastern zone mean daily global radiation varies from 4.0 to 5.4 KWhm^{-2} day^{-1}. The southern peninsula is having a range of 5.4 to 5.8 KWh^{-1} day.$^{-1}$ The western and northern zone is having a range of 5.6 to 6.4 and 5.4 to 5.8 KWh m^{-2} day^{-1}.

There is a low gradient of radiation intensities on a clear day in winter for the north and high for the south. But the situation reverses for the May-July with the apparent north ward movement of the sun and the onset of the monsoon over the peninsula. During April, the radiation received is high and fairly uniform over the subcontinent. The highest value of over 220 KWh/m^2/month is received in the month of April-June in arid and semi-arid zone of the subcontinent. It is low and fairly uniform again in August (140 KWh/m^2/month) when the monsoon has covered the whole country. The lowest value occurs in July-August and November-February.

On the whole, the global radiation received is 7.5 KWhm^2 day^{-1} or 225 KWh m^{-2} month^{-1} over the arid and semiarid areas in the north and north-west.

Diffuse Radiation : Diffuse radiation distribution matches with the distribution of cloudiness. For the eastern region, the mean daily diffuse radiation varies from 2.4 to 2.6 KWh m^{-2} day^{-1} The southern peninsula is having a range of 2.2 to 2.4 KWh m^{-2} day^{-1} and the western zone having variation from 1.4 to 2.0 KWh m^{-2} day^{-1}. Diffuse radiation in the northern India lies between 1.8 and 2.2 KWh m^{-2} day^{-1}.

Considering the year as a whole 700 KWh/m^2 of diffuse radiation is received over the country with maximum in the extreme south-west and north-east regions where the maximum cloudiness occurs. About 50% of the diffuse radiation occurs during the monsoon months and 30% during the cloud less dusty summer months.

The diffuse radiation as a fraction of global radiation varies widely depending on the cloudiness of the sky. The maximum 77% occurs during June-August and a minimum 17% during the November-February. This implies that as much as 80% of shortwave radiation received is scattered during the monsoon months. In arid and semi-arid regions 20-25% of the global radiation is diffuse even with clear skies. It increases to 35% in June. Delhi receives about 3.5 kwh/m^2/day as diffuse radiation in June.

Direct Solar Radiation : Direct Solar radiation is maximum in winter and minimum in monsoon and summ~~b~~er months, for the same optical airmasses and solar elevations. The lower value in premonsoon months can be attributed to scattering and absorption by dust and aerosols. It is highest when the atmosphere is dry and dust-free. The rain out and washout decreases the dust but increases the water vapour and thus reduces the intensity of solar radiation.

Solar radiation is attenuated in the atmosphere. It is therefore necessary to understand the characteristics of attenuating parameters i.e. wavelength exponent (α) and turbidity (β) and their spatial distributions.

Wavelength Exponent (α) : The southern half of the subcontinent is having 'α' as 1.0 throughout the year. This condition occurs for North India only during the winter months. In summer the value of 'α' falls to zero or becomes negative indicating neutral haze scattering and presence of predominantly large particles.

Turbidity (β): For the whole year, the values of β are higher over the north and central India than over the peninsula. They are highest during the hot, dry summer months and least during the winter for the whole subcontinent (Mani et. al. 1969).

The present dissertation aims at analysing the radiation parameters of Delhi.

Delhi (latitude 28°12′ longitude 77°23′) is selected because of quite good amount of available data. Secondly, Rajasthan, being in proximity to the Union Territory, plays a vital role in Delhi's radiation climatology especially during summer. So one can readily observe the influence of this desert. For, Delhi, winter to summer contrast occurs in humidity and aerosol content. A marked change occurs particularly at the onset of monsoon.

These factors give rise to a peculiar shortwave attenuation at Delhi. All attenuation factors show a pronounced annual trend. Monsoon months show maximum absorption and then decreasing slowly. Aerosol scattering increases steadily from January to June with a significant change during monsoon (Latteu, 1961).

All these factors lead to an interesting annual trend and interrelationships between radiation parameters and attenuation parameter.

The study therefore comprises of (1) Correlation studies between radiative parameters and sunshine duration (ii) interrelationship between the radiative parameters and (iii) the turbidity and its relationship with the radiative parameters.

Correlation between total radiation and sunshine duration was first observed by Kimball (1919) and later Angstrom (1924) gave relationship by taking it as a fraction of a perfectly clear day insolation. This method was followed by Fritz and MacDonald (1949) who based their work on eleven stations in United States to give a different equation. Keeping a view of the problem arising out of the insturments which are unable to record during the period when sun is less than 5° above the horizon. Mateer (1935) incorporated the correction factor for it, to come up with a new correlation. To remove the difficulty in defining a perfectly clear day, Prescott (1940) replaced the perfectly clear day insolation with extraterrestrial radiation. Based on Prescott's equation, many researchers performed regression analysis for different places to compute different values of slope and intercept of the regression equation. Iqbal (1979), Scerri (1982), Andretta et.al. (1962) carried out their work based on Prescott's equation. In India, Modi and Sukhatme (1979) performed similar regression analysis by dividing the country into two zones depending on the winter monsoon characteristics of the places. This regression analysis was performed not only with sunshine but also with cloud amount and precipitation. Rietveld (1978) carefully scrutinised the intercept and slope values of Prescott's linear regression equation to eventually find out that intercept is linearly related and slope hyperbolically related with the mean value of sunshine. Hence he gave a correlation believed to be applicable globally. Some researchers tried to incorporate geographic factors such as latitude and elevation. Glover and McCulloch (1958) incorporated latitude effect whereas Bernet (1965) incorporated the elevation. Hay (1979) introduced ground albedo and cloud cover factor to give site independent correlation. Hay, while correlating, assumed albedo of the cloud free atmosphere to be 0.25 and that of cloud base is 0.6. Taking these two values and using Mateer's elevation correction in sunshine duration, Hay (1979) introduced a new site independent correlation. His method is preferred by Mani and Rangarajan (1982) in India who performed similar regression analysis for 15 stations spread over the country.

Many of the interrelationships between the radiation parameters are worked out by Iqbal (1979) who proposed a linear form of equation based on the data of three Canadian cities. The diffuse radiation in this case was taken as a fraction of total radiation. Later he removed this restriction by replacing the total radiation by extraterrestrial radiation. Hay (1976) generalised the procedure by considering radiation before and after multiple reflections between earth and cloud cover.

Iqbal (1979) gave a regression equation relating beam as a fraction of total radiation to sunshine. Later he replaced total radiation by extraterrestrial radiation to give another relation-ship.

The first to relate the diffuse radiation to total radiation was Parmalee (1954) who performed it for cloudless day. Later on Liu-Jordon (1960) extended it for cloudy day too. Apart from the distinction based on meteorological (cloudless or cloudy) conditions, the correlations between the radiative parameters are categorised in accordance to the type of interval chosen. The first catagory involves hourly, second daily and third monthly average values of the radiation parameters used.

The hourly correlations are expressed as interrelationship of the ratio of hourly diffuse radiation to the hourly global radiation, to K_T, the ratio of the hourly global radiation to hourly extra terrestrial radiation. The correlation of this type is attempted by Boes (1975), Orgill and Holland (1977) and Bruno (1978). Burgler (1977) developed the correlation of hourly global radiation to $K_{\hat{T}}$, the ratio of hourly global radiation to an estimate of hourly "clear" radiation. Randall and Whitson (1977) developed a statistical algorithm to estimate beam radiation.

Daily correlations relating daily diffuse radiation fraction to K_T, the ratio of daily global radiation to daily extraterrestrial radiation H/Ho is worked out by Liu-Jordon (1960) Choudhury (1965), Stanhill (1968) Tuller (1976) and Collares-Pereira and Rabl (1979).

The monthly average daily correlations relating fraction of diffuse radiation to K_T, ratio of monthly-average daily global radiation to monthly average daily extraterrestrial radiation are of two types ; (1) Liu-

Jordon equation (2) Page's Linear regression equation. Liu-Jordon (1960) developed a correlation which is applicable globally based on several station's data with a substantial range of K_T. This correlation was later studied by Klein-Duffe (1976), Iqbal (1979) and Modi-Sukhatme (1979) and found the applicability of the equation although the equation arrived at was not identical owing to the geographic and climatic factors. Page (1940) developed a linear regression equation based on data from ten locations between 40°N and 40°S latitude. Iqbal (1979) further developed it slightly by adding shadow band correction. Collaris-Pereira and Rabl (1980) Vignola and Mcdanials (1984) developed a correlation whose coefficients vary with season.

All the three types of correlations (i.e. hourly, daily and monthly average relationships) differ from each other considerably. The discrepancies are due to variation in instrumentation, measurement techniques, different methods of correlating the data, locational dependence of data or insufficient data (Erbs et.al. 1982) etc.

Turbidity was first systematically defined by

Linke (1922) who considered all the wavelengths which undergo Rayleigh scattering. Angstrom (1964) used RG-2 filters to take only the irradiance band of 0-0.63 b and Scheupp (β) preferred to take only the 0.5 h of the visible spectrum.

Some interrelationships between these three coefficient are established by Katz, Baille and Mermeir (1962). In India, Majumdar et. al (1965) attempted to establish a new index analogous to Linke's paramter with less virtual variation with air mass. The new index of turbidity is defined on the basis of two measurements of direct solar intensity with and without filter. Ramanathan and Karandhikar (1949) carried out a comprehensive study in Delhi to find the effect of haze scattering on the measurements of ozone with Dobson spectrophotometer. Rangarajan (1960) carefully scrutinised the data at Delhi and Pune to conclude that aerosol scattering over India is independent of wavelength and aerosol particles at New Delhi and the particle size distribution of India is different than that of other temperate latitude places. Mani et.al. (1969) observed seasonal changes in Angstrom turbidity for a number of stations in India. The wavelength exponent (α) distribution was also studied.

Krishna Nand and Maske (1983) observed seasonal variance of the turbidity index over India with Volz sunphotometer.

Relationship between turbidity and radiative parameters has been found by many authors. But most of them are either too elaborate in computational procedures or not accurate enough. Among them Braslan and Dave's model (1972) fits best. Hoyt's model (1978) incorporates Rayleigh's and dust scattering. This model is preferred by Mani and Rangarajan (1984) to estimate turbidity from nomogram based on formula relating β to the ratio of diffuse and direct radiation.

CHAPTER - II

MATERIALS AND METHODS

This study is designed to understand the nature of atmospheric constituents which attenuate and determine the solar radiation received ultimately at the ground. Secondly, the study aims to determine the long term trends in the transmission and attenuation of solar radiation.

Keeping these in view, three radiation parameters namely, global, diffuse and direct radiation were chosen. Sunshine duration and two extinction/attenuation or pollution parameters i.e. wavelength exponent (α) and the turbidity (β) were also taken into account.

Radiation and sunshine duration data for five years (1983-87) of Safdarjung, New Delhi were collected from India Meteorological Department. Available Volz sunphotometer data for one and half years (1987-88) were collected from India Meteorological Department to compute the wavelength exponent (α) and the turbidity factor (β).

Global Radiation:

Global Radiation consists of (a) the beam or direct radiation and (b) the diffuse radiation. Infact, it is the total incoming shortwave radiation hence often known as Insolation. This is generally measured with a thermoelectric pyranometer coupled to a recorder - either a strip chart or an integrator printer. The pyranometer consists of thin blackened surface i.e., a black body supported inside a relatively massive well polished case. When exposed to the solar radiation, the black surface temperature rises until its rate of loss of heat is equal to the rate of gain of heat. This rise of temperature sets up a thermo electromotive force (e.m.f.) The thermo e.m.f. is caused by the temperature difference of the black surface and the well polished case which is kept at ambient temperature by the massive body of the case. Maintenance of the ambient temperature is achieved with the help or gaurd plate which covers it from direct radiation.

A pyranometer measures the incoming shortwave radiation from a solid angle of 2 π stardians i.e., a hemisphere. This has a linear thermal response throughout the range so that the electrical output is directly related to the radiation input. It has relative freedom from the thermal effect so that the cal~~l~~ibration factor is only a small function of temperature of the observing instruments. It has uniform spectral response across the whole range of wavelengths so that the calibration factor does not depend on the precise solar energy spectrum. It has accurate cosine response so that the instrument gives an accurate output to the radiant inputs that are incident on the surface obliquely, i.e.

$$H_s = \cos i.$$

Where H_s = Irradiance on the surface
H_n = Irradiance normal to the solar beam
i = Angle of incidence.

It should have the relative freedom of azimuth effects i.e., instrument should read the same readings regardless of the direction from which solar radiation is incident. Finally, it has freedom from weather effects due to wind. So, in accordance to the last requirement, the thermopile surface is protected from wind and temperature by a pair of high quality optical glass domes. These domes are double grazing i.e, which do not modify the incoming radiation to much amount. The black thermopile surface is obtained by using durable optical black paint.

Lastly, the instrument is to be levelled for accuracy especially at low solar altitude. (Page, J.K. 1979).

The above discussion points out that the global radiation measurements involve lot of complications. In order to obtain global radiation from easily measureable parameters, global radiation is correlated with sunshine duration which is much more easier to measure.

In this approach, the monthly average daily radiation was used as a fraction of extraterrestrial radiation. This fraction is correlated with different parameters including the sunshine duration. These relations signify the importance of global radiation. It is also expected to give a long term trend apart from giving an estimation of unknown parameters from the basic relation relating them. This can be computed by substituting the values of known parameter to find the unknown. A good relation is necessary with all other parameters to serve this purpose.

Direct or Beam Radiation:

Direct or beam radiation is the radiation incident normally from the Sun. Instrument for the measurement of direct radiation is called pyrheliometer. A pryheliometer is a device to study the input of any focussing system. The direct rays are associated with any area of sky of higher radiance, mainly due to forward scattering. This circumsolar sky radiation may also be focussed. The best way is to use a standard meteorological aperture of the pyrheliometer to the collector. If the aperture is too small, instrument alignment problem arises. If it is wide or big, it allows too much circumsolar sky radiation to study the properties of direct solar radiation. The blackened absorbing surface of collector (thermopile) must have uniform absorptance over the entire solar specturm. The most widely used instruments are the Line Feussner Actinometer which has a diaphragmed aperture angle $10^{\circ}12'$ and the temperature sensitivity of about -0.2% per degree celsius. (Page, J.K, 1979)

Second one is known as Eppley's normal incidence pyrheliometer with a narrow aperture of $5^{\circ}43'$ and a temperature dependence of 1% over the ambient temperature range -20°C to 40°C. A thermo resister temperature compensating circuit is in the heat sink of the thermopile. Both are relative instruments requiring accurate calibration against a radiation standard before setting in use. (W.M.O. 1957).

The beam or direct radiation in this study is based on a ratio of both global radiation (H) and the extraterrestrial radiation (H_o). These ratios are correlated with a number of other parameters in order to obtain a long term trend. An attempt is also made to estimate the values of radiation.

Diffuse Solar or Sky Radiation :

When the solar radiation enters the atmosphere, it is scattered by air molecules and aerosol particles to yield diffuse radiation. This diffuse radiation is due to two types of scattering. Firstly, the primary scattering which takes place because of the first interaction with the air molecules and aerosol particles. Secondly, the multiple scattering, which takes place by the numerous scatterings of the same ray by different particles. The contribution in the generation of diffuse radiation is maximum by the primary scattering. (Iqbal, 1983).

There are three methods of obtaining diffuse radiation on a horizontal surface. The first is to combine the observations of pyrheliometer with those made with global pyranometer. Using Cosine Law and assuming the cosine response of the pyranometer the diffuse radiation can be estimated. The estimation is made by taking the difference between the measured global radiation and the resolved component for the horizontal surface of the direct beam irradiance obtained by the pyrheliometer. The second method of measuring diffuse radiation is by shading ring method. In this method, one shades the horizontal surface pyranometer with a movable occulating disc. The occulating disc is chosen to have same shading area as a standard pyrheliometer would have been used in that place. The disc is rotated on a equitorial mount to follow accurately the motion of the sun to record the diffuse radiation only. The advantage of occulating disc is that it covers only a very small portion of the sky. So no correction is needed for the obstructed sector of the sky. The main problem lies in devising an instrument which will help the disc to give accurate shading. The third method which is widely used is the method of shading band. In this case, the shading is done by mounting a band on a pyranometer so that sun's rays do not fall directly on the pyranometer. The advantage of shading band is that no mechanical moving parts are necessary. The disadvantage is that the instrument is to be adjusted daily with the change in the sun's declination. But the greatest disadvantage lies in the errative assumption of considering sky of a uniform radiance. The sky radiation is in fact having very strong non isotropic effect which ultimately gives the error in the data. (Steren, W. 1980). The diffuse radiation forms about 17 percent of global radiation on a clear day and can be as high as 35 percent with hazy sky and 80 percent during monsoon months. (Mani and Rangarajan, 1983).

The diffuse radiation is expressed as a fraction of global radiation (H) and used in the study. Some correlations are made with other parameters to understand the role of diffuse radiation in the radiative processes in the atmosphere. An estimation of diffuse radiation values was attempted. Same attempt was made regarding the establishment of some global radiation equations under this terrain conditions. Likewise attempts were made by taking the diffuse radiation as the fraction of the extraterestrial radiation (H_o).

Sunshine Duration :

The number of hours of sunshine is a very important parameter which determines the amount of solar radiation reaching the earth's surface. There are two types of sunshine duration sensors namely focussing type and photovoltaic types.

The focussing type is the Campbell-Stokes sunshine recorder. It consists of a solid polished sphere of precision optical glass. It is mounted on a brass-bowl with grooves to hold the recorder cards. The sphere burns a trace on the card which is held always at the focal length of the spherical lens when exposed to the sun. The length of the trace is a direct measure of duration of bright sunshine. The major drawback with this instrument is the effect of humidity on cards and its ability to establish a fixed threshold level of radiation. Under very humid conditions, burn may not begin until the threshold level is 280 Wm^{-2} while in very dry climates it may begin at 70 Wm^{-2}.

The sunshine hours expressed as a fraction of possible sunshine hours (S) can be obtained from

$S = \bar{n} / \bar{N}d$

Where '$\bar{n}$' is the monthly average number of instrument recorded bright sunshine hours per day, and

'$\bar{N}d$' is the average day length.

For a given month, the average day length can be obtained from

$$\bar{N}d = \frac{1}{(n_2 - n_1)} \sum_{n=n_1}^{n_2} [\frac{2}{15} \cos^{-1} (- \tan\phi \tan\delta)] \quad \cdots (1)$$

Where 'n_1' and 'n_2' are day numbers at the beginning and end of the month.

'ϕ' is the latitude of the station, and

'δ' is the declination.

Assuming the sunshine hour angle is equal to the sunset hour angle except for the sign difference, the average day length becomes :

$$\bar{N}d = \frac{2}{15} \cos^{-1} (-\tan\phi \tan\delta_c) \quad \text{[Iqbal,1983]} \cdots (2)$$

where 'δ_c' is the characteristic declination.

This method is particularly suggested by Iqbal (1979) for establishing correlations between sunshine duration and other radiative parameters.

Wave Length Exponent (α) and Turbidity Coefficient (β) :

It is well known that there is always some difference in sun's intensity at the top of the atmosphere and down at the ground. This depletion of solar radiation intensity can be partly attributed to the particulates present in the atmosphere. Conversely it can be said turbidity is partly responsible for this depletion. The essence of this study lies in the fact that one can relate a radiation parameter to a pollution index. Not much is done either in instrumentation or in clearly defining the parameters so far.

Turbidity is a measure of the total vertically integrated particulate load in the atmosphere. (Mani et.al. 1984). It is a useful parameter influencing the incoming solar radiation flux and is a measure of the amount of air pollutants.

The wave length exponent 'α' is a measure of the particulate size distribution, 'α' can vary from 0 to 4 but in practice it falls between 0.5 and 3.0 In many cases, it is considered as a constant. More details are given while defining the Angstrom turbidity Coefficient. (Mani, Rangarajan, 1983).

Linke (1922) first defined a turbidity parameter (T) indicating the number of standard atmospheres of pure and dry air which produces the same depletion or give rise to the same intensity of direct radiation as in given turbid condition. This is based on the consideration that scattering and absorption by pure, dry air is the basic atmospheric effect (Majumdar et.al.) Therefore, Linke factor, T, can also be defined as the ratio of mean extinction coefficient to the mean Rayleigh extinction coefficient.

$$T = \bar{a} / \bar{a}_R \text{ (Karz et.al., 1982) } \cdots\cdots (3)$$

But this Linke's parameter is having one disadvantage i.e. even under constant turbidity, 'T' was found to exhibit diurnal variations or the virtual variation with airmass. One can say that 'T' is not strictly independent of airmass. This is ascribed to the dependence of extinction coefficient on wavelength of radiation (Robinson, 1966). In order to eliminate the effect of water vapour which Linke's factor has taken care of, Angstrom introduced the Scott red filter RG-2 having transmission from 0.63 to 2.8 μm. This accounts for two basic effects i.e. moleculer or Rayleigh scattering and scattering due to aerosols.

Angstrom (1929, 1930) gave an empirical relationship relating extinction coefficient 'a_{D_λ}' with wavelength

'$a_{D\lambda}$' in the form:

$$a_{D\lambda} = \beta \lambda^{-\alpha} \text{ .... } (4)$$

Voltz (1956) and Angstrom (1961) found that $\alpha = 1.3 \pm 0.2$ can be taken as average value and when substituted in the equation (4) we get.

$$a_{D\lambda} = \beta \lambda^{-1.3} \text{ .... } (5)$$

But it is erroneous to take 'α' as a constant for tropical country like India and the present study also does not confirm this hypothesis. The approach taken for computing 'α' and 'β' is as follows.

The basic equation used for computing the extinction coefficient '$a_{D\lambda}$' is of the form.

$$a_{D\lambda} = \log \frac{I_{o\lambda}}{\frac{I_{\lambda} s}{m_n}} - (a_{R\lambda} + a_{z\lambda}) \frac{P}{P_o} \quad \ldots \quad (6)$$

Where,

$I_{o\lambda}$ is the extra terresterial intensity for the wavelength 'λ' at mean sun-earth distance

I_{λ} is the intensity at wavelength 'λ' observed.

m_h is the relative airmass

$a_{R\lambda}$ Rayleigh extinction coefficient

$a_{z\lambda}$ is the absorption coefficient of Ozone

S is the reduction factor for mean solar distance

P is the surface pressure at the station

P_o is the mean sea level pressure

The instrument measuring the turbidity is called Sunphotometer. Sunphotometer does not give the actual solar intensity but a meter reading 'J ' which is proportional to the intensity. The calibration constant of the instrument '$J_{o\lambda}$' is taken in such a way to give the extra terresterial intensity '$I_{o\lambda}$' respectively to get.

$$a_{D\lambda} = \frac{\log \frac{J_{o\lambda}}{J_{\lambda}S}}{m_h} - (a_{R\lambda} + a_{z\lambda}) \frac{P}{P_o} \quad .... (7)$$

One can ask the purpose of 'm_n' the relative airmass and the pressure 'P' in this equation. The answer is in the difinition itself. Relative airmass is defined as the ratio of the optical path along with the oblique trajectory, to the vertical path in the zenith direction (Iqbal, 1983). So, one can see that this ratio gives the relative distance the light has travelled. The ratio of the station level pressure (P) to the sea level pressure (P_o) gives the total height of the air column. ~~The ray travelled to reach the ground~~. Combining these two definitions one can see that the former gives direct information about the total distance travelled by light and the latter gives the total length at which depletion can occur. The volz twin filter sunphotomer used in this study had two selective wavelengths or filters i.e. 640 nm and 440 nm. The Rayleigh extinction coefficient ($a_{R\lambda}$) and absorption coefficient of Ozone ($a_{z\lambda}$) were taken from the standard tables. The relative airmass (m_h) is calculated as a function of the apparent solar height. Corresponding pressure is measured. By taking these readings, i.e. pressure, meter deflection and relative airmass the values of 'α' are obtained after computing 'α' by using following equations.

$$\alpha = \frac{\log a_{D\lambda_1}/a_{D\lambda_2}}{\log(\lambda_2/\lambda_1)} \quad \ldots\ldots\ldots (8)$$

This 'α' was latter used to compute 'β' by calculating first 'B_1' from

$$B_1 = a_{D\lambda_1} \; x'(2\lambda_1) \quad \ldots\ldots\ldots (9)$$

and then 'β' by using following relationship :

$$\beta = B_1/2 \quad \ldots\ldots\ldots (10)$$

These values of 'β' are also correlated with other factors. After computing and tabulating each parameter, an attempt has been made to correlate these parameters to determine the degree upto which these relationships are reliable. The objective is also to compare the results of the present study with the earlier studies. Keeping these objectives in view, following methods are identified.

a) Correlating the Average Daily Global Radiation with the Hours of Sunshine :

Since it is a known fact that more sunshine will yield more insolation and vice-versa, there has to be a direct relationship with the number of sunshine hours and the insolation.

Kimball, (1919), and Angstrom (1924) studied the relation between sunshine hours and the average daily global radiation. Angstrom found out the following relationship.

$$\bar{H} / \bar{H}_o = a_1 + (1-a_1)\ S$$

$$= a_1 + b_1\ S \ \ldots\ldots\ldots\ldots \ (11)$$

Where H is perfect clear day horizontal insolation and S the monthly mean daily fraction of possible sunshine obtained from

$$S = \bar{n} / \bar{N}d \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (12)$$

Where n = monthly average number of instrument recorded hours of bright sunshine per day.

$\bar{N}d$ = Average day length which can be calculated from

$$\bar{N}d = \frac{1}{n_2 - n_1} \sum_{n=n_1}^{n_2} \left[\frac{2}{5} \cos^{-1} (-\tan\phi + \tan\delta) \right] \qquad ..... (13)$$

Where n_1 and n_2 are the number of days at the begining and end of the month, ϕ is the latitude of the location and δ is the declination. $\bar{N}_d$ is calculated in this case by replacing 'δ' by 'δ_c' i.e., the characteristic declination of that month. This 'δ_c' or characteristic declination is the declination at which the extraterrestrial irradiation is identical to monthly average value. Characteristic declination varies slightly with the latitude. So the characteristic declination is calculated from the table based on 35° N latitude and substituted in the following relationship to compute the values '$\bar{N}_d$'

$$\bar{N}d = \frac{2}{5} \cos^{-1} (-\tan\phi \ \tan\delta_c)$$

(Iqbal, 1983)

.... (14)

a_1 and b_1 are empirical coefficients obtained from regression analysis using measured value of H and S.

But the main problem with the eq. (11) is to define the perfectly clear day from which to calculate $\overline{H}$. Therefore, Prescott (1940) and others modified the equation by replacing H by extraterrestrial irradiation, equation (11) gets modified to

$$\overline{H} / \overline{H}_o = a + b\ (\overline{n} / \overline{N}_d)$$
$$= a + b\ S \ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

This equation is used in the present study by computing $\overline{H}_o$, the extraterrestrial radiation, from the standard table for the particular latitude.

In this relation, it can be seen that $\overline{n}/\overline{Nd}$ becomes zero under overcast conditions. This in fact implies that 'a' is a measure of the global radiation received at the ground through an overcast sky as a fraction of extraterrestial radiation. The coefficient 'b' shows the rate of increase of $\overline{H}/\overline{H}_o$ with increase of $\overline{n}/\overline{N}_d$. So the magnitude of 'a' should be depending on the type and the thickness of prevailing clouds and 'b' on the transmission characteristics of cloud-free atmosphere. The value of 'a' varies from 0.14 to 0.54 and that of 'b' from 0.18 to o.73. But remarkably the values of (a+b) or transmitivity is constant for a location. So if the values of 'a' increases for a set of years, the values of 'b' should decrease and vice-versa. The sum assumes the values ranging from 0.65 for a moist turbid atmosphere to 0.8 for dry and dust-free atmosphere. (Mani and Rangarajan, 1983).

In this correlation, knowing 'a' and 'b' one can estimate the values of H or the average daily global radiation for any location provided the sunshine hours are available.

After finding the regression coefficients, the correlation coefficient (r) is found out to establish the validity of the estimation method of the global radiation. The coefficient of determination (r^2) and standard error are found out to further confirm the result.

b) Correlation of Diffuse Radiation with Sunshine Duration:

Both sunshine duration and the fraction of diffuse radiation are dependent on the cloud cover hence the relationship between them can be established.

Iqbal (1978) expressed the average horizontal diffuse radiation as a fraction of maximum possible sunshine hours as

$$\bar{H}_d/\bar{H} = (1 - \frac{\bar{n}}{\bar{N}_d}) \ldots\ldots\ldots\ldots \quad (16)$$

Where $\bar{H}_d$ is the monthly average daily diffuse radiation

$\bar{H}$ is the monthly average daily global radiation

$\bar{n}$ is the average number of bright sunshine hours per day and

$\bar{N}_d$ is the monthly average day length.

The eq (16) can be written as

$$\bar{H}d / \bar{H} = c + d (\bar{n} / \bar{N}_d) \ldots\ldots\ldots \quad (17)$$

where it was assumed that C = + 1 and d = -1. In practice, the values of 'c' and 'd' were obtained by regression analysis

The correlation coefficient (r), coefficient of determination (r^2) and the standard error are determined.

As discussed earlier sometimes problem arises in measuring H or the monthly average daily global radiation. To eliminate this, following equation relating H with sunshine was used to find the empirical relationship between diffuse radiation and sunshine duration

$$\bar{H} / \bar{H}o = a + b\ (\bar{n}/\bar{N}_d) \ldots\ldots\ldots\ldots (18)$$

This relation given by Angstrom (1924) is critically reviewed by Schulze (1976) particularly the estimation method.

Multiplying equation (17) with eq. (18) we get

$$\bar{H}_d/\bar{H}_o = a_1 + a_2\ (\bar{n}/\bar{N}_d) + a_3\ (\bar{n}/\bar{N}_d) \ldots (19)$$

(M. Iqbal, 1979)

This equation is solved by method of least squares and the standard error is found out.

c) Correlation of Beam Radiation with Sunshine Hours:

As in the case of diffuse radiation, the fraction of beam radiation also can be correlated with the sunshine hours. The beam radiation is taken as the difference between the global and the diffuse radiation. (Iqbal 1983). Both global and diffuse radiations are functions of sunshine hours. Hence the beam radiation i.e., their difference should also be a function of sunshine hours.

The average beam radiation on a horizontal surface is

$$\bar{H}b = \bar{H} - \bar{H}_d \ldots\ldots\ldots\ldots (20)$$

Substuting this in equation (17) one gets

$$\frac{\bar{H} - \bar{H}b}{\bar{H}} = C + d\left(\frac{\bar{n}}{\bar{N}_d}\right)$$

$$1 - \bar{H}b/\bar{H} = C + d\,(\bar{n}/\bar{N}d)$$

$$\text{or } \bar{H}b/\bar{H} = J+K\,(\bar{n}/\bar{N}d) \;\ldots\ldots\ldots\ldots\; (21)$$

Again dividing the original equation by Ho

$$(\bar{H} - \bar{H}d)/\bar{H}o = \bar{H}/\bar{H}o - \bar{H}d/\bar{H}o \;\ldots\ldots\ldots\; (22)$$

Inserting in eq. (21) and (19) in the right side of (22) one gets.

$$\bar{H}b/\bar{H}o = a_8 + a_9\,(\bar{n}/\bar{N}d) + a_{10}\,(\bar{n}/\bar{N}d)^2 \;\ldots\ldots (23)$$

(Iqbal, 1979)

Using Gaussian-Newton least square technique of curve fitting, the coefficients a_8, a_9, a_{10} are found out. The standard error is also estimated.

d) Correlation between Diffuse Radiation and Global Radiation

On a cloudy day, the global radiation received is an indication of the extent of cloudiness and hence should be an indicator of diffuse radiation. So, for a location, the parameter $K_T = H/H_o$ is an indicator of clearness, can be related to the fraction of diffuse radiation, K_d where $K_d = H_d / H_o$ (. Iqbal 1983). This relation based on daily values can be extrapolated to monthly averages. So, the fraction of monthly average of the diffuse radiation $\overline{K}d$ Where $\overline{K}_d = \overline{H}_d / \overline{H}$ can be related to the fraction of global radiation $\overline{K}_T$, where $\overline{K}_T = \overline{H}/\overline{H}_o$.

Using data for ten widely spread sites located between 40^o N and 40^o S, Page (1961) arrived at a linear relation

$$\overline{H}_d/\overline{H} = 1.0 + 1.13\ \overline{K}_T \ \ldots\ldots\ldots\ldots \quad (24)$$

Where $\overline{K}_T = \overline{H}/\overline{H}_o$ is the cloudiness Index.

Liu-Jordon (1960) gave a new dimension to the whole approach by generalising this distribution. He used global data to obtain a relationship of the form

$$\overline{H}_d/\overline{H} = A_1 - A_2\overline{K}_T + A_3\overline{K}_T - A_4\overline{K}_T \text{ (Liu-Jordon, 1960)} \ldots (25)$$

The present study is to examine the validity of this equation in this condition with the help of available data using Gaussian - Newton Least Square method.

e) Correlation between Turbidity and Radiation Parameters :

Solar radiation gets depleted as it passes through the earth's atmosphere. The particulate load causing this depletion, as already mentioned, can be termed as turbidity. As discussed earlier, not much work has been done in the field of instrumentation for measuring the turbidity. The present available insturmentation has one great disadvantage. The sunphotometer used to measure the turbidity cannot be used during too much of hazy and cloudy months. Therefore in monsoon months it practically becomes non-operative. But radiation measuring instruments are operative round the year with no such restrictions. So, here an attempt is made to observe any kind of relationship with the turbidity and the radiation parameters. This attempt is based on the study of Mani and Rangarajan (1983) who estimated turbidity from the ratio of diffuse radiation to the beam radiation. They observed a linear relationship between them. In the present study also regression analysis is made to substantiate the earlier results.

f) Annual Variation of Wavelength (alpha) and Turbidity Coefficient (beta) :

As discussed earlier on Angstrom's (1963) assumption to have a constant value of 1.3 was verified here. The values of 'β' are added to give a monthly average. This procedure is followed for each month. Annual variation of alpha is then observed. Similarly, for turbidity coefficient, the daily values are added to give the monthly averages. Annual variation of turbidity as well as periods of differing turbidity are observed and suitable physical explanations are proposed for the variations.

CHAPTER III

RESULTS AND DISCUSSION

Correlation Between the Global Radiation and Sunshine Duration:

The regression equation according to Prescott (1940) is

$$\bar{H}/\bar{H}_o = a + b\ (\bar{n}/\bar{N}_d)$$

Where

$\bar{H}$ = Monthly average caily global radiation

$\bar{H}_o$ = Monthly average daily extraterestrial radiation

$\bar{n}$ = Average number of instrument recorded bright sunshine per day

$\bar{N}_d$ = Average day length.

and 'a' and 'b' are regression constants

For Delhi

$$\bar{H}/\bar{H}_o = 0.4065 + 0.3387\ (\bar{n}/\bar{N}_d) \qquad (26)$$

For this author, 'a' was found out to be 0.4065 and 'b' to be 0.3387. In other words the global radiation received under overcast condition as the fraction of extraterrestrial radiation (ETR) came to 0.4065 and the rate of increase of global radiation with respect to ($\bar{n}/\bar{N}d$) be 0.3387. (a+b) or transmittance is 0.7452.

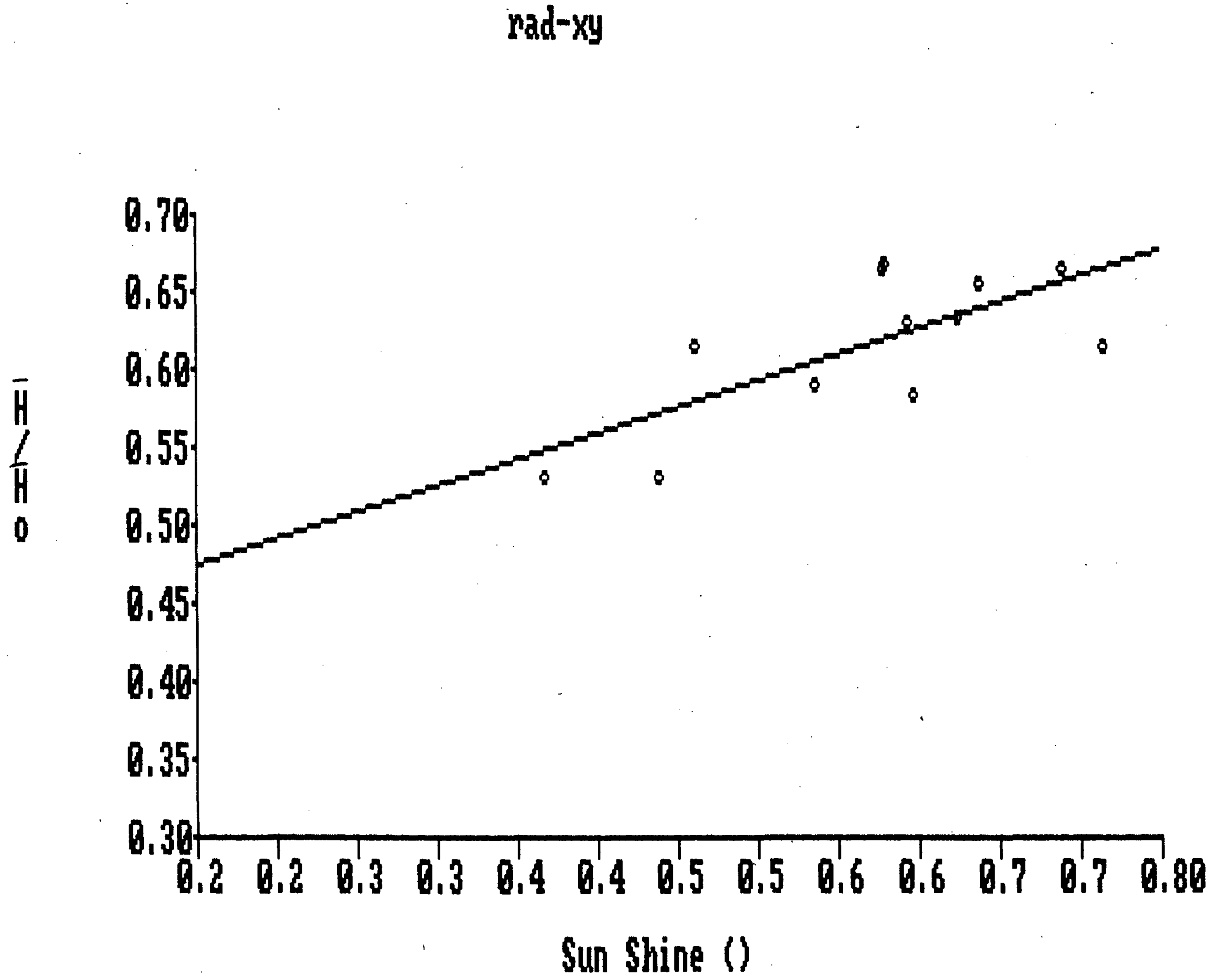

rad-xy
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
$\bar{H}/H_o$
0.2
0.2
0.3
0.3
0.4
0.4
0.5
0.5
0.6
0.6
0.7
0.7
0.80
Sun Shine ()

Fig. 1

It is not the 'a' and 'b' which are site specific but (a+b) which remain characteristic of a place over the years. This is confirmed by comparing the present values with those obtained by Mani and Rangarajan (1981). The values of 'a' and 'b' obtained by them for the same site were 0.256 and 0.434 respectively. Although they are quite different individually but their sum is equal to 0.71 which is comparable to the present author's value. This unique characteristic of constant sum attests the reliability of the data used.

Iqbal 1979), deduced the constants 'a' and 'b' for several U.S. and Canadian cities.

Table

Station	a	b
Resolute	0.319	0.683
Bergen	0.175	0.633
Trappes	0.219	0.468
Montreal	0.295	0.371
Carpentras	0.313	0.386

By comparing these results with the present study one can observe that (a+b) values of Carpentras are closest. The reason for this proximity is attributed to the monthly average hours of bright sunshine (Yorke and Kendall, 1983 In: Solar Radiation). In this study Carpentras with 2773 hrs is the closest to that of present site. Another interesting thing one observes is that (a+b) is maximum for Resolute than for any other site. Although there is no sun shine during first two months for this place, both H/Ho and sunshine hours abruptly increase for six months and drop down to zero for next four months. So, these phenomenon give rise to this peculiar behaviour of high (a+b) value. The high values of (a+b) observed at Resolute and Bergen indicate their dry and dust free atmosphere. Though (a+b) values of Resolute is not in confirmity with the limit drawn by Anna Mani & Rangarajan (1983) but it can be attributed to the prevailing climatic condition of that location.

Andretta et.al. (1982), from global radiation and sunshine duration data for Italy, found a regression equation of the form

$$\bar{H}/\bar{H}o = 0.23 + 0.37\ (\bar{n}/\bar{N}d) \qquad (27)$$

This regression equation is valid for Italy as a whole. Individual analysis for 25 cities yielded this form of the regression equation. The individual (a+b) values of each site is found to be between 0.5 and 0.7. This gives an idea of moist and turbid atmospheric condition prevailing at the place. It also shows that the transmittance of Italy's atmosphere is much lower than that of Delhi.

Biga and RUI Rosa (1979) carried out similar analysis for Lisbon and arrived at a regression equation of the form

$$\bar{H}/\bar{H}o = 0.24 + 0.52\ (\bar{n}/\bar{N}d) \qquad (28)$$

One can observe here also that the (a+b) is 0.76 which is comparable to the present study. It may be inferred also that the radiation climates of these two places are similar, for both of them are having same type of dry and hazy climate.

Scerri (1982) found out for Malta, relationship between $\bar{H}/\bar{H}o$ and $\bar{n}/\bar{N}d$

$$\bar{H}/\bar{H}_o = 0.254 - 0.498\ (\bar{n}/\bar{N}d) \qquad (29)$$

No physical explanation could be given to the negative slope in the equation as it is contrary to the basic concept. Ibrahim Said (1985) correlated $\bar{H}/\bar{H}_o$ and sunshine for seven Egyptian cities and generalised his result as

$$\bar{H}/\bar{H}_o = 0.32 + 0.43\ (\bar{n}/\bar{N}_d) \qquad (30)$$

The sum of (a+b) in this case also is 0.75 which reflects the dry and hazy conditions of the location. This value is comparable to the author's result showing similarity between Delhi's and Egypt's climate

In India for 8-21 years data, regression analysis was performed and the values of 'a' and 'b' were tabulated (Mani and Rangarajan, 1982) It may be interesting to note that the individual values of 'a' vary between 0.24 to 0.3 and the values of 'b' lie within 0.4 and 0.46. But in the present study the individual values of 'a' and 'b' are quite different. This further shows that the individual values of 'a' and 'b' are also dependent upon the group of years taken into account. Therefore, it is (a+b) value which characterises the site but not the individual values of 'a' and 'b'. Another interesting observation is that the (a+b) values for a vast country like India lie within a small range or 0.68 and 0.71. This small variation of (a+b) can be attributed to the average over a large number of years taken. This gives scope for further investigation of this aspect.

As already stated (a+b) value of the present study is close to that of Mani and Rangarajan (1982) but they are not equal. This difference may be due to the methodology adopted to calculate the average day length. Mani and Rangarajan (1982) followed Hay's (1979) method i.e. average day length or '$\bar{N}d$' is taken as a

$$\bar{N}d = \frac{\text{arc Cos}\left(\dfrac{\cos 85^{\circ} - \sin\phi \sin\delta}{\cos\phi \cos\delta}\right)}{7.5}$$

But $\bar{N}d$, in the present study, is based on characteristic declination.

Secondly, the method adopted to find extraterrestrial radiation is different from that of Mani and Rangarajan (1982).

Modi and Sukhatme (1979) carried out the studies all over the subcontinent and divided it in two zones. Delhi lies in zone II with the values of which a comparison has been made.

For the zone II Modi and Sukhatme (1979) found out the following relationship.

$$\bar{H}/\bar{H}_o = 0.412 + 0.334\ (\bar{n}/\bar{N}_d) \qquad (31)$$

One can observe that even the values of 'a' and 'b' coefficients and obviously the (a+b) values for this zone which is 0.744 are the same as that of the present results. Further it shows that though 'a' and 'b' coefficients change with the group of years taken, (a+b) values remain constant irrespective of all other factors.

Also based on the study of Modi and Sukhatme (1979) one may conclude that this result is valid for all the places which fall under zone II i.e. Ahmedabad, Bhavnagar Goa, Jodhpur and Poona. It is valid even for the radiation conditions of Pakistan. For zone I, Modi and Sukhatme (1979) obtained following relationship.

$$\bar{H}/\bar{H}_o = 0.429 + 0.27(\bar{n}/\bar{N}d)$$

Even this is comparable to the present result. The comparability of results gave inspiration in the present study to try to find out whether the global data satisfying empirical relationships like Liu-Jordon (1960) is valid for the present set of data or not.

To substantiate the result statistically, correlation coefficient (r) between global radiation and sunshine duration, coefficient of determination (r^2) and standard error were determined for equation (26). The correlation coefficient (r) was found to be 0.7174 and the coefficient of determination (r^2) was 0.515. In comparison to the present result, the correlation coefficient (r) and coefficient of determination (r^2) of Mani and Rangarajan (1962) were as high as 0.87 and 0.760 respectively. This perhaps may be because of the analysis performed involving data for quite a large number of years. The bias of difference, variance with the estimated value and the Mean Square error (M.S.E.) in the present study are as low as 0.0035. 0.0368 and 0.0011 respectively. Standard error obtained by Mani and Rangarajan (1982) was 0.042.

The mean percentage error found out by Modi and Sukhatme (1979) was 2.3 for zone I and 2.6 for zone II.

Broadly one can easily say that the result obtained is valid for the present site and statistical analysis of the data confirms the estimation method.

An attempt was also made to examine the applicability of Rietveld equation which is supposed to be globally applicable.

$$\bar{H}/\bar{H}_o = 0.18 + 0.62\,(\bar{n}/\bar{N}d) \qquad (32)$$

For the above equation, the test for finding standard error has been performed. It shows a bias of difference and the variance from the estimated value to the 6.495

$\times 10^{-2}$ and 2.4×10^{-5} and average absolute gross error to be 7.14×10^{-2}. The mean square error is 6.447×10^{-3}. Hence, it can be concluded that Rietveld equation is applicable for Delhi too.

Correlation Between Diffuse Radiation and Sunshine Duration

Regression analysis gives equation of the form

$\bar{H}d/\bar{H} = c - d\,(\bar{n}/\bar{N}d)$ [Iqbal, 1979]

Where

$\bar{H}d$ = Monthly average daily diffuse radiation

$\bar{H}$ = Monthly average daily global radiation

$\bar{n}$ = Number of instrument recorded bright sunshine hours per day

$\bar{N}d$ = Average day length

and 'c' and 'd' are regression coefficients

The regression equation obtained in the present study is of the form

$$\bar{H}d/\bar{H} = 0.88 - 0.765\,(\bar{n}/\bar{N}d) \qquad (33)$$

One can infer from this equation that 88% of global radiation diffuses under overcast conditions. And the rate of decrease of diffuse radiation is 0.765 with the increase in sunshine duration.

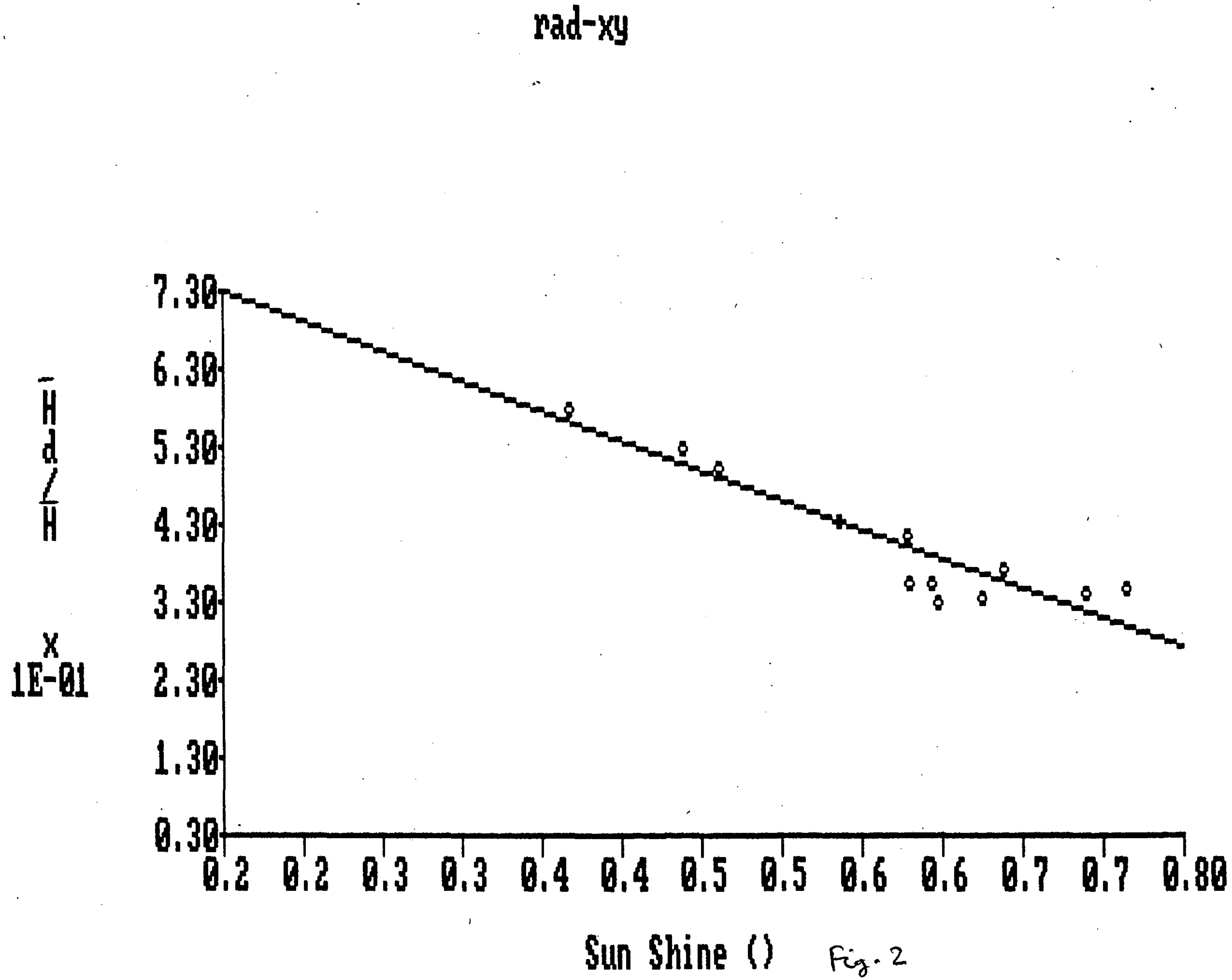

rad-xy
$\bar{H}_d/\bar{H}$
x
1E-01
7.30
6.30
5.30
4.30
3.30
2.30
1.30
0.30
0.2
0.2
0.3
0.3
0.4
0.4
0.5
0.5
0.6
0.6
0.7
0.7
0.80
Sun Shine ()

Fig. 2

Iqbal (1979) found out c and d for three Canadian cities in the range 0.729 to 0.828 and 0.534 to 0.704 respectively. of these cities, Goose Bay is having comparative result with the present value.

The equation obtained by Iqbal (1979) for Canada based on data from three stations is

$$\bar{H}d/\bar{H} = 0.791 - 0.635\ (\bar{n}/\bar{N}d) \qquad (34)$$

One can readily observe that both the diffuse radiation under over cast conditions and the rate of decrease with sunshine duration, are quite less than that of Delhi.

Scerri (1981) from similar analysis for Malta found a regression equation as

$$\bar{H}d/\bar{H} = 0.832 - 0.626\ (\bar{n}/\bar{N}d) \qquad (35)$$

it can be seen that the diffuse radiation fraction is 0.83 which is quite comparable to the present result but the rate of decrease of diffuse radiation is 0.626 which is comparatively quite low. Scerri (1981) replaced '$\bar{H}$' by '$\bar{H}o$' and correlated $\bar{H}/\bar{H}o$ and sunshine and obtained following relationship.

$$\bar{H}_d/\bar{H}_o = 0.385 - 0.215\ (\bar{n}/\bar{N}_d) \qquad (36\ \ )$$

Similar attempt was made for the present site

$$\bar{H}_d/\bar{H}_o = 0.435 - 0.3\ (\bar{n}/\bar{N}_d) \qquad (36b)$$

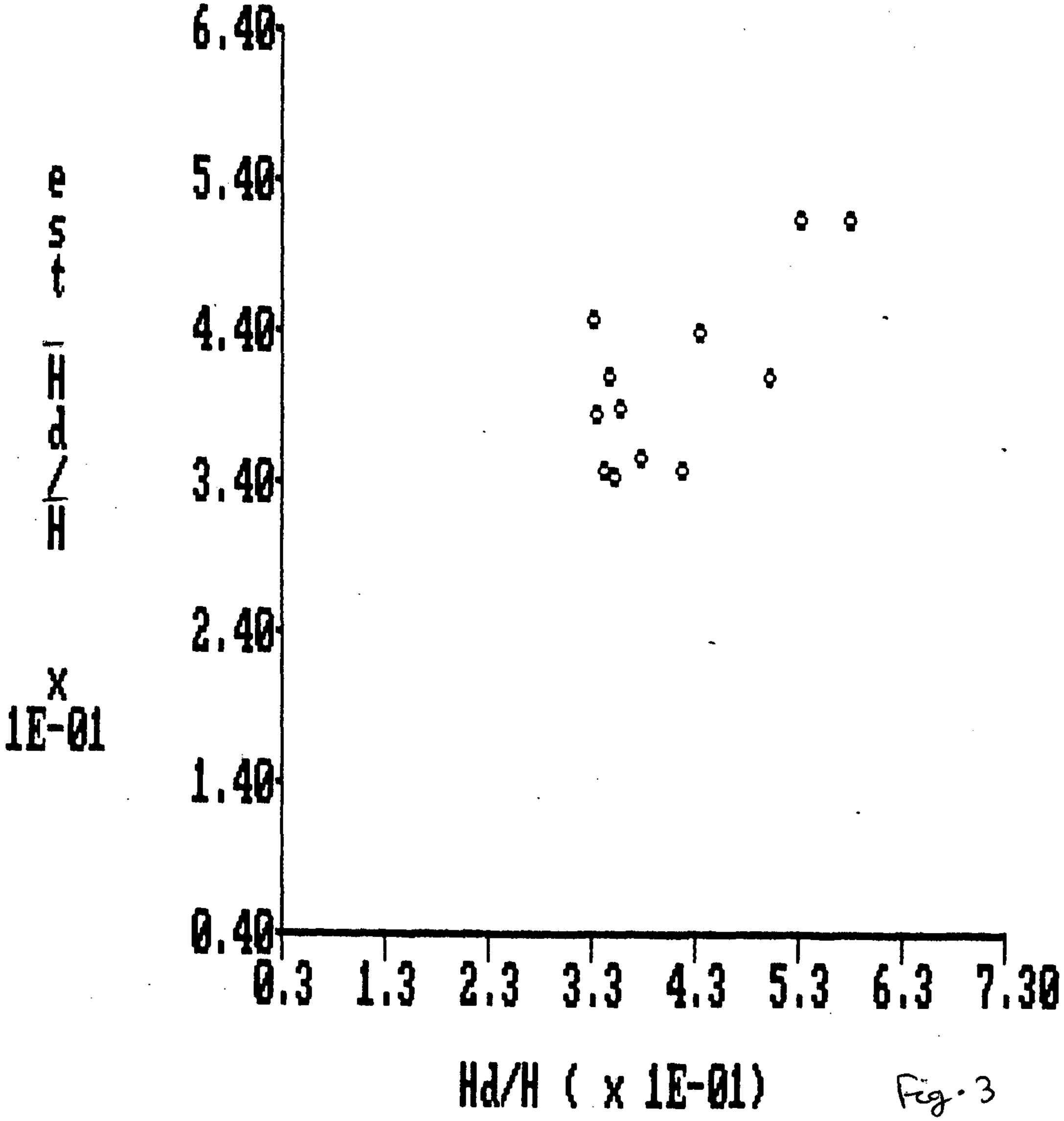

6.40
5.40
4.40
3.40
2.40
1.40
0.40
est
Hd/H
x
1E-01
0.3
1.3
2.3
3.3
4.3
5.3
6.3
7.30
Hd/H (x 1E-01)

Fig. 3

Close scrutiny of the last four equations suggests that the rate of decrease of diffuse radiation at Malta is smaller in comparison to that of . Delhi inspite of having comparable diffuse radiation under over cast conditions. This clearly shows that Delhi is having relatively more turbid conditions than that of Malta.

Correlation coefficient (r) between Hd/H and sunshine was found out to be -0.92 which is quite high. For the same equation, coefficient of determination (r^{-2}) was 0.85. The bias of difference was 4 x 10^{-3} and the variance from the estimated values was 0.0012. Mean square error and average gross error came out to be 0.011 and 2.9 x 10^{-2} respectively.

The statistical analysis shows that the above equation may be used for the prediction or estimation of diffuse radiation for Delhi.

An empirical relationship was proposed by Iqbal (1979) eliminating $\bar{H}$ and substituting by $\bar{H}o$ in equation as

$$\bar{H}_d/\bar{H}_o = a_1 + a_2 (\bar{n}/\bar{N}_d) + a_3 (\bar{n}/\bar{N}_d)^2$$

By using Newton's least square method, a similar equation of the following form was obtained

$$\bar{H}_d/\bar{H}_o = 0.2858 + 0.222\ (\bar{n}/\bar{N}_d) - 0.451\ (\bar{n}/\bar{N}_d)^2 \quad (37)$$

Using Canadian data, Iqbal (1979) recommended following

$$\bar{H}_d/\bar{H}_o = 0.163 + 0.478\ (\bar{n}/\bar{N}_d) - 0.655\ (\bar{n}/\bar{N}_d)^2 \quad (38)$$

correlation. A critical look at all these equations for different stations around the world shows that ratio of diffuse to global radiation is quite high for Delhi. But it is known that higher latitude stations like Canadian and even to some extent Malta are having higher air mass and larger surface albedo which generally increases the ratio of diffuse to global radiation. This is contrary to the present results. This indicates that local climate is having greater contribution in predicting diffuse radiation. The local climate of Delhi which is greatly affected by the westerly winds from Rajastan and clouding during monsoon season offsets the latitude effect. It may therefore be concluded that no site independent predictive correlation of this order can be obtained.

Correlation between Diffuse Radiation and Global Radiation

It is perhaps the most widely worked out relationship over the globe. Page (1940) gave the following form

$$\bar{H}_d/\bar{H} = 1.00 - 1.13\ \bar{K}_T \qquad (39)$$

Where

$\bar{H}d$ = Monthly average daily diffuse radiation

$\bar{H}$ = Monthly average daily global radiation

$\bar{K}_T = \bar{H}/\bar{H}_o$

$\bar{H}_o$ = Monthly average daily extraterrestrial radiation.

The regression analysis in the present study shows the following form.

$$\bar{H}_d/\bar{H} = 1.181 - 1.253\ \bar{K}_T \qquad (40)$$

The interecept is the fraction of total radiation that is diffused when the total radiation received at the earth's surface is very small. Page (1940) recommended an ideal value of 1.0, when the total radiation is fully converted into the diffuse radiation. This is the maximum vlaue one can get theoretically but in practice one can see that present correlation gives much higher intercept. The reason being that the instrument used for measurement of diffuse radiation was not

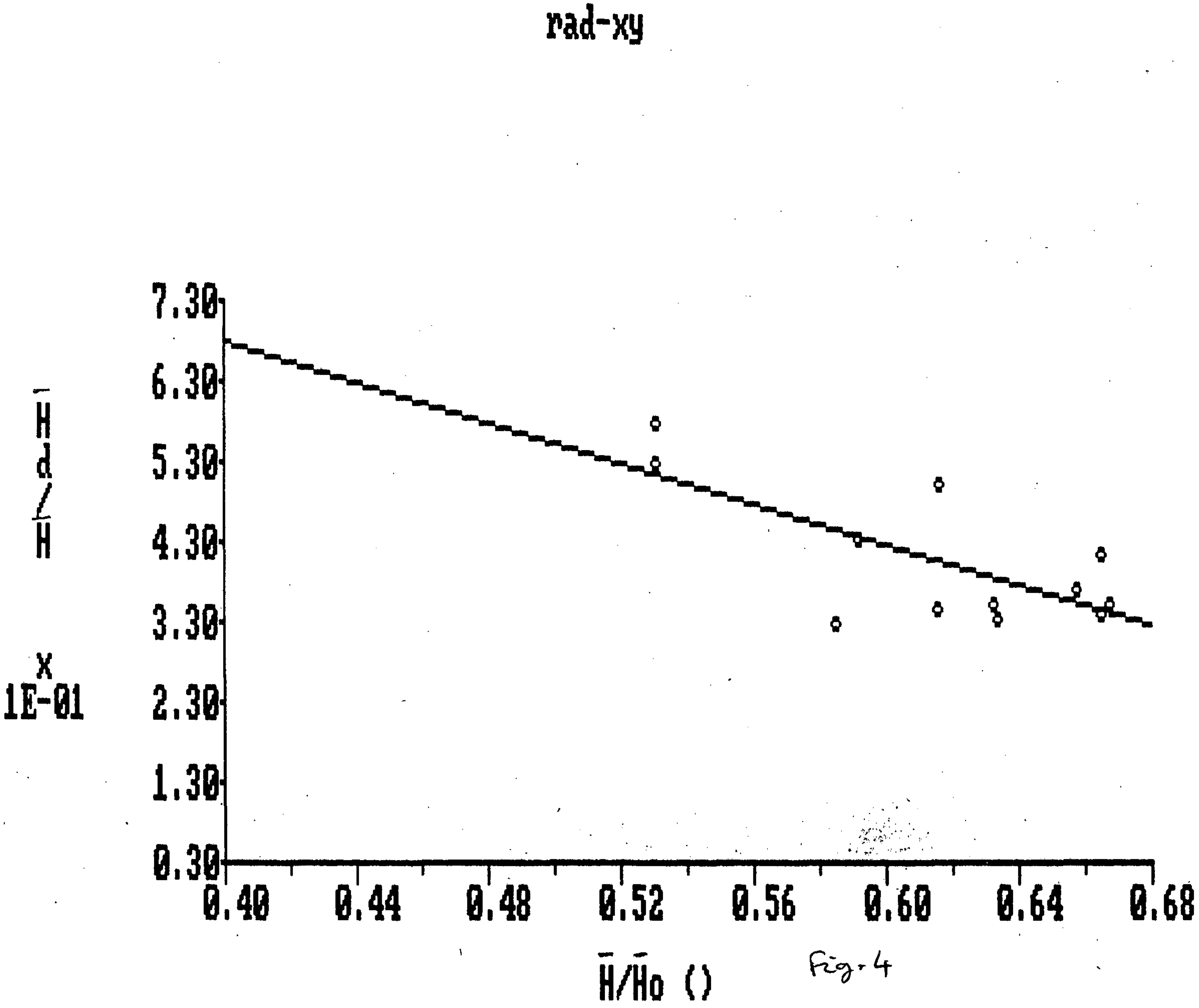

rad-xy
H̄d/H̄
x
1E-01
7.30
6.30
5.30
4.30
3.30
2.30
1.30
0.30
0.40
0.44
0.48
0.52
0.56
0.60
0.64
0.68
H̄/H̄o ()

Fig. 4

(62)

having a proper shadow band correction. It naturally includes the multiple reflected diffuse radiation. The negative slope indicates the rate of decrease of diffuse radiation fraction with the increase in Global radiation fraction. This is obvious due to the fact that $\bar{H}/\bar{H}_o$ indicates the clearness, and more the clearness, less is the diffuse radiation.

Mani and Ranjarajan (1982) carried out similar studies for 14 stations all over India and computed the coefficients. The intercept varied from 1.108 to 1.469 and the slope between 1.351 and -1.809. For New Delhi, the coefficients are 1.137 and -1.373 which are comparable with results of present study. The minor difference may be due to different values of solar constant used and the method of computation.
Mani and Rangarajan (1962) also reported the coefficients greater than 1. Therefore, in their case also, perhaps the correction for the Shadow band was not taken into account.

For Malta, Scerri (1981) obtained a relationship of the form

$$\bar{H}_d/\bar{H} = 1.103 - 1.179\ \bar{K}_T \qquad (41)$$

The intercept and the slope of the above equation are much closer to the Page's equation (1940) than the present result. This obviously indicates a better result obtained owing to the accuracy of the measuring instruments. High correlation of -0.98 further confirms this.

Vignola and Mcdanells (1983) correlated diffuse and global radiation for the North-Pacific with different intervals to identify the best fitted interval of averaging the data for such study. For 30 days average, the coefficients came out to be 1.093 and -1·313 and for the 15 days average, these coefficients turned out to be 1.104 and -1.325. For 10 and 5 days average, these coefficients were 1.118, - 1.341, 1.155 and -1.388 respectively. Although it is quite evident that the error increases with the decrease in the time interval but even a 5 days average can be used for this purpose with only a small degree of error.

Therefore, in the present study, the monthly average taken is expected to give the utmost accuracy baring the instrumental errors. It can be also observed that the results obtained by Vignola and Mcdaneils (1983) are comparable to the results of present study. Hence it not only corroborates Page's (1940) equation but also supports the equation obtained after the regression analysis of the available data. It also shows that with a small degree of error, the equation is applicable globally.

Iqbal (1979) too carried out such a study to propose a slightly different correlation using Canadian data which are corrected for the shadow band effects. He also used different value for solar constant than that of Page (1961). He proposed

$$\bar{H}_d/\bar{H} = 0.958 - 0.982\ \bar{K}_T \qquad (42)$$

Which has $\bar{K}_T$ value between 0.3 and 0.6. Here it is interesting to note that he has specifically given an extra stress on the range of $\bar{K}_T$ which unfortunately most other authors ignore. Here one should understand that although for a small range of $\bar{K}_T$ Page's equation behaves ideally but it is mostly site specific. There is a possibility of its dependence on latitude and hence becomes site specific.

For the long range of $\bar{K}_T$, Liu Jordon (1960) proposed an empirical relationship. The value of $\bar{K}_T$, for the present study ranged between 0.5309 and 0.6649 which is very small. Therefore, the equation can be rewritten as

$$\bar{H}_d/\bar{H} = 1.181 - 1.253\ \bar{K}_T,\ 0.5 < \bar{K}_T < 0.7 \qquad (43)$$

Another important point is that most other authors ignore to spell out the magnitude of solar constant used. Page (1981) while proposing the equation used the older value of 2.0 langley for the solar constant whereas Iqbal (1979) used the latest based on the NASA design value of solar constant 1355 wm^{-2}. For the present study latter's solar constant is used in the computations.

As stated earlier, Liu-Jordon (1960) to obtain universal correlation, tried to establish a distribution curve with a substantial range of $\bar{K}_T$ values (0.3 - 0.7) based on global radiation data of several stations.
He found out a relationship of the form.

$$\bar{H}_d/\bar{H} = 1.39 - 4.027\ \bar{K}_T + 5.531\ \bar{K}_T^{\ 2} - 3.108\ \bar{K}_T^{\ 3} \quad \ldots\ (44)$$

The results in the present study were found to be quite different. The Newton - least square method was used to get the equation in the following form.

$$\bar{H}_d/\bar{H} = -0.713 + 1.33\ \bar{K}_T - 1.13\ \bar{K}_T^{2} + 3.39\ \bar{K}_T^{3} \quad .. (45)$$

Modi and Sukhatme (1979) obtained a linear correlation for India as.

$$\bar{H}_d/\bar{H} = 1.411 - 1.696\ \bar{K}_T \qquad (46)$$

and found that Liu-Jordon equation (1960) is valid for Indian conditions. The reason for this descripancy lies in the fact that Modi and Sukhatme used a large range (0.34 - 0.73) while in the present study the range is very small.

As Liu-Jordon equation is valid for a very wide range, it is not surprising that it failed to satisfy the above equation. One may conclude therefore that even all other equations one satisfies, the Liu-Jordon equation (1960) cannot be satisfied unless one has a large range of $\bar{K}_T$ values although Klein and Duffie (1978) suggested this even for large range of K_T, Liu-Jordon equation is generally dependent on the geographic and climatic conditions of the station. Several authors viz M. Iqbal (1979) D.G. Erbs et.al (1982) Vignola and McDaniels (1983) used $\bar{K}_T$ with a very large range to sastisfy Liu-Jordan equation.

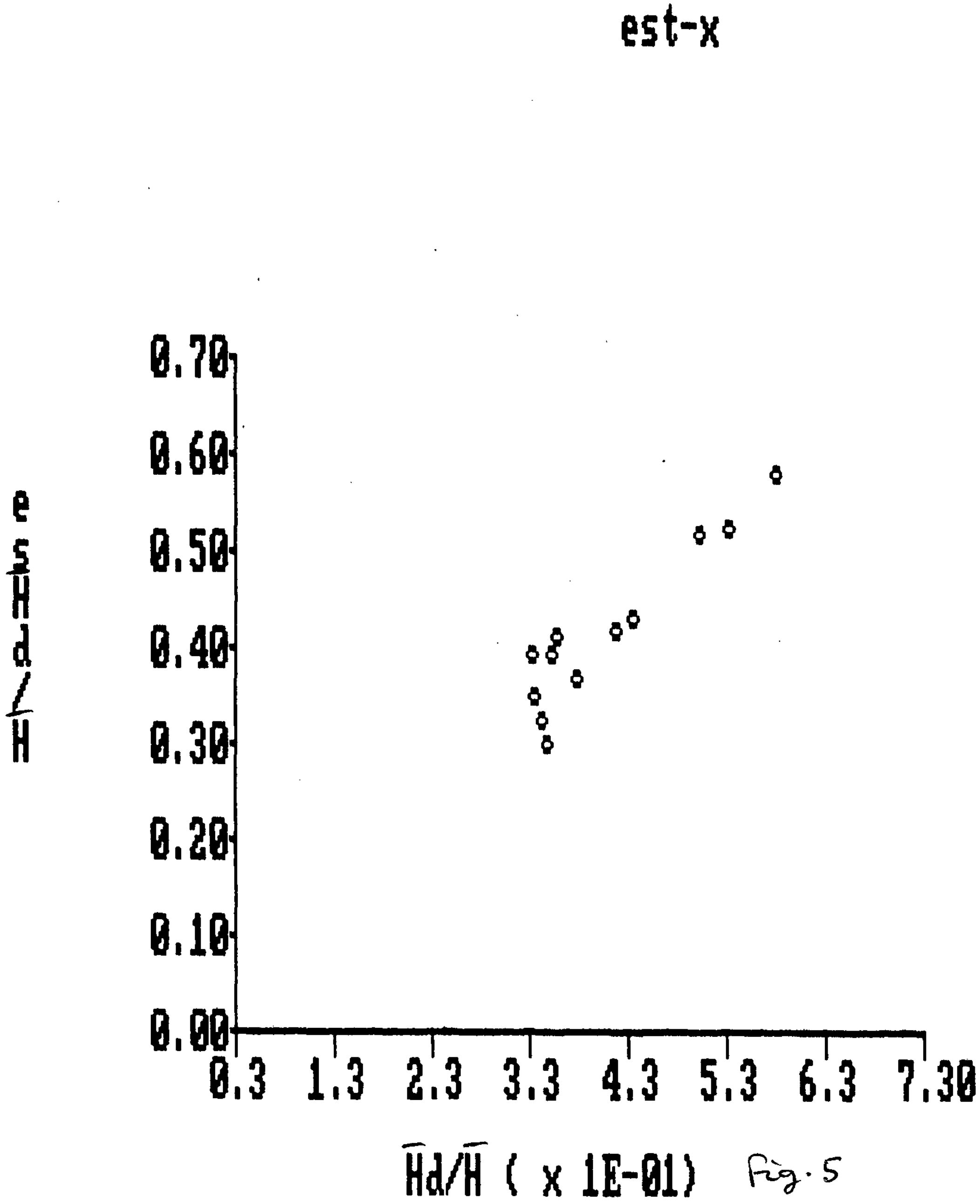

est-x
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
esHd/H
0.3
1.3
2.3
3.3
4.3
5.3
6.3
7.30
Hd/H (x 1E-01)

Fig. 5

The correlation coefficient between diffuse radiation obtained in the present study is lower than that obtained by Mani and Rangarajan (1982). They had obtained a correlation coefficient of 0.89 were as the present study gives only 0.72. Consequently, the coefficient of determination came out to be 0.8 for Mani and Rangarajan (1982) and only 0.504 for the present study. The coefficient of determination for Modi and Sukhatme (1979) too came to be as high as 0.93
To further confirm the result, standard errors were estimated for the equation (40). The bias of difference from the estimated values came out to be 0.0117 and the variance came out to be 0.0037. The mean square error was found out to be 0.0034 and the average gross error was estimated to be 0.0468. All these show quite low values of error in estimation. Hence these statistical analysis not only confirmed the result for the location but also gives enough support for the validity of the estimation method.

Using the equation developed, the author estimated the diffuse radiation fraction for all the months. The result shows that the observed diffuse radiation

is less than the estimated during the winter probably due to prevailing dust free atmosphere.
During premonsoon seasons, the radiation reflected from the earth gets relfected back to the earth by the prevailing dust particles in the atmosphere. These reflected short wave radiation inflates the observed diffused radiation.
The underestimation of the diffuse radiation during the monsoon months is a result of increase in water vapour content in the air. Since water vapour's forward scattering component is quite higher than Rayleigh scattering by air molecules, the high concentration of water vapour increase the diffuse radiation to result in the under-estimation of observed diffuse radiation.

Hence, incorporation of earth's albedo or reflectivity in premonsoon months and effect of water vapour scattering during the monsoon months should give more realistic approach in the estimation method.

Correlation Between Beam Radiation and Sunshine Duration:

The beam radiation as a fraction of global radiation is related to sunshine duration as

$$\bar{H}_b/\bar{H} = J + k\,(\bar{n}/\bar{N}_d)$$

Where

$\bar{H}_b$ = Monthly average daily beam radiation

$\bar{H}$ = Monthly average daily global radiation

$\bar{n}$ = Number of instrument recorded bright sunshine hours per day

$\bar{N}_d$ = Average day length

and 'J' and 'k' regression constants

Regression analysis of the present data yields the following equation

$$\bar{H}_b/\bar{H} = 0.135 + 0.74\ (\bar{n}/\bar{N}_d) \qquad (47)$$

The intercept in this equation shows that 13.5% of global radiation is beam part under the overcast conditions. The slope of the equation shows that there is a rate of increase of 0.74 in the beam radiation fraction for the increase in the sunshine duration.

The correlation coefficient (r) between beam radiation and sunshine duration was found to be 0.914 and coefficient of determination (r^2) as 0.835. Standard error methods applied to it, gave the bias of difference from the estimated value to be 0.008. Both variance and mean square error come out to be 0.001 but the average gross error is 0.024. All these confirm the

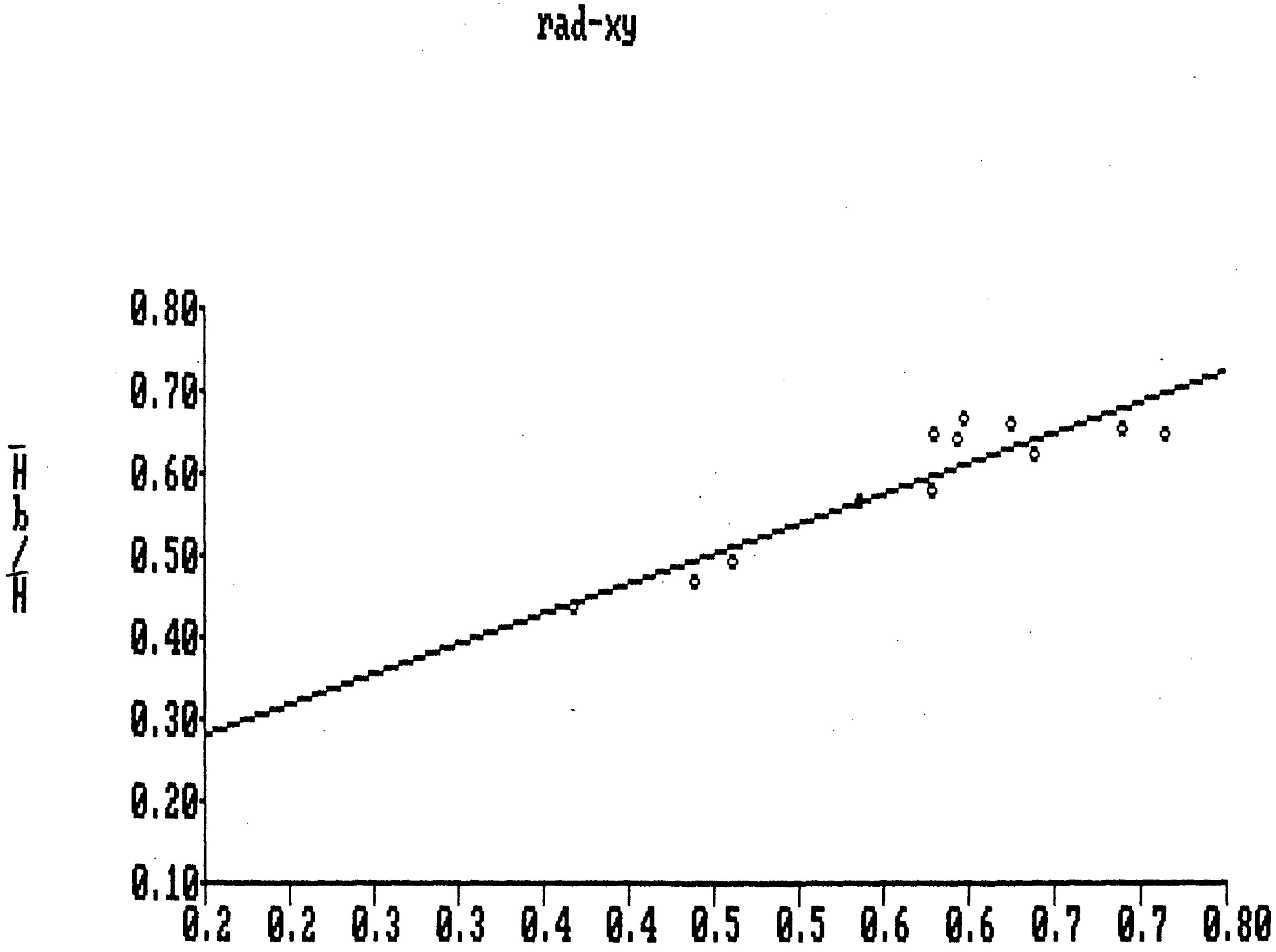

rad-xy
H̄b/H̄
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.2
0.2
0.3
0.3
0.4
0.4
0.5
0.5
0.6
0.6
0.7
0.7
0.80
Sun Shine ()

fig. 6

result and also validates the estimation method.

Iqbal (1979) proposed an empirical relationship with sunshine duration as

$$\bar{H}_b/\bar{H}_0 = a_8 + a_9 (\bar{n}/\bar{N}_d) + a_{10} (\bar{n}/\bar{N}_d)^2$$

Using Newton's least square method, the above equation was solved for the present site to get

$$\bar{H}_b/\bar{H}_0 = -0.001 + 0.69 (\bar{n}/\bar{N}_d) - 0.06 (\bar{n}/\bar{N}_d)^2$$

ANNUAL VARIATION OF WAVELENGTH EXPONENT AND TURBIDITY COEFFICIENT :

The annual variation of turbidity (β) is shown in fig. 7 for the year 1988. Turbidity (β) steadily increases form January to June i.e. in the winter and pre-monsoon period. This is because of the advection of dust from Rajastan, by reentrainment of dust in the lower atmosphere by surface winds and by transport of this dust by convection and turbulance into the higher levels (Rangarajan, 1966).

With the advent of monsoon i.e. in July, there is a steep fall in the turbidity. This is due to the rain out of hygroscopic dust within the clouds and washout

ANNUAL VARIATION OF BETA

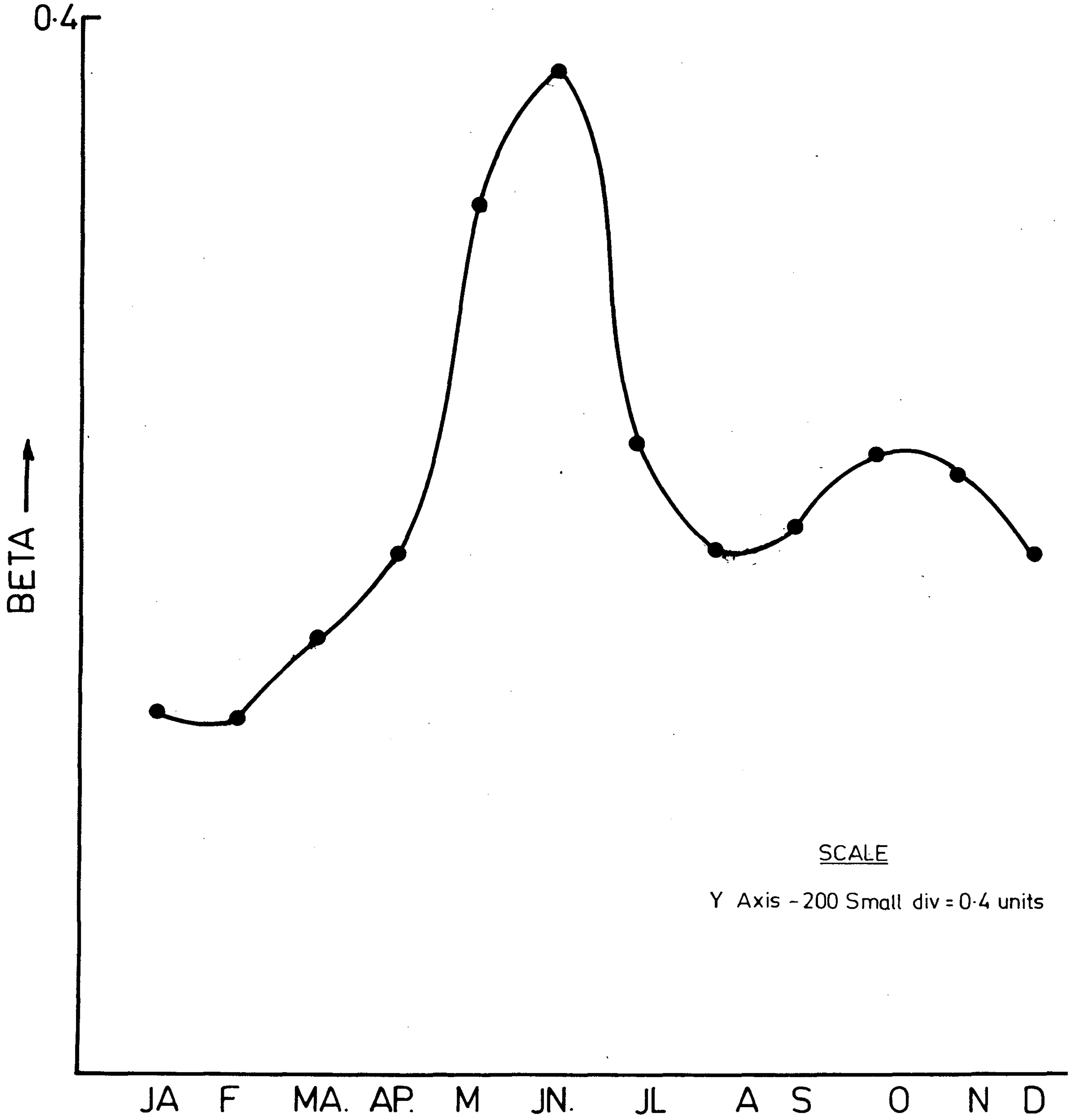
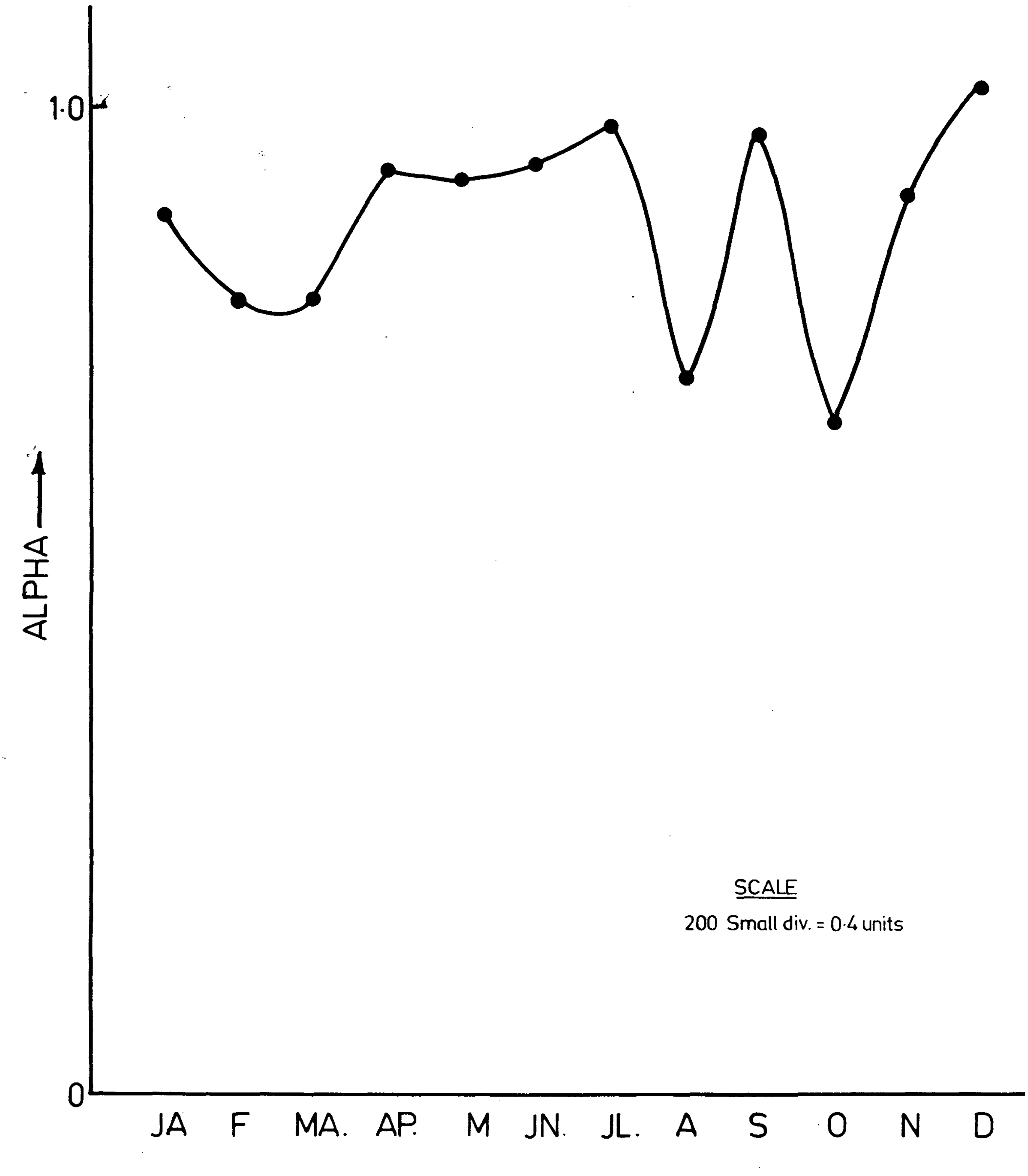


Fig. 7

below the clouds. (Mani et.al 1969) After the withdrawal of monsoon turbidity increases slightly again during the winter. This is due to calm winds, inversions and suspension of inorganic and organic particles which are light brown in colour (winter haze) in the air. This winter haze generally settles during hight and rises up in the forenoon and gets dissipated by thermal turbulence and mixing of upper winds by noon (Ramanathan and Karnadikar, 1949). The annual average turbidity was calculated to be 0.221 which is higher than 0.182 observed by Mani et.al (1969). This shows that Delhi's atmosphere has become more turbid over the years.

The wavelength exponent (α) remained more or less steady throughout the year. Although there has been marked increase in turbidity (β) no much variations are observed in the wavelength exponent. This implies that concentration of particles increase is summer to three to four times the winter values. This shows particle size distribution remain unchanged through out the year and is independent of β. This result does not support Rangarajan (1966). But it is felt that previous year's synoptic situations influence the succeeding year's atmospheric optical characteristics..



VARIATION OF ALPHA OVER THE YEAR

fig(8)

The year 1987 was a drought year with meagre rainfall. Small suspended particles remained suspended in the atmosphere through out the year and contributed to the size distribution of particles in the next year, 1988. The average particle size distribution came to 0.88 for the year 1988. This shows that there is a decrease in the particle size as Mani et.al. (1969) show that the average alpha (α) to be 0.7.

It can therefore be concluded that although there is a general decrease in particle size there is an increase in turbidity over the year. This fact directly indicates that there is a marked increase in the number of particles remaining suspended in the atmosphere. The study thus points out that there is a steep increase in the amount of pollutants or particulates through the years in the atmospheric environment over the Capital, New Delhi.

Correlation Between the Radiative Parameters and Turbidity:

As discussed earlier, the radiative parameter and turbidity are related because of latter's role in depleting the former and its contribution to diffuse

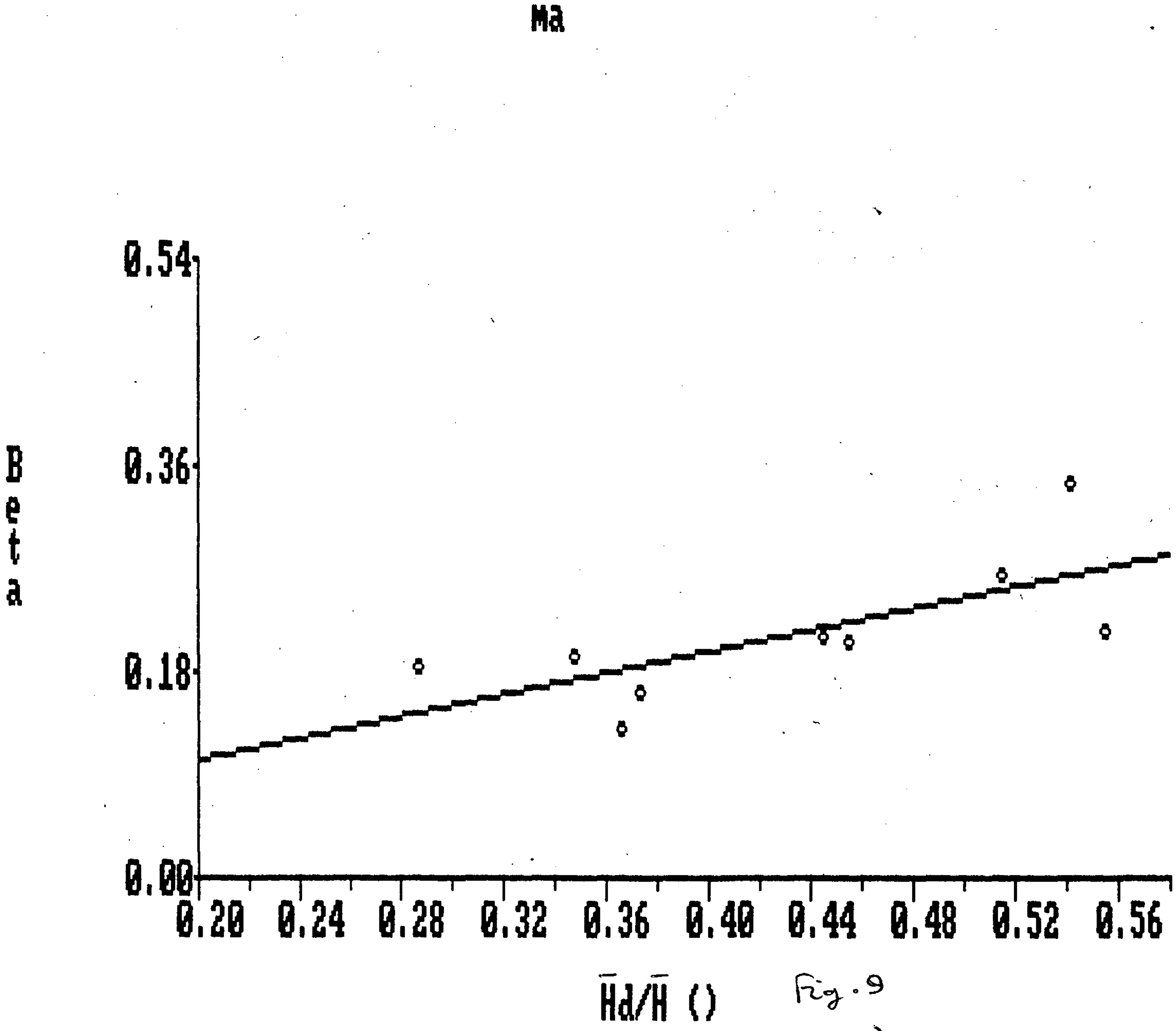

Ma
Beta
0.54
0.36
0.18
0.00
0.20
0.24
0.28
0.32
0.36
0.40
0.44
0.48
0.52
0.56
H̄d/H̄ ()

Fig. 9

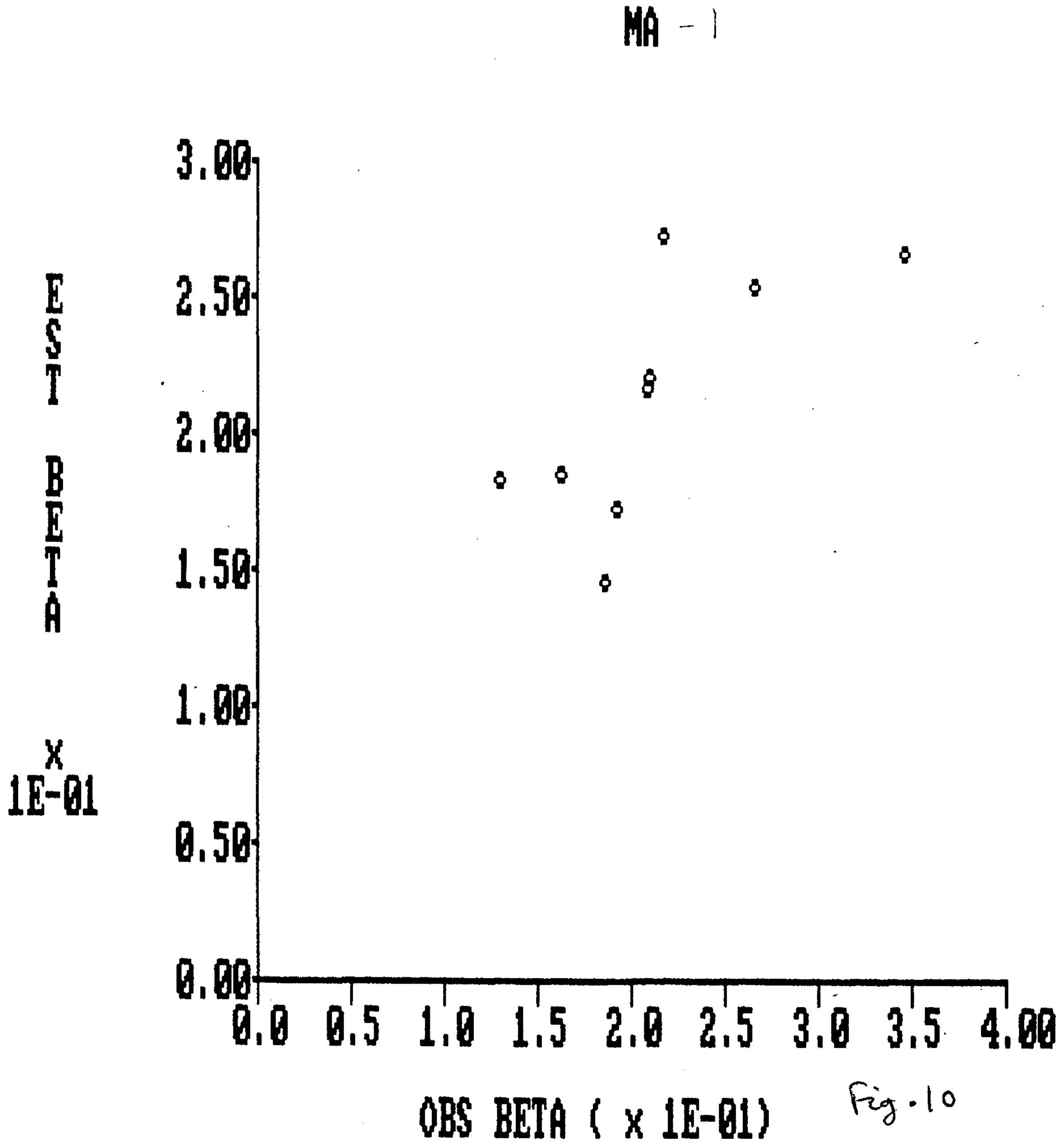

MA - 1
EST BETA
x 1E-01
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.00
OBS BETA (x 1E-01)

Fig. 10

radiation. According to Mani and Rangarajan (1982) and Hoyt (1972) a linear correlation is expected.

Regression analysis of diffuse radiation and turbidity yields the following relation.

$$\beta = 8.687 \times 10^{-3} + 0.4745 \left(\frac{\bar{H}_d}{\bar{H}}\right) \qquad (48)$$

The small intercept indicates the dependency of diffuse radiation on β. The rate of increase of β with respect to diffuse radiation is 0.47.
Since the aim of this equation is to estimate β, the correlation coefficient (r) and the coefficient of determination (r^2) were calculated which came out to be 0.71 and 0.5041 respectively. The bias of difference from the estimated value is 6.67×10^{-4} and the variance is 1.88×10^{-3}. The mean standard error (MSE) is 1.57×10^{-3} and similarly aveage gross error is 3.3×10^{-2}.

The regression analysis of the beam radiation with turbidity yields

$$\beta = 0.4736 - 0.4604 \left(\frac{\bar{H}_b}{\bar{H}}\right) \qquad (49)$$

This equation clearly indicates the beam radiation and turbidity are not closely related. The rate of decrease

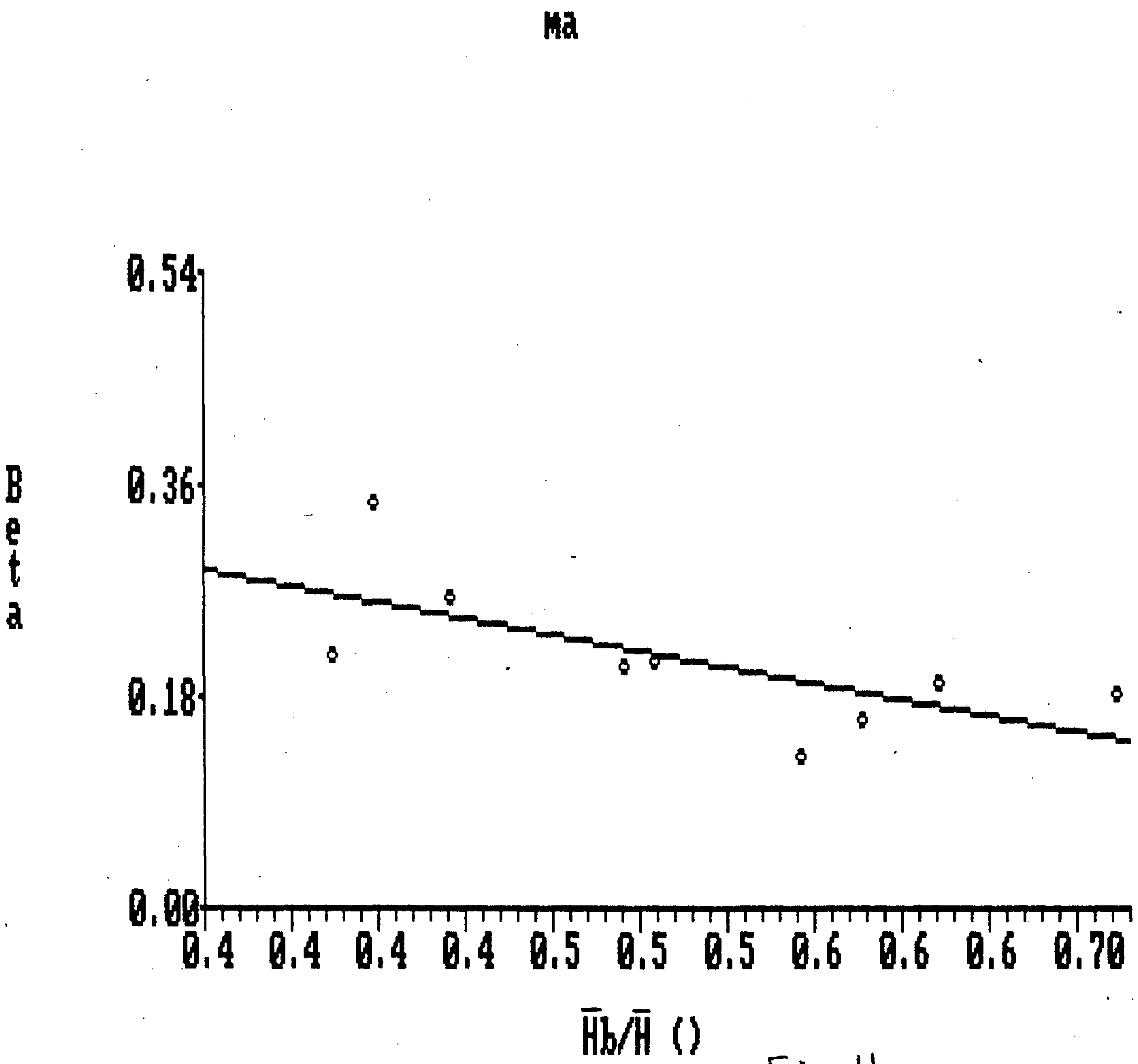

Ma
Beta
0.54
0.36
0.18
0.00
0.4
0.4
0.4
0.4
0.5
0.5
0.5
0.6
0.6
0.6
0.70
$\bar{H}b/\bar{H}$ ()

Fig. 11

MA -2

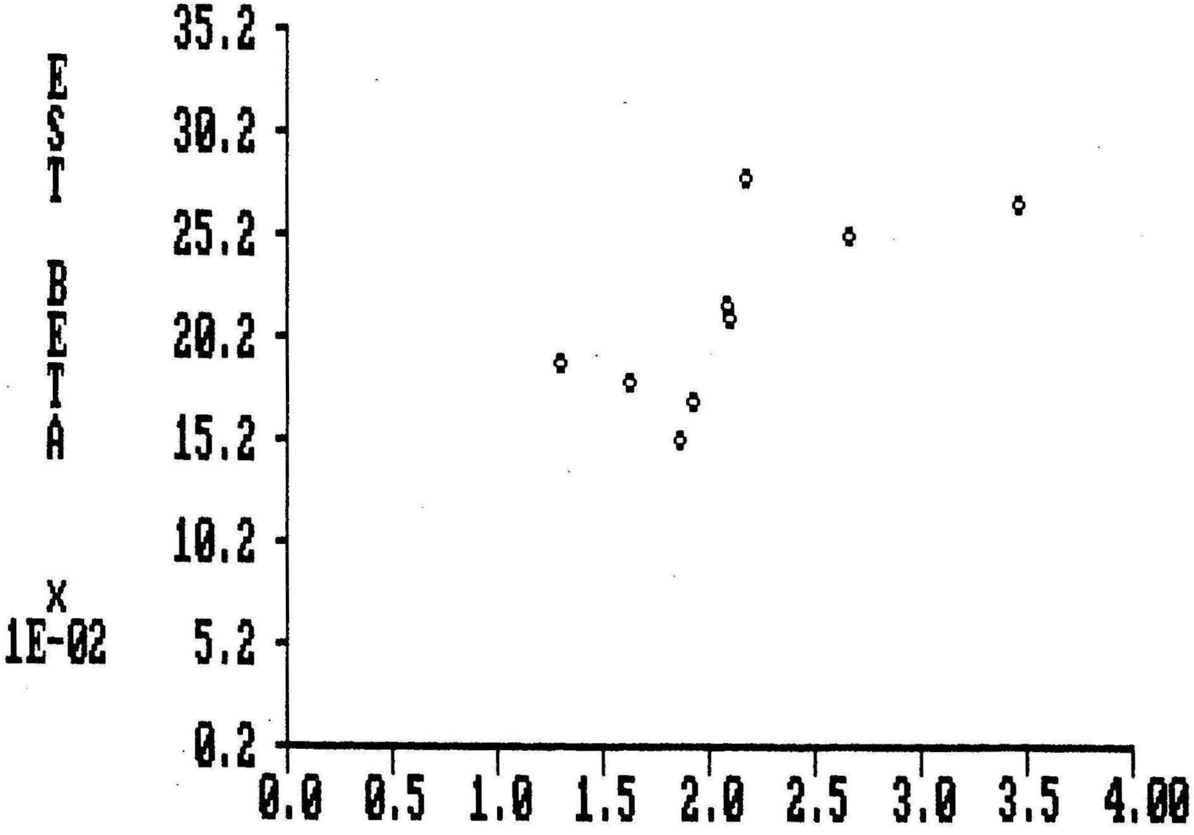

EST BETA
x
1E-02
35.2
30.2
25.2
20.2
15.2
10.2
5.2
0.2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.00
OBS BETA (x 1E-01)

Fig. 12

(82)

β with increase in beam radiation is 0.4604.
The correlation coefficient (r) and the coefficient of determination are 0.68 and 0.4624 respectively. The bias of difference and the variance from the estimated value are 3.3×10^{-5} and 2.11×10^{-3} respectively. The mean square and the average gross error were 1.87×10^{-3} and 3.55×10^{-2} respectively.

The regression analysis of the ratio of diffuse radiation to beam radiation and turbidity yields following relation

$$\beta = 0.0925 + 0.149 \left(\frac{\bar{H}_d}{H_b}\right) \qquad (50)$$

In this case too, β is much dependent on the diffuse to beam radiation ratio. The rate of increase of 'β' for the increase in the diffuse to beam radiation ratio is 0.149.
The correlation and the coefficient of determination are 0.71 and 0.5041 respectively. The bias of difference and variance from the estimated values are 5.5×10^{-5} and 1.9×10^{-3} respectively. The mean square and the average gross error are 1.73×10^{-5} and 3.29×10^{-2} respectively.

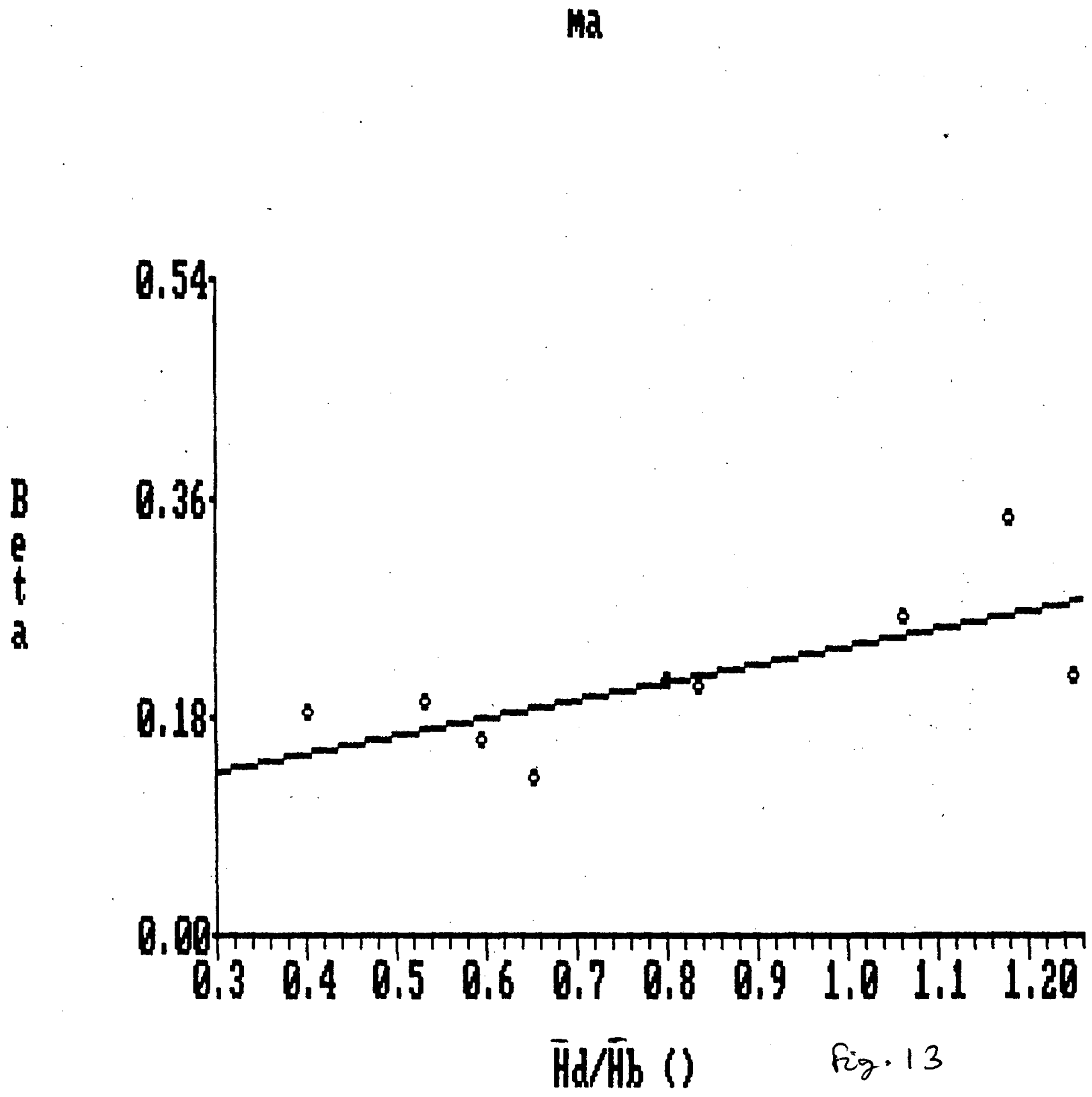


Fig. 13

(84)

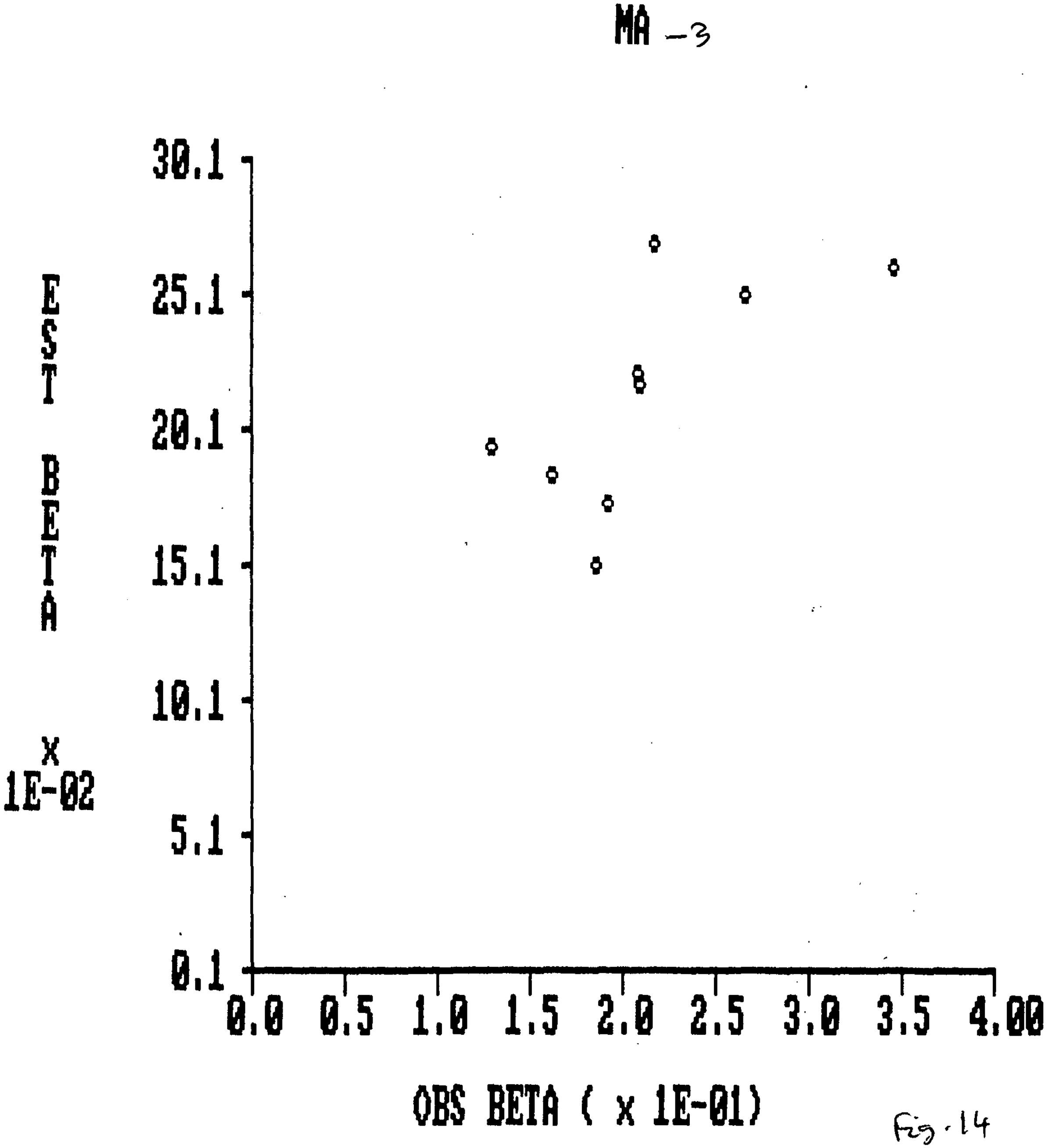

MA -3
30.1
25.1
20.1
15.1
10.1
5.1
0.1
EST BETA x 1E-02
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.00
OBS BETA (x 1E-01)

Fig. 14

(85)

Although the statistical analysis of the entire data gives indication of a good estimation but individual seasons/months show some discrepancy.

Estimated values for monsoon months are low and for post monsoon are higher. In the monsoon months the diffuse radiation is due to the clouds and turbid atmosphere. This leads to under estimation of the turbidity by the equation. During post monsoon most of the large particles are scavenged from the atmosphere either due to rainout or washout leaving clear skies. Hence turbidity is over estimated by the equation.

Should the correlation for albedo of clouds during monsoon and for rainout/washout during post monsoon are incorporated into the regression equation, it is expected to give more realistic results. This is a potential problem for future research.

CHAPTER IV

SUMMARY

Interrelationship between 1) diffuse and global radiation 2) global, diffuse and beam radiations with sunshine duration and turbidity have been established.

Global radiation and sunshine duration are related as

$$\bar{H}/\bar{H}_o = 0.4065 + 0.3387\ (\bar{n}/\bar{N}_d)$$

Where

$\bar{H}$ = Monthly average daily global radiation

$\bar{H}_o$ = extraterrestrial radiation

$\bar{n}$ = Instrument recorded bright sunshine per day

$\bar{N}_d$ = Average day length

The sum of the slope and intercept of the above equation came out to be 0.7452 which indicates transmittance of Delhi's atmosphere Physically, it means that the atmosphere over Delhi is dry and turbid.

The available data satisfies Rietveld equation viz. $\bar{H}/\bar{H}_o = 0.18 + 0.62\ (\bar{n}/\bar{N}_d)$. This further confirms the authenticity of the data used.

Correlation between diffuse and sunshine duration yielded the follwing result

$$\bar{H}_d/\bar{H} = 0.88 - 0.765\ (\bar{n}/\bar{N}_d)$$

Where

$\bar{H}_d$ = Monthly average daily diffuse radiation

Physically it means that 88% of the radiation is getting under overcast condition and the rate of decrease of diffuse radiation with increase in sunshine duration is 76.5%.

An empirical equation connecting diffuse radiation as a fraction of extraterrestrial radiation and the fraction of actual possible sunshine is obtained by using Newton's least square method.

$$\bar{H}_d/\bar{H} = 0.2858 + 0.22\ (\bar{n}/\bar{N}_d) - 0.451\ (\bar{n}/\bar{N}_d)^2$$

Correlation between beam radiation and sunshine duration yielded

$$\bar{H}_b/\bar{H} = 0.135 + 0.74\ (\bar{n}/\bar{N}_d)$$

This can be interpreted as 13.5% of total radiation is left undisturbed as beam radiation under overcast condition and the rate of increase of beam radiation with the sunshine duration is 74%.

The interrelationship between diffuse and global radiation is as follows:

$$\bar{H}_d/\bar{H} = 1.181 - 1.253\ \bar{K}_T$$

Although theoretically it can have maximum intercept of 1.0 i.e. when all the total radiation will be converted to diffuse radiation but due to multiple reflections, the intercept greater than 1.0 is obtained. Shadowband correction if applied for the instrument is likely to give more realistic result.

Liu-Jordon equation could not be satisfied with the present data, Newton's Least square method was applied to get the following result.

$$\bar{H}_d/\bar{H} = - 0.713 + 1.33 \bar{K}_T - 1.13 \bar{K}_T^2 + 3.39 \bar{K}_T^3$$

The failure of data to satisfy Liu Jordon equation may be attributed to the small range of $\bar{K}_T$ obtained for Delhi. The turbidity was related with all three radiative parameters. Regression analysis of diffuse radiation and turbidity yields

$$\beta = 8.687 \times 10^{-3} + 0.4745 \left(\frac{\bar{H}d}{H}\right)$$

The equation shows total dependence of turbidity over diffuse radiation. The rate of increase of turbidity with diffuse radiation is 47.45%.

Regression analysis of beam radiation and turbidity yields

$$\beta = 0.4736 - 0.4604 \left(\frac{\bar{H}_b}{H}\right)$$

The above equation shows that turbidity and beam radiations are not closely related. The rate of decrease of turbidity with the increase of beam radiation is 46.04%

Lastly regression analysis is performed with the ratio of diffuse to beam radiation and turbidity. It gave

$$\beta = 0.0925 + 0.149 \left(\frac{\bar{H}_d}{\bar{H}_b} \right)$$

It shows that the turbidity is dependent on the above ratio and the rate of increase of turbidity with the increase of diffuse to beam radiation is 14.9%

All these relations are confirmed with suitable statistical tests. Some discrepancies are noticed for some individual months which are due to the prevailing climatic conditions. Suggestions for proper corrections for the interfering factors are indicated to obtain more realistic results.

Turbidity shows marked annual variation. High turbidity is noticed in premonsoon periods which falls abruptly during monsoon due to washout and rain out.

Wavelength exponent (α) did not show any annual variation.

There is an overall increase in turbidity through the years and decrease in the particulate size over the years indicating that the atmospheric environment over Delhi is getting more and more polluted by particulate matter of small size which can remain longer in the air owing to their low density and settling velocity.

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APPENDIX

Wind Power as Transmuted Solar Energy:

Wind is mostly generated due to thermal imbalances between two surfaces which manifests as air movement or wind. One may therefore consider wind power as transmuted solar radiant energy. Keeping in view of this fact, wind power analysis was performed for Delhi.

Wind Power Analysis for Delhi:

Wind energy is perhaps the oldest form of non conventional energy whose application goes as far as 400 B.C. in Hindu classic Arthasastra. By 4th Century A.D., wind mills were widely used in Persia presently known as Iran and then it spread its sphere of utility over Europe. There it was used as a power source for domestic and industrial purposes. The discovery of internal combustion engine caused 27,000 large wind mills in Germany alone to disappear. Thousands of windmills in Australia, France and United Kingdom suffered the same fate. But with the threat of rapidly depleting oil resources and equally big threat of environmental pollution, there has been a revival of interest for developing small and large sized wind mills in recent years and attempts are underway all the world over to introduce cost effective wind power system for pumping water for electric generators.

It has been estimated that 10^6 -10^7 MW of usable power is continously available in the surface wind. Hence for developing countries like India, wind power utilization can play useful role in water management and agriculture (in ECDCTCDC). At Delhi with growth of urban population the demand for power both domestic and industrial purposes has increased many fold. The two local power stations namely Indraprastha and Badarpur cannot meet the demands of Delhi. Hence it has to draw power from the northern grid to make up the deficit. Under such state of power deficit it is always advisable to look for an alternate source. It is a known fact that any unit of Thermal Power Station cannot be operated for all the 24 hours and also it is known that one unit takes around six to seven hours to reach its full efficiency. So if the deficiency occuring during that time can be provided by the windmills there is less need of borrowing power from the northern grid or placing extra load on other working units. So this study is thus aimed at assessing the usable energy from wind at each hour in a month.

Ramanathan and Viswanath (1963) found out the hourly wind speeds at New Delhi and estimated the energy obtained. Similar work was attempted for Madras, Lucknow and Jodhpur. Thomas (1981) classified the wind velocities in the four classes and worked out the percentage frequencies for Ahmedabad and Baroda. A comparative study (1985) showed that out of three stations Jamnagar is most favourable to derive wind energy with 68.9% of winds above 9 kmph which is the threshold for economic wind energy utilization

The ideal way of predicting wind potential of a region is to acquire long term records of wind speed. To estimate long term average at a site minimum continuous observations of one year is needed. (Ramsdell et al. 1980). In this case, five years data of the Safdurjung are collected from India Meteorological Department. These data were recorded using Dyne's Pressure tube amenograph. The wind velocity is recorded at 10m hight as per the standards of World Meteorological Organisation.

There are three ways of estimating wind potential

a) Calculation of theoretical wind power available.

b) Calculation of practical power obtainable from the wind i.e. after the conversion, a known "wind energy conversion system" (WECS)

c) Estimating the practical power with rules of thumb.

The first method was chosen for its simplicity and availability of data required.

All wind power calculations are based on the fact that wind power increase with cube of wind speed. So the power due to the kinetic energy of wind with a constant speed V passing through an area A is given by $P = \rho \frac{1}{2} A V^3$ where ρ is the density of air and P is expressed in watts or kilowatts.

The 'ρ' is taken as 1.29 Kg m^{-3} and the unit of area is in Sq.m.

The power density or power per unit area normal to the wind is given by $P_d = \frac{1}{2} \rho v^3$

Since the velocity is in m/s. the overall equation comes out to be

$$P_d = 0.64 \; V^3 \text{ watts}$$

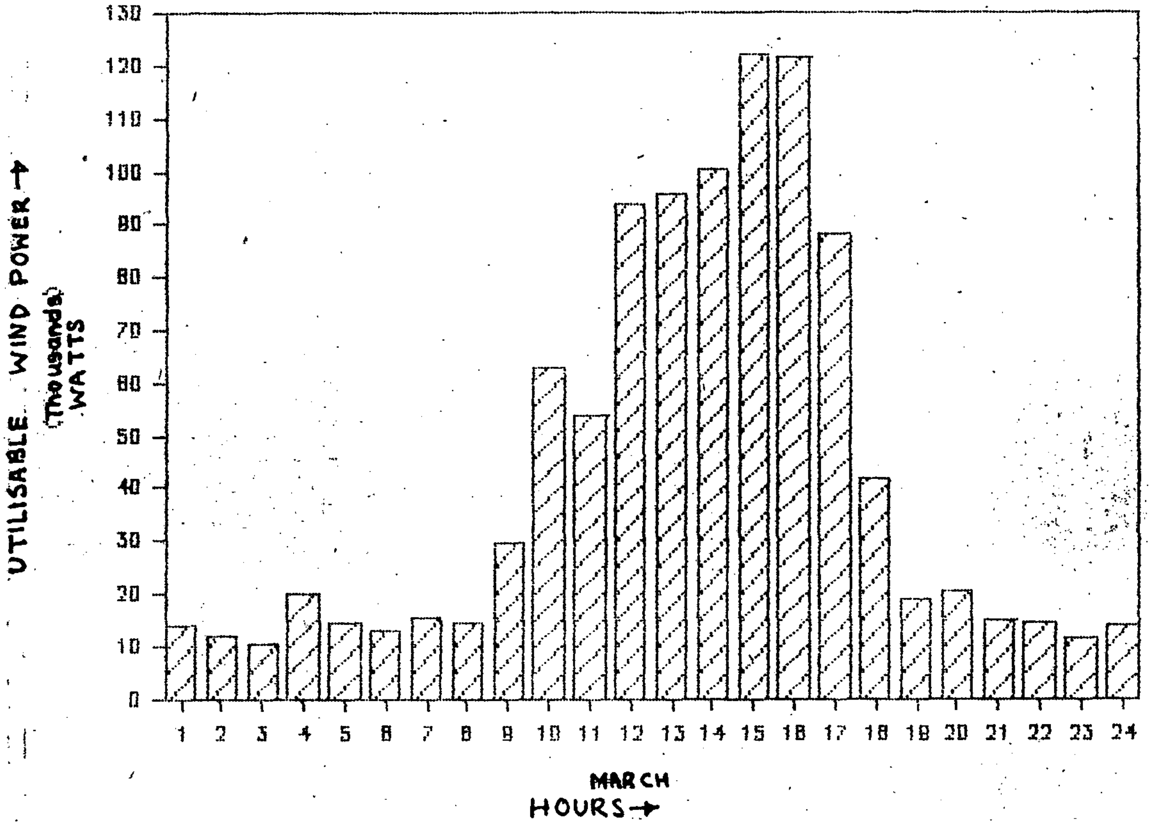
Using the above equations data for the five years are analysed. The results are tabulated.(Table -1)

<u>Conclusion</u> : Although Delhi is having appreciable amount of utilizable power throughout the year but from March to June significant power between 10th and 16th hour is available. So one can really harness the energy out of the wind during these periods to supplement the needs.

TABLE 1

UTILISABLE WIND POWER

MONTH	MAXIMAM UTILISABLE WIND POWER IN KILOWATTS	HOURS OF OCCURANCE
JANUARY	80-140	14,24
FEBRUARY	100	14
MARCH	120	15,16
APRIL	80	13,14,15
MAY	100	18
JUNE	150	9,10
JULY	80	10,13
AUGUST	50	11,12
SEPTEMBER	50	10,11,12
OCTOBER	80	18,20,24
NOVEMBER	19	14
DECEMBER	70	13,14,15


UTILISABLE WIND POWER →
(Thousands)
WATTS
130
120
110
100
90
80
70
60
50
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
MARCH
HOURS →

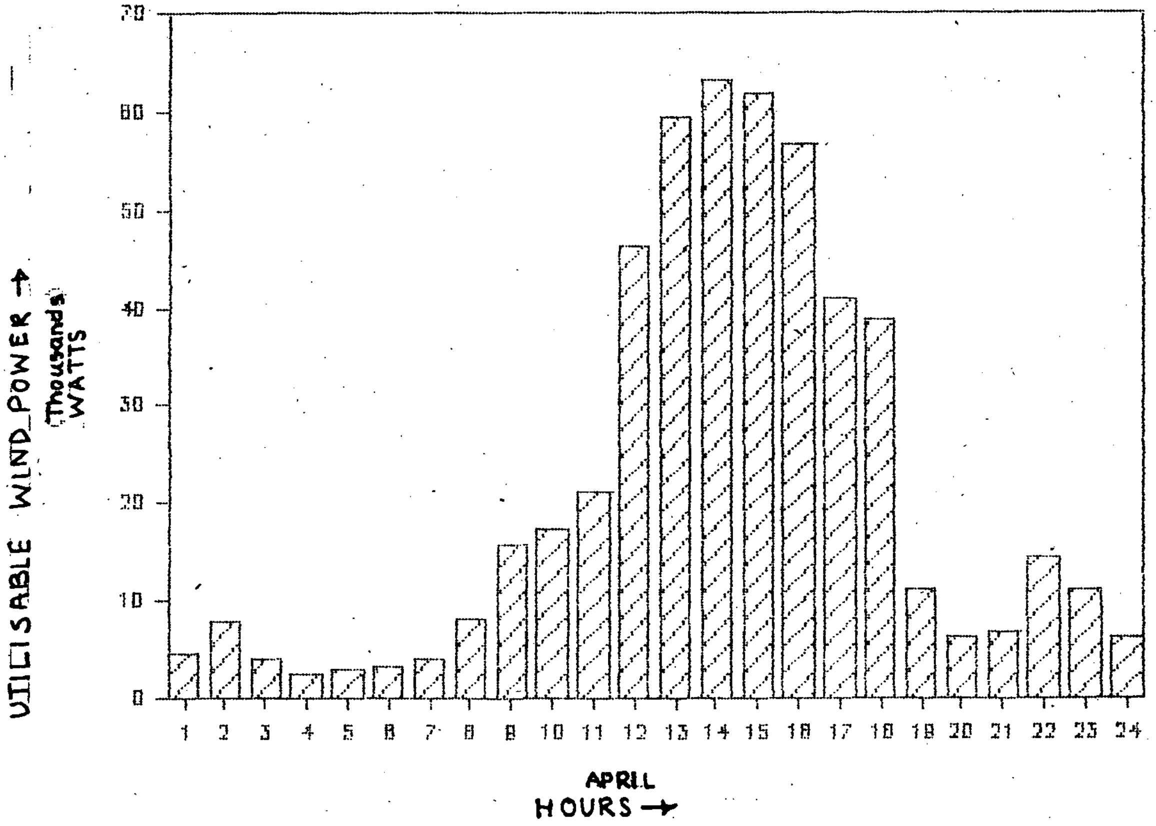

UTILISABLE WIND POWER →
(Thousands)
WATTS
70
60
50
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
APRIL
HOURS →

Fig. 15

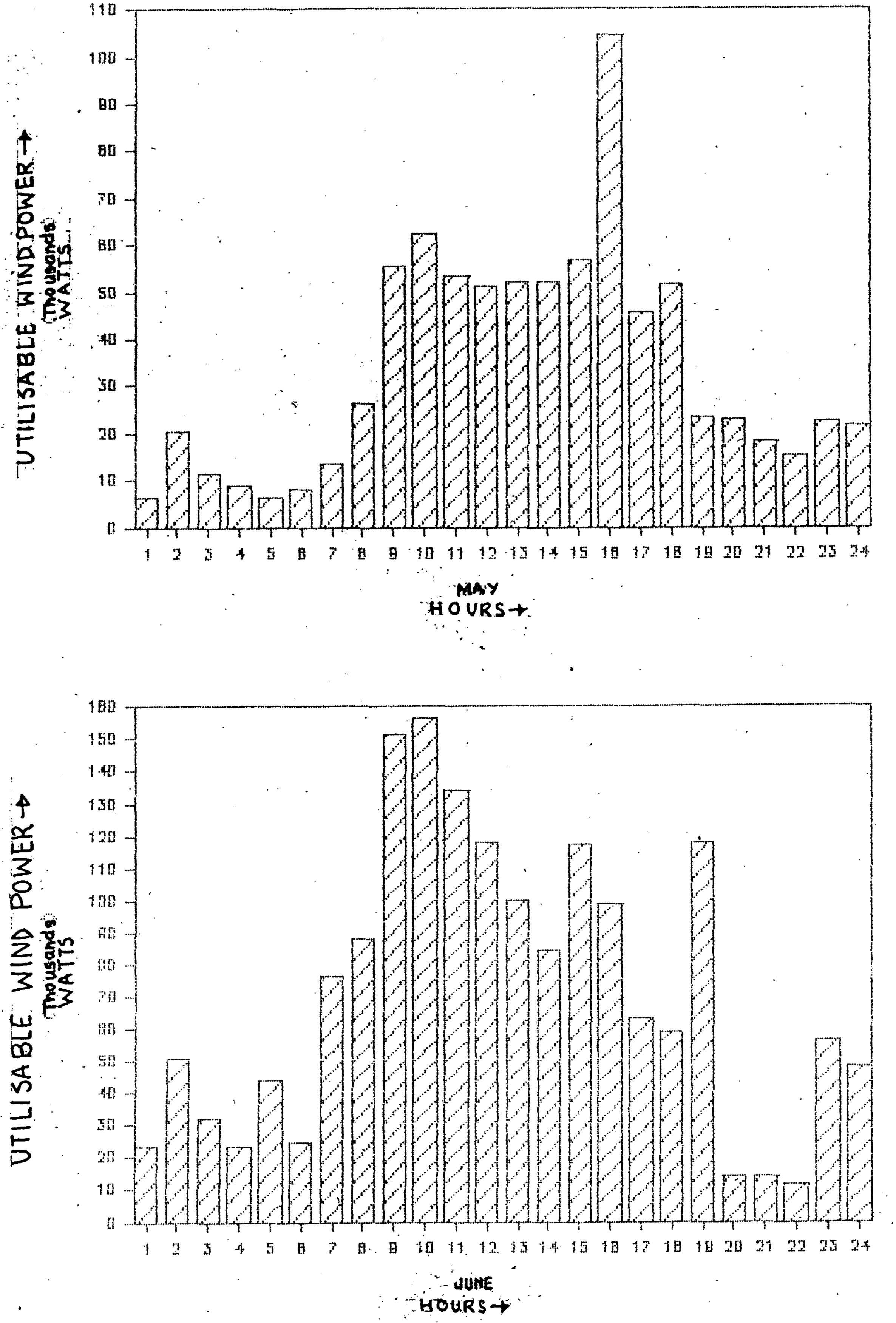

UTILISABLE WIND POWER →
(Thousands)
WATTS
0
10
20
30
40
50
60
70
80
90
100
110
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
MAY
HOURS →
UTILISABLE WIND POWER →
(Thousands)
WATTS
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
JUNE
HOURS →

Fig. 15

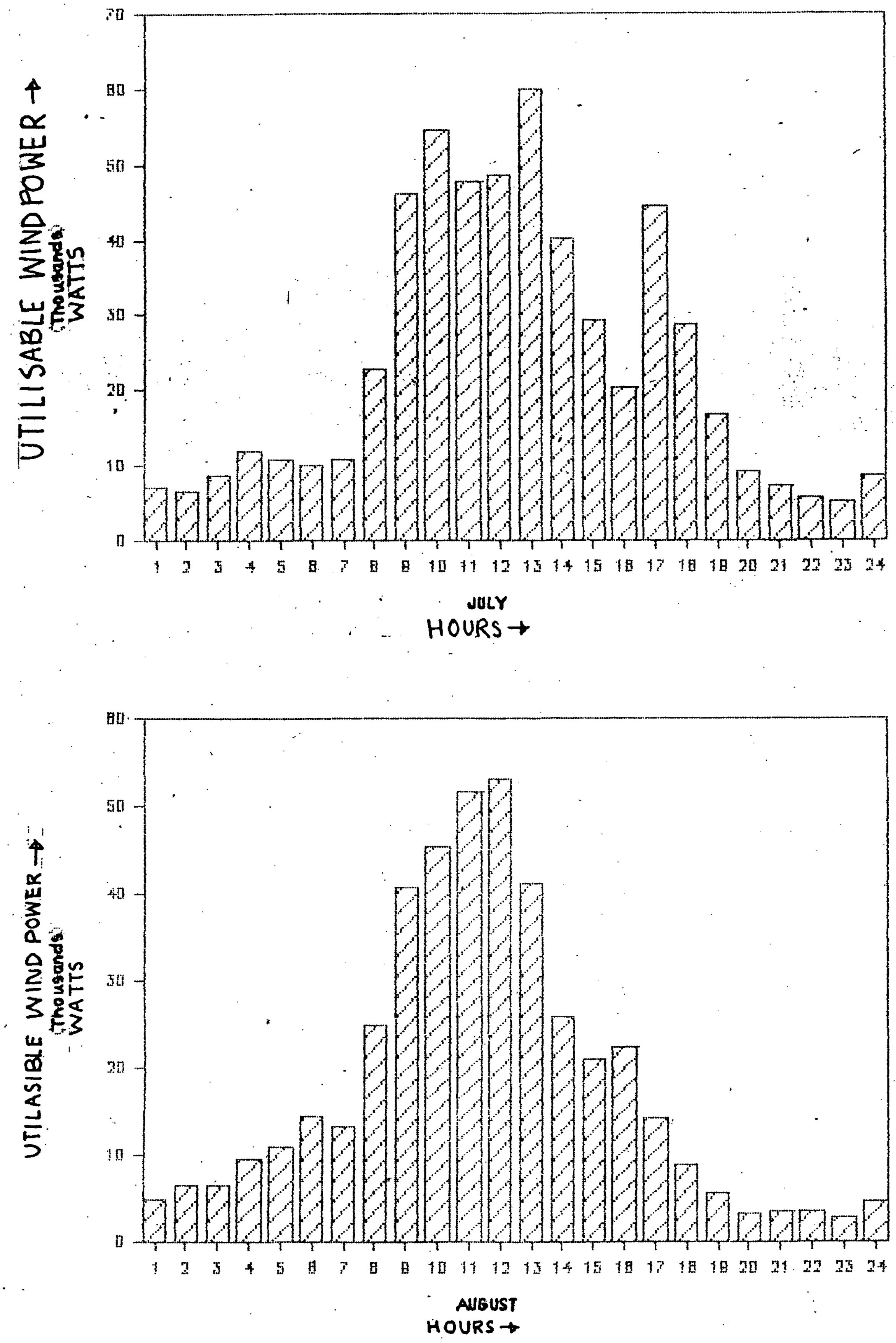
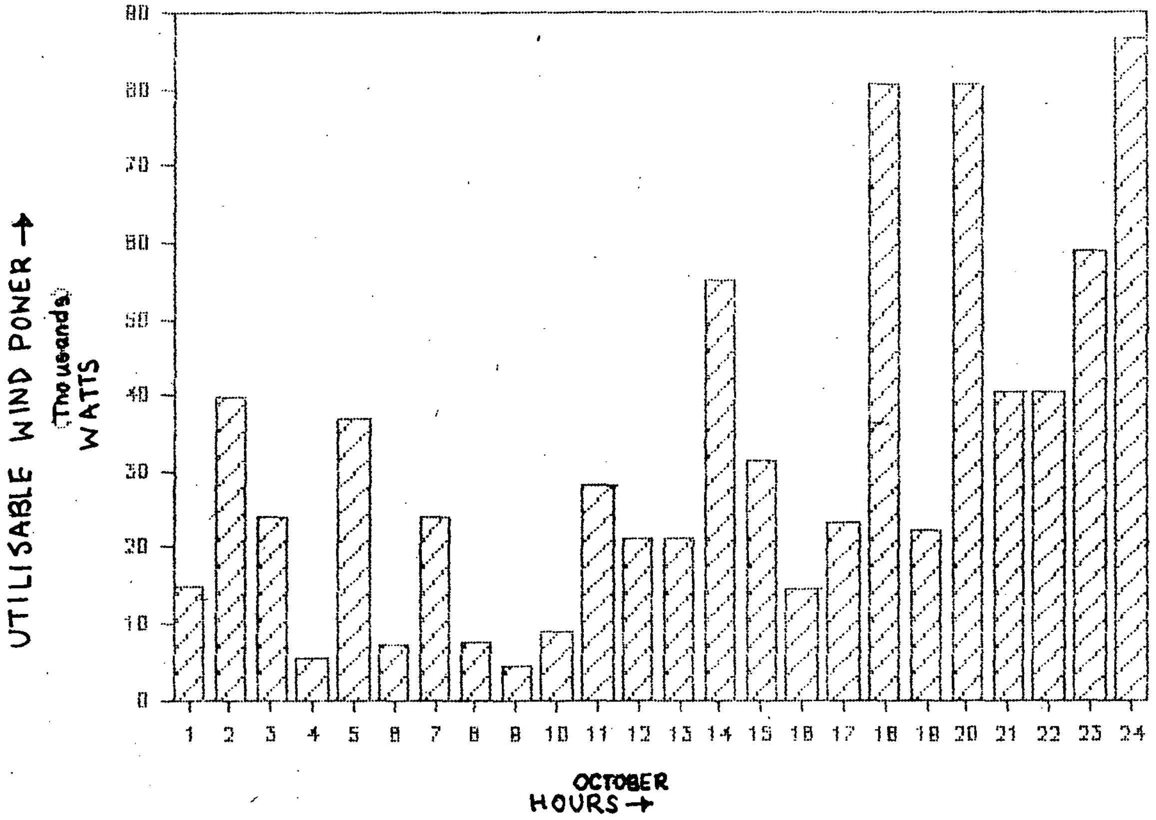

UTILISABLE WIND POWER →
(Thousands)
WATTS
70
60
50
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
JULY
HOURS →
UTILASIBLE WIND POWER →
(Thousands)
WATTS
60
50
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
AUGUST
HOURS →

Fig. 15


UTILISABLE WIND POWER →
(Thousands)
WATTS
0
10
20
30
40
50
60
70
80
90
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
OCTOBER
HOURS →

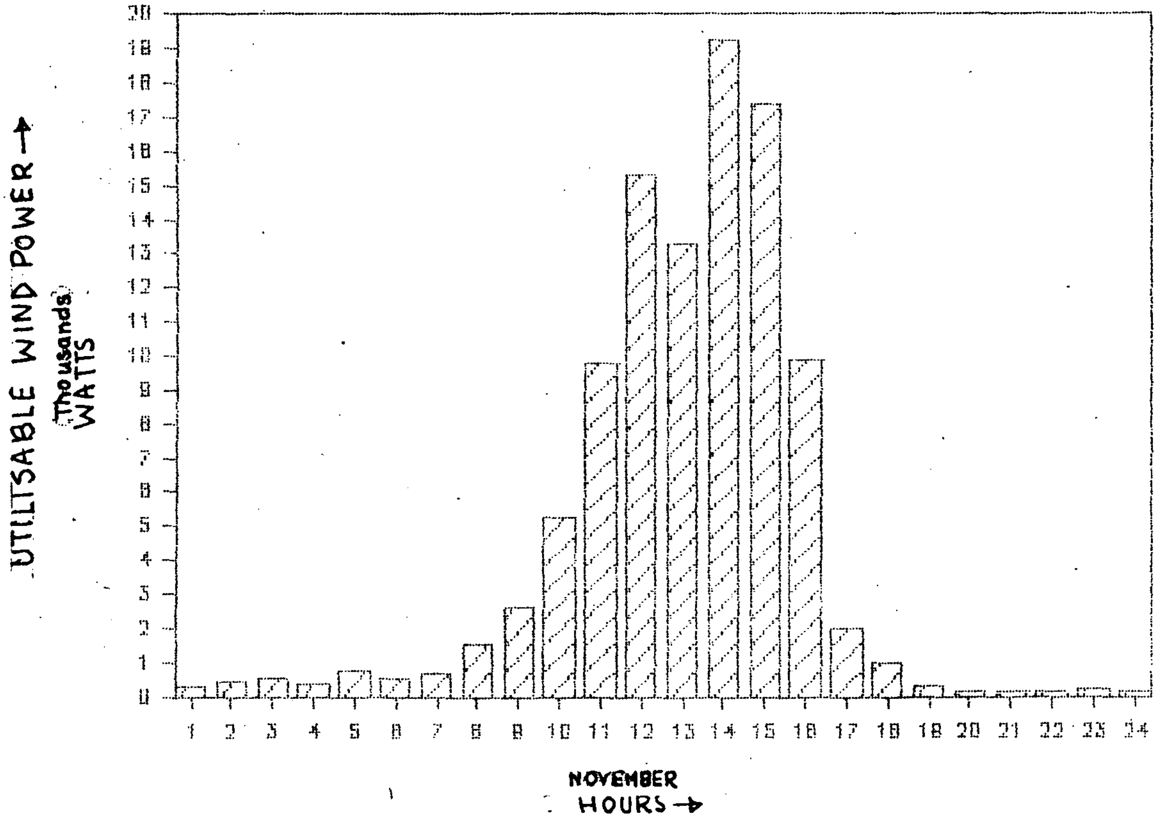
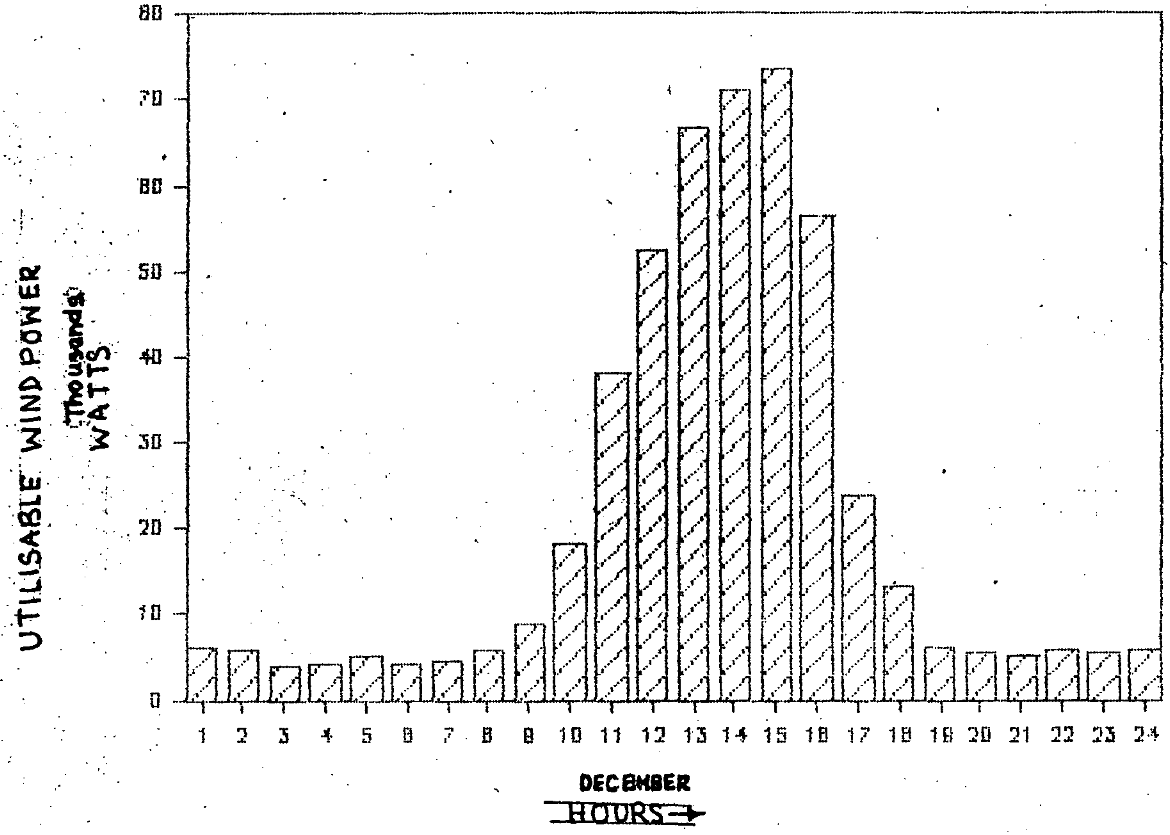

UTILISABLE WIND POWER →
(Thousands)
WATTS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
NOVEMBER
HOURS →

Fig. 15


UTILISABLE WIND POWER
(Thousands)
WATTS
0
10
20
30
40
50
60
70
80
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
DECEMBER
HOURS →

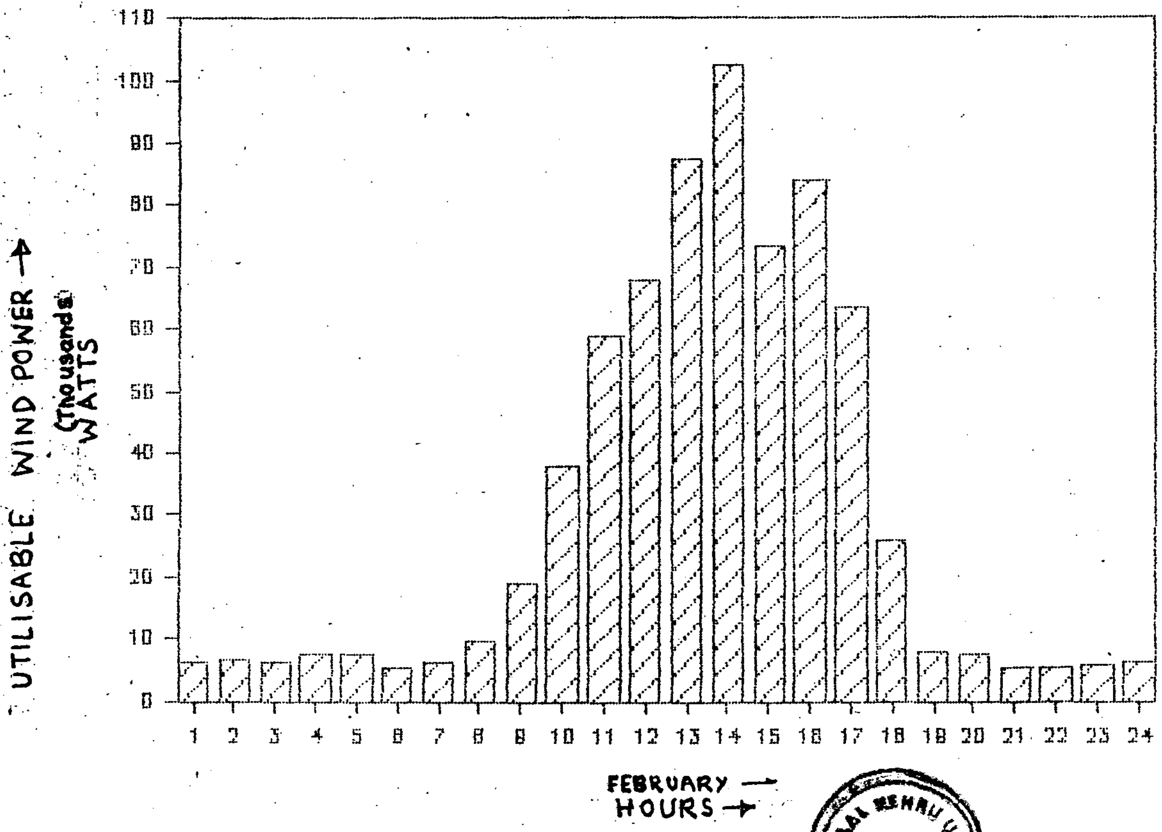
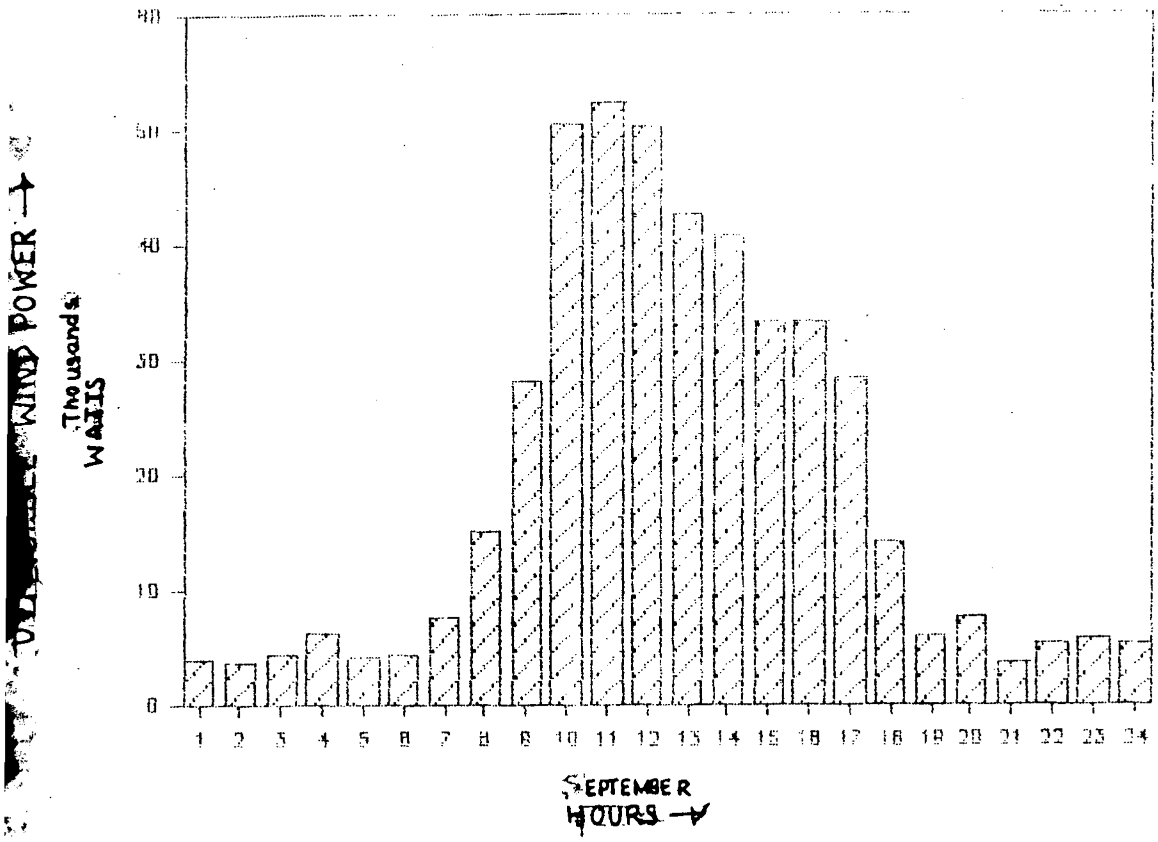

UTILISABLE WIND POWER →
(Thousands)
WATTS
0
10
20
30
40
50
60
70
80
90
100
110
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
FEBRUARY →
HOURS →

Fig. 15


WIND POWER →
Thousands
WATTS
0
10
20
30
40
50
60
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
SEPTEMBER
HOURS →

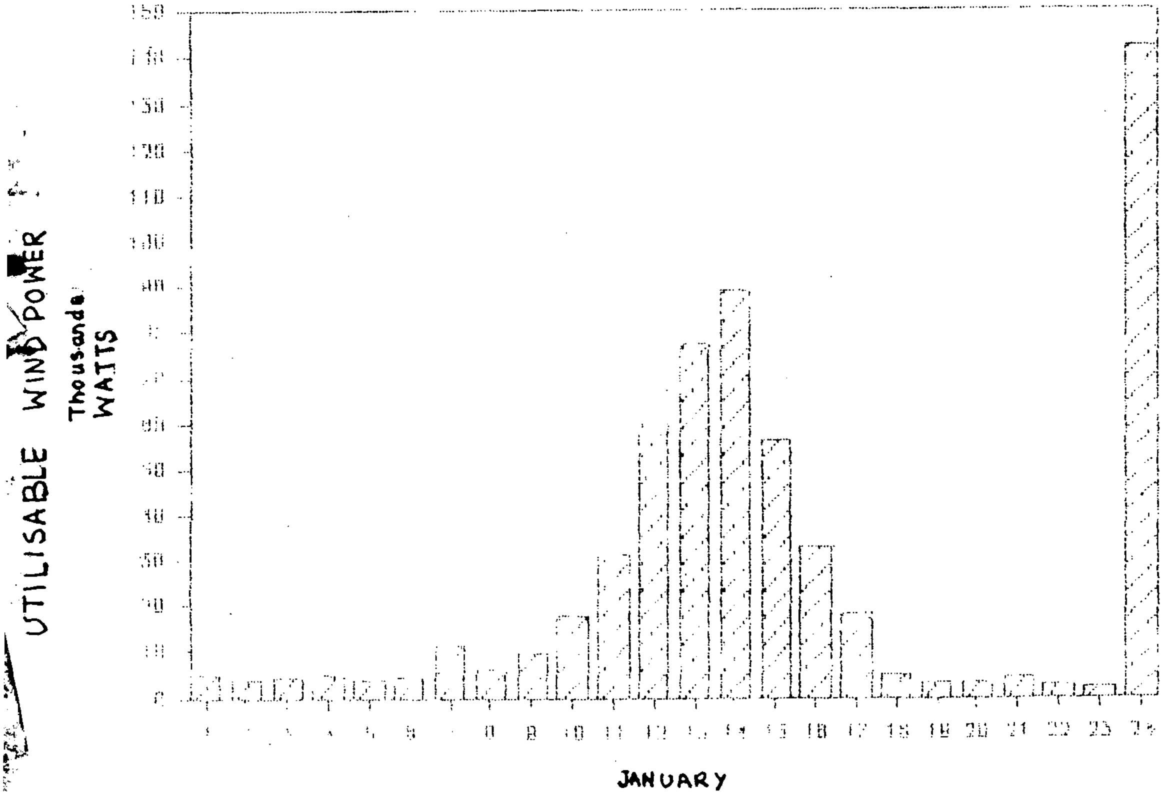

UTILISABLE WIND POWER
Thousands
WATTS
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
JANUARY
HOURS →

Fig. 15