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HOURLY SOLAR RADIATION MODELS FOR JORDAN AND APPLICATION FOR SIMULATION OF HEATING SYSTEMS

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NOMENCLATURE

A : Medium area $[m^2]$

A_i : Surface area of part *i*, $[m^2]$.

A_m : Maximum radiation occur at solar noon

a : Constant defined in equation 1.2.

a_1 : Constant defined in equation 1.22.

a_2 : Constant defined in equation 1.24.

b : Constant defined in equation 1.2.

b_1 : Constant defined in equation 1.22.

b_2 : Constant defined in equation 1.24.

C : 0.5 day length

C_p : Specific heat, $\left[\frac{Wh}{kgc^0}\right]$.

f_i : Internal air resistance $[m^2.c^0/w]$

f_0 : External air resistance, $[m^2.c^0/w]$

G_{sc} : Solar Constant, 1367, $(\frac{W}{m^2})$.

H : Daily total raidiation, $(\frac{W}{m^2})$.

H_0 : Extraterrestrial daily insulation received on a horizontal surface, $(\frac{W}{m^2})$.

I : Hourly global radiation, $(\frac{W}{m^2})$.

I_b : Hourly beam radiation, $(\frac{W}{m^2})$.

I_c : Hourly global radiation for clear sky condition, $(\frac{W}{m^2})$.

I_{cal} : Calculated hourly radiation, $(\frac{W}{m^2})$.

I_d : Measured hourly diffuse radiation on a horizontal surface $(\frac{W}{m^2})$

I_0 : Intensity of solar radiation outside the atmosphere $(\frac{W}{m^2})$.

I_m : Measured hourly radiation $(\frac{W}{m^2})$.

$K_{a,b,c}$: Conductivities of building elements a,b,c $(\frac{W}{mc^0})$.

K_c : The ratio of hourly global to clear sky radiation.

k_T : Clearness index.

L : Crack length [m]

N : Day of the year

P(t): Normal distribution equation.

Q : Heat load [W]

Q_{inf}: Infiltration heat losses, [W]

q_h : Infiltration rate [m^3/hr/m].

r : Ratio of solar radiation intensity at normal incidence outside the atmosphere of the earth to solar constant.

R_b : Geometric factor

r_d : Hourly diffuse to monthly average daily ratio

r_t : Hourly global to monthly average daily ratio.

S : Absorbed energy by flat plate collector $(\frac{W}{m^2})$.

S_d : Monthly average daily sunshine duration.

S_0 : Monthly average daily value of the maximum sunshine duration.

t : Time from solar noon [hr].

t_d : Day length, [hr].

T_i : The inside temperature of the residential house [c^0].

T_0 : The outside temperature of the atmosphere [c^0].

U : The overall heat transfer coefficient [W/m^2 c^0].

U_i : Heat transfer coefficient for area part *i* [W/m^2 c^0].

w : Hour angle, degree.

w_s : The sunset hour angle, degrees.

w_2-w_1: A period of an hour, where $w_2>w_1$.

X : The ratio of hours from solar noon to sunset angle ratio.

$X_{a,b,c}$: Thickness of each building element [m].

Y_t : Hourly global to monthly average daily ratio multiplied by the day length.

Greak symbols

α : Absorbtivity.

β : The tilt angle of the flat plate collector, degrees.

δ : Solar declination, degrees.

η : The efficiency of the flat plate collector.

ρ : The air density, $\left[\frac{kg}{m^3}\right]$

ρ_{ref} :Reflectivity of the ground.

ϕ : Solar altitude angle, degrees.

σ : The standard deviation.

τ : Transmissivity of flat plate collector cover.

ABSTRACT

Measured global, diffuse and beam radiation on a horizontal surface for Amman and Aqaba are investigated.Hourly global to monthly average daily ratios in addition to hourly diffuse and hourly beam to hourly global radiation ratios are computed. Several available hourly global, diffuse and beam radiation models are tested against measured data for both Amman and Aqaba.

Comparison based on all and averaged data showed that Collares Pereira [2] and Garg and Garg [3] are the best fits among other available global models such as Liu and Jordan [1], Newell [4] and M. Alsaad [6] models for both Amman and Aqaba.

Comparison based on all measured data showed that Liu and Jordan model [1] fits adequately measured diffuse data better than other available diffuse models investigated such as Garg and Garg [3], Newell [4] and Orgill and Hollands [10] models, while comparison based on averaged measured data showed that Garg and Garg model [3] is the most suitable among other diffuse models.

In this work an attempt is made to develop new radiation models for Amman and Aqaba that are based on local weather data by using the following approaches:

(1) Hourly global models are developed on the basis of variation of hourly global to monthly average daily ratio

multiplied by the day length ($r_t * t_d$) in terms of hours from solar noon to sunset angle ratio, ($\frac{w}{w_s}$).

(2) Hourly diffuse models are obtained by examining the relation between hourly diffuse to hourly global ratio ($\frac{I_d}{I}$) in terms of clearness index (k_T) in one case, while the behavior of hourly diffuse to monthly average daily ratio multiplied by the day length ($r_d * t_d$) in terms of hours from solar noon to sunset angle ratio ($\frac{w}{w_s}$), is studied in another case.

(3) Hourly beam models are studied by considering the variation of hourly beam to hourly global ratio, ($\frac{I_b}{I}$), in terms of clearness index.

The obtained correlations for the above models are linear and polynomial regressions of second and third degree. The developed radiation models were tested by using i) all measured data and ii) averaged data.

Comparison between results of the developed models showed that global models that properly fit measured data for both Amman and Aqaba are found to be second degree and third degree polynomials.

The adequate hourly diffuse models for Amman and Aqaba are found to be third degree polynomials, of the form $r_d * t_d = f(\frac{w}{w_s})$ when all and averaged data are examined.

The results obtained indicate that the adequate beam models for Amman are linear regressions when all and averaged measured data are tested, while that for Aqaba is linear and second degree polynomial, when all and averaged measured data are used, respectively.

The obtained solar radiation models were used to estimate the collecting area needed to heat a medium size house. A general computer program was developed to simulate the heat load needed for such house. Required area of flat plate collectors to meet the heating load is found and compared with the corresponding area calculated using observed data. Results showed an excellent agreement with calculation based on measured data.

CHAPTER ONE

INTRODUCTION AND LITERATURE SURVEY

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INTRODUCTION AND LITERATURE SURVEY

Solar radiation is considered one of the main substitutes to conventional energy sources. The amount of solar radiation reaching the surface of the earth is attenuated by the terrestrial atmosphere. Attenuation of solar energy is caused by scattering and absorption. Therefore, solar radiation reaching the earth contains both beam and diffuse components.

Measured data of solar radiation are obtained by using several instruments such as pyrheliometer which measures beam radiation and pyranometer which measures global (beam and diffuse) solar radiation.

1.1 Introduction

The design of solar devices such as flat plate collectors which are widely used in Jordan require information on the availability of hourly solar radiation. In locations such as Jordan where hourly radiation measurements are scarce, the need of accurate estimates of the available solar radiation becomes more important.

Several theoretical models had been developed for this purpose. Such models are used to estimate global, diffuse and beam radiation. These models were not developed specifically for application in Jordan.

In general, existing models are obtained by examining hourly global (or diffuse) to monthly average daily ratio in terms of sunset angle and hourly global (or diffuse) to monthly average daily ratio multiplied by the day length in terms of hours from solar moon to sunset angle ratio and by examining hourly diffuse (or beam) to hourly global ratio in terms of clearness index.

In the present research, available hourly solar radiation models are tested against available measured data for both Amman and Aqaba. Based on the above findings, simple and more accurate global, diffuse and beam hourly radiation models are developed for Amman and Aqaba. These models are intended to be linear and polynomials of second and third degree. A comparison of these models on the basis of calculating the percentage error between measured and calculated data is performed.

The present work includes the following objectives :

-Validity of available hourly radiation models for application to Jordan.

-Development of new hourly radiation models using different approachs.

-Applicability of developed models to heating systems.

The available and developed models are applied to two locations in Jordan, namely, Amman (latitude $32^{o}.01'$ N, longitude $35^0.53'$ E and altitude 980 m a.s.l) and Aqaba (latitude $29^0.33'$ N, longitude 35^0E and altitude 51 m a.s.l)

1.2 Literature Survey

Several mathematical approaches have been investigated by many researchers to develop hourly global, diffuse and beam radiation models. However, these models were intended for applications to various locations in several countries other than locations in Jordan.

1.2.1 Hourly global models

Liu and Jordan [1] recomended to use the following theoritical model for the computation of r_t:

$$r_t = \frac{\pi}{24} \frac{(\cos w - \cos w_s)}{(\sin w - w_s \cos w_s)} \qquad \text{..........(1.1)}$$

Where

r_t: hourly global to monthly average daily ratio

w : hour angle

w_s: Sunset angle

Collares-pereira and Rabl [2] investigated hourly global to monthly average daily ratio in terms of sunset angle, w_s. Data were obtained from five stations in the U.S.A for a period of two years.

To reduce the scatter in the results, averages over all days within an w_s for a month are taken. A modified model of equation (1.1) was obtained using least square fit as:

$$r_t = \frac{\pi}{24}(a+b \cos w) * \frac{(\cos w - \cos w_s)}{(\sin w_s - w_s \cos w_s)} \quad ....(1.2)$$

where

$$a = 0.409 + 0.5016 \sin (w_s - 1.047)$$

$$b = 0.6609 - 0.4767 \sin (w_s - 1.047)$$

This model is recommended to provide a complete description of the long term average insolation incident on horizontal surfaces of arbitrary orientations [2].

Garg and Garg [3] tested both Liu and Jordan and Collares-pereira models for four Indian stations: Newdelhi (28^0 $35'$ N), Calcutta (22^0 $39'$N), Poona (18^0 $32'$) and Madras,(13^0 N). Liu and Jordan model was found to be insufficient to predict hourly global radiation from daily sums, while results obtained by using Collares Pereira model were in excellent agreement with the observed values which ensures the validity of this model for India [3]. Garg and Garg [3] modified Liu and Jordan model and developed a new correlation to estimate global radiation for India,

$$r_t = \frac{\pi}{24} \frac{(\cos w - \cos w_s)}{(\sin w_s - w_s \cos w_s)} - 0.008 \sin 3(w-0.65).....(1.3)$$

A simpler alternative expression to that obtained by Liu and Jordan was developed by T.A Newell [4]. Parabolic and cosine models, were investigated using Swanson transformation, who showed that equation (1.1) can be recast such that r_t is a function of one variable. The following transformations are performed.

$$Y_t = r_t * t_d \text{ and } x = \frac{w}{w_s}$$

The integrated value of r_t over the entire day should be unity, i.e,

$$\int_{-c}^{+c} r_t dt = 1$$

Radiation is assumed to be symmetric around solar noon with a continuous distribution from sunrise to sunset. Based on this, the Parabolic form of hourly radiation, I, would be :

$$I = A_m - (A_m/C^2)t^2$$

where

A_m : Maximum radiation (occurs at solar noon)

C = half day length and equals to $\frac{1}{2}$ t_d

t = time from solar noon, hours

The daily total radiation is obtained by integrating hourly radiation over a day length.

$$H = \int_{-c}^{+c} [A_m - (A_m/C^2)t^2] \, dt$$

A_m, can be found by solving this integral

$$A_m = 3H/4C$$

The ratio of I/H is given by the following parabolic correlation :

$$r_t = \frac{I}{H} = (3/4c)(1-t^2/c^2) \quad \text{..............(1.4)}$$

on the other hand, the cosine model form is,

$$r_t = \frac{I}{H} = (\frac{\pi}{4c}) \cos (\pi t/2c) \quad \text{..............(1.5)}$$

Detailed solar system simulation results show that model 1.4 and 1.5 yield accurate results. The main purpose of these models is in conjunction with simplified solar design method development as stated by Newell [4].

P.C Jain [5] analyzed global radiation data for Trieste, Italy for eleven years, 1972-1982 and global and diffuse data for Montreal for eleven years, 1964-1975. The following normal distribution equation was found to fit the analyzed data fairly well.

$$P(t) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left(- \frac{(t-12)^2}{2\sigma^2}\right) \quad \text{...........(1.6)}$$

The standard deviation, σ, needed to predict hourly global radiation is obtained from the following correlations.

$\sigma=0.461 + 0.192\ S_0$, for Treiste ....(1.7)

$\sigma=0.294 + 0.209\ S_0$, for Montreal................(1.8)

Where S_0 is the monthly average daily value of the maximum sunshine duration. Mean error was found not to exceed ±5%. Large disagreement was found 1-2 hours after sunrise and 1-2 hours before sunset but good agreement was found for all the months irrespective of the seasonal and climatic conditions. Jain claimed that his model is recommended to be of universal applicability.

Al-Saad [6] following Jains approach, derived a linear correlation to estimate the standard deviation, σ, in order to predict hourly global radiation for Amman, Jordan.

$$\sigma = 0.153 + 0.226\ S_0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots(1.9)$$

He stated that his correlation can be used for estimating the hourly global radiation at any place in Jordan where measurements are not available.

In another approach, sinusoidal model to predict hourly global radiation was developed by Al-Saad [7]. The general expression of this model is

$$G_h(t) = A_h + B_h \sin[(2\pi/365)n - F_h] \qquad \ldots\ldots\ldots\ldots\ldots(1.10)$$

where

$G_h(t)$:Average global radiation for a given hour, h.

A_h :Mean value of hourly global radiation.

B_h :Amplitude of the sinusoidal function which specifies the amount of the global radiation oscillation about its average value,

t :Period in units of the time,

n :day number,

F_h:Phase angle which parameterises the extent to which the sinusoidal function is shifted horizontally.

A_h, B_h, F_h where obtained by using the following third degree polynomials.

$A_h = 2702.525 + 697.089h - 42.031h^2 + 0.613h^3$

$B_h = 29.683 + 5.771h + 4.797h^2 + 0.291h^3$

$F_h = 68.889 + 0.100h - 0.369h^2 + 0.019h^3$

M.Audi and M.Al-Saad [8], tested three simple global radiation models, namely a normal distribution, half-sine wave and polynomial models using data for a period of five years of the area of Amman, Jordan. None of these models found to fit measured data adequately. Specifically the results show that polynomial model represents the data in about 42% of the hours of the year, the half-sine wave model about 34% and normal distribution model about 32%. A new model which is a combination of the above three simple models was developed to provide a comprehensive representation of the tested data. This new model found to fit the data in about 74%.

Alfonso Soler [9], using Jains approach, also derived an expression to calculate σ, the standard deviation. Measured global radiation data for Uccle, Belgium (48^0N latitude, 50 m.a.s.l) during the period 1951-1980 were used. The obtained correlation is:

$$\sigma = 0.313 + 0.218\ S_0 \qquad \text{..............(1.11)}$$

1.2.2 Hourly diffuse models

Liu and Jordan [1] developed a theoretical model (equation 1.1) to estimate hourly diffuse radiation as well as the hourly global radiation.

His model was derived by equating the diffuse ratio, r_d with the ratio $\frac{I_0}{H_0}$ at same latitude where,

$$I_0=rG_{sc}(\cos\phi\cos\delta\cos w+\sin\phi\sin\delta), \quad \ldots\ldots\ldots\ldots(1.12)$$

$$H_0=\frac{24}{\pi}rG_{sc}(\cos\phi\cos\delta\sin w+w_s\sin\phi\sin\delta), \quad \ldots\ldots(1.13)$$

The sunset hour angle, w_s, is obtained from the relation:

$$\cos w_s=-\tan\phi\tan\delta \quad \ldots\ldots\ldots\ldots(1.14)$$

Ten years data for Blue Hill, Massachusetts and four year data for Helsingfors, Finland were tested against theoretical ratio, r_d. Data were averaged around solar noon using hour angle at $\frac{1}{2}$, $1\frac{1}{2}$, $2\frac{1}{2}$ ...etc. mid hours from solar noon. An excellent agreement between the theoretical ratios is recorded [1].

T.A. Newell [4] Stated that equations (1.4) and (1.5) are suitable to estimate diffuse radiation as well as global radiation. In this case subscript "t" is replaced by subscript "d".

Garg and Garg [3] modified the Liu and Jordan model (equation 1.1) to suit Indian data. The obtained correlation is

$$r_d = \frac{\pi}{24} * \frac{(\cos w - \cos w_s)}{(\sin w - w_s \cos w_s)} + 0.01 \sin 3(w-0.65) \quad .....(1.15)$$

Liu and Jordan model was tested against four Indian stations. Only the rainy months data showed good agreement and were well fitted. If rainy months data were excluded, no points were found to fit exactly the theoretical curve. Equation (1.15) was tested against measured data. Results showed that the difference between observed and calculated data has been narrowed.

Orgill and Hollands [10] examined hourly diffuse to hourly global ratio in terms of clearness index, k_T. Four year measured data for Toronto, Canada ($43^0 48' N$) were tested. For each interval of k_T equal to 0.05 the corresponding values of $\frac{I_d}{I}$ were averaged. Hourly midpoint method is recommended to be used for calculating the extraterrestrial radiation in order to reduce computation time. These averages were plotted against k_T for the mid point of that interval. Segmented linear correlations have been obtained as:

$$\frac{I_d}{I} = \begin{cases} 1.0 - 0.249\ k_T, & k_T \le 0.35 \\ 1.557 - 1.84\ k_T, & 0.35 \le k_T \le 0.75 \\ 0.177, & k_T \ge 0.75 \end{cases} \quad ....(1.16)$$

It is noted that 62% of the data are included in the range of k_T, 0.35 - 0.75 while the range k_T > 0.75 included only 5.6% [9].

P.C Jain [11] examined eleven-year data for Montreal, Canada during the period 1964-1975 against solar time. Hourly diffuse data were found to fit the normal distribution curve closely. The mean distribution is taken at solar noon. The standard deviation, σ, was obtained by matching the value of p(t) for t=12 as:

$$\sigma = 0.270 + 0.222\ S_0 \qquad \text{...........(1.17)}$$

Jain recommended that his model is universally applicable, to hourly diffuse data [11].

Alfonso Soler [9] examined diffuse radiation behavior using Jain's method to estimate r_d for Uccle-Belgium for the period 1951-1980. The standard deviation,σ,correlations obtained were

$$\sigma = 0.335 + 0.233\ S_0 \qquad \text{..............(1.18)}$$

for clear skies and average turbidity and

$$\sigma = 0.295 + 0.217\ S_0 \qquad \text{..............(1.19)}$$

for overcast skies. Values obtained in most cases are different from the corresponding experimental values.

Alfonso Soler [12] in another research examined r_d in terms of (S_d/S_0), monthly average hourly sunshine fraction and I/I_0, the clearness index, taking into consideration different sky conditions. He found out that $r_d = f\left(\frac{I}{I_0}\right)$ fits better the observed data for 1951-1980 regardless the state of the sky. This is due to the smaller scattering of data, when the

$r_d=f(I/I_0)$ model is used.

M. Iqbal [13] and [14] examined whether or not the canadian data fit Liu and Jordan model. Data for diffuse radiation were obtained from three stations, Toronto (latitude $45^0 30'$N) for the period 1967-1975, Montreal (latitude 43^0 48´N) for the period 1964-1975 and Goose Bay (latitude 53^0 18´N) for the period 1962-1975. In general, calculated data of diffuse radiation from the three Canadian stations fit adequately theoretical curves obtained by Liu and Jordan. As a rule, the correspondence is very close during the summer period. On the other hand, as the the day length becomes shorter (mainly at early morning and late after noon) measured data were found to deviate from the theoretical curves.

Erbs etal. [15] investigated hourly diffuse to hourly global radiation ratio versus clearness index. Results were compared with Orgill and Hollands theoretical curve. Data were obtained from four locations in U.S.A. Fort hood (31^0 08´N, 1080 m.a.s.l), Livermore ($37^0 7'$N,486 m.a.s.l), Raleigh (35^0 87´, 441 m.a.s.l) and Maynard (42^0 42´ N, 203 m.a.s.l). A relationship was developed using combined data for the four U.S locations. The following segmented linear equations were obtained:

$$\frac{I_d}{I} = \begin{cases} 1.0 - 0.09\,k_T & , \quad k_T \le 0.22 \\ 0.9511 - 0.1604\,k_T + 4.388\,k_T^2 & \\ -16.638\,k_T^3 + 12.336\,k_T^4 & , \quad 0.22 \le k_T \le 0.8 \\ 0.165 & , \quad k_T \ge 0.8 \end{cases} \quad ..(1.20)$$

A comparison with Orgill and Hollands relation Showed that the two correlations are within 4% of each other for all values of k_T. Furthermore, data were grouped into four seasons and the standard deviation, σ, was found for each of the four locations. Results showed that the correlation tends to overpredict the diffuse radiation in the fall and winter and underestimate the measured data in the spring and summer seasons.

Furthermore, $\frac{I_d}{I}$ against k_c, the ratio of hourly global to clear sky radiation, was studied in order to reduce the standard deviation. It revealed that using k_c as an independent variable did not reduce the uncertainty of the estimated hourly diffuse fraction sufficiently to warrant the extra calculations required when compared with the use of k_T.

Similar study of $\frac{I_d}{I}$ against k_T for Dahran, Saudi Arabia was reported by Baksh, etal. [16]. Segmented linear equations were obtained using measured data for a period of 15 months.

$$\frac{I_d}{I} = \begin{bmatrix} 1.0 - 0.22\,k_T \,, & k_T \le 0.23 \\ 1.235 - 1.26\,k_T \,, & 0.23 \le k_T \le 0.8 \\ 0.225 \,, & k_T \ge 0.8 \end{bmatrix} \quad \ldots.(1.21)$$

It was noticed that 60% of the data points are in the intermediate range, while only 6% are in the range of $k_T < 0.23$.

Turner and Mujahid [17] investigated $\frac{I_d}{I}$ in terms of k_T for Blytheville, Arkansas for the period 1978-1980. Segmented linear equations were obtained in the form of

$$\frac{I_d}{I} = a_1 + b_1 k_T \quad \ldots\ldots\ldots\ldots.(1.22)$$

where a_1 and b_1 are constants that vary with solar altitude angle. Their values for altitude range between 20^0-40^0 are as indicated in Table 1.1.

Table 1.1 :tabulated values of a_1 and b_1 for use with equation (1.22).

k_T range	a_1	b_1
$0 < k_T \le 0.1$	1.000	-0.04
$0.1 < k_T \le 0.2$	1.001	-0.05
$0.2 < k_T \le 0.3$	1.093	-0.51
$0.3 < k_T \le 0.4$	1.330	-1.30
$0.4 < k_T \le 0.5$	1.490	-1.70
$0.5 < k_T \le 0.6$	1.740	-2.20
$0.6 < k_T \le 0.7$	1.500	-1.80
$0.7 < k_T \le 0.8$	0.520	-0.40
$k_T > 0.8$	0.200	-0.00

Bugler [18] also studied hourly diffuse to hourly global ratio in terms of k_c. Data used were for Melbourn, Australia (latitude 38^0S). By plotting data separately in 10^0 ranges of solar altitude the following correlations were obtained:

$$\frac{I_d}{I} = \begin{bmatrix} 0.94 & , & 0 < \frac{I}{I_c} \le 0.4 \\ \dfrac{1.29 - 1.19(\frac{I}{I_c})}{1.00 - 0.334(\frac{I}{I_c})} & , & 0.4 < \frac{I}{I_c} \le 1.0 \\ 0.15 & , & \frac{I}{I_c} \ge 1.0 \end{bmatrix} \quad .....(1.23)$$

M.Audi and M.Al-Saad [19] developed a new model for predicting hourly diffuse radiation for Amman. In a similar way to the global radiation model developed by both researchers [8], the diffuse model consists of three components, namely normal distribution, half-sine wave and a polynomial of fourth degree. These components were tested individually as seperate models. Non of them was found to be adequately acceptable for the tested data. In the other hand results based on the new model showed that data can be represented up to 92.4% of the time if the two early morning and the two late afternoon hours are neglected.

1.2.3 Hourly beam models

Turner and Mujahid [20] investigated hourly beam to hourly global ratio in terms of clearness index for Blytheville, Arkansas for the period 1987-1980. Segmented linear equations were obtained in the form.

$$\frac{I_b}{I} = a_2 + b_2 k_T \qquad ....(1.24)$$

where a_2 and b_2 are constants vary with solar altitude angle. Their values, for altitude range between 20^0- 40^0 are shown in Table 1.2.

Table 1.2 : Tabulated values of a_2 and b_2 for use with equation (1.24)

k_T range	a_2	b_2
0.0 - 0.1	0.000	0.02
0.1 - 0.2	-0.003	0.05
0.2 - 0.3	-0.007	0.39
0.3 - 0.4	-0.239	0.95
0.4 - 0.5	-0.663	2.01
0.5 - 0.6	-0.748	2.18
0.6 - 0.7	-0.640	2.00
0.7 - 0.8	-0.480	0.40
0.8 - 0.9	-0.800	0.00

Alfonso Soler [9] used Jain's approach to estimate hourly beam radiation. Data for Uccle, Belgium for the period 1951-1980 were used. The standard deviation σ values were found to bear linear correlation with S_0. Two expressions were derived:

$$\sigma = 0.104 + 0.216\ S_0 \qquad ....(1.25)$$

For clear sky condition and minimum turbidity and

$$\sigma = -0.07 + 0.217\ S_0 \qquad ....(1.26)$$

for all data regardless of the state of the sky.

CHAPTER TWO

ANALYSIS AND SAMPLE OF CALCULATION

CHAPTER TWO

2.1 Analysis

Measured hourly global and diffuse radiation data were obtained from the Solar Energy Center at the Royal Scientific Society for both Amman and Aqaba. Four year 1984-1988, data, for Amman and one-year 1987,data, for Aqaba are available. Data points for the first two early morning hours and late two afternoon hours for both Amman and Aqaba were discarded due to possible measuring errors. Amman measured data for the year 1985 were incomplete. Five months data, namely January, July, October, November and December were not recorded. To incorporate the year 1985 in the present calculations, the unrecorded data are replaced by the averages of similar months from years 1984, 1987 and 1988. The global and diffuse radiation data for Amman were averaged over four-year period and reduced to 144 points each. The available measured radiation data are presented only graphically in chapter 5 due to space limitation. These data are available upon request from the author.

Hourly beam radiation data are obtained by substracting the hourly diffuse radiation from the hourly global radiation. The results are presented graphically in chapter 5.

In order to test the applications of the various available models and to develop new models for Jordan the following ratios and parameters are evaluated using the available data:

(1) Hourly diffuse and beam to hourly global ratios.

(2) Hourly global and hourly diffuse to monthly average daily ratios (multiplied by the day length).

(3) Averages of measured hourly diffuse to hourly global ratios within 0.05 clearness index interval.

(4) The ratio of hours from solar noon to sunset hour angle.

The above calculated ratios are presented graphically in chapter 5

Extraterrestrial radiation on a horizontal surface for an hour is calculated using the following equation [21]

$$I_o = \frac{12*3600}{\pi} G_{sc}\left[1+0.033 \cos\left(\frac{360n}{365}\right)\right] x\left[\cos\phi \cos\delta(\sin w_2 - \sin w_1) + \frac{2\pi(w_2 - w_1)}{360} \sin\phi \sin\delta\right)] \quad ....(2.1)$$

where G_{sc} is the solar constant and equal to $1367\frac{W}{m^2}$.

Hourly extraterrestrial radiation for Amman and Aqaba were calculated using equation 2.1. The clearness index $\frac{I}{I_o}$ is then obtained.

Available models, equations (1.1-1.4), (1.6) and (1.9) for global radiation and equations (1.1), (1.4) (1.15) and (1.16) for diffuse radiation in addition to equation (1.24) for beam radiation have been tested against measured data for both Amman and Aqaba. Calculated values based on the above models are obtained by using basic programs. Errors for each hour and monthly average daily measured error between measured and calculated data were found by using Lotus 123 program. The error is defined as

$$\text{Error} = \frac{I_m - I_{cal}}{I_m} \qquad \text{..............(2.2)}$$

I_m : measured hourly radiation.

I_{cal}: calculated hourly radiation.

New models have been developed using Ener Graphics program. Hourly global and diffuse to monthly average daily ratio multiplied by the day length in terms of hours from solar noon to sunset angle ratio in addition to hourly diffuse and beam to hourly global ratio in terms of clearness index are studied for both Amman and Aqaba. This study is performed for the average and all data. Furthermore, hourly diffuse to hourly global radiation ratio in terms of clearness index is tested using Orgill and Hollands approach.Models obtained, as applied to Amman and Aqaba, are polynomial fits of linear, second and third degree. These developed models are tested against measured data. Errors obtained based on developed global, diffuse and beam models are calculated and a summary of the results is presented in chapter 4.

The developed models estimate hourly solar radiation on horizontal surface. To evaluate the performance of flat plate collectors, the geometric factor R_b must be calculated by using the following equation [21].

$$R_b = \frac{\cos(\phi-\beta)\cos\delta\cos w + \sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\cos w + \sin\phi\sin\delta} \quad ..(2.3)$$

Where β is the tilt angle. The total solar radiation on a tilted surface, I_t is calculated using equation [21].

$$I_t = I_b R_b + I_d\left(\frac{1+\cos\beta}{2}\right) + (I_b+I_d)\,\rho_{ref}\left(\frac{1-\cos\beta}{2}\right) \quad ...(2.4)$$

Calculation of heat losses needed for estimating the heat load of a medium size house is performed by using the equation,

$$Q = U.A.\ (T_i - T_0) \quad ....(2.5)$$

where,

U is overall heat transfer Coefficient in W/m^2C^0, which can be evaluated using the relation.

$$\frac{1}{U} = f_i + \frac{X_a}{k_a} + \frac{X_b}{k_b} + \frac{X_c}{k_c} + f_0 \quad ....(2.6)$$

A : Surface area, m^2

T_i is the inside temperature and

T_0 is the outside temperature.

The overall heat transfer coefficient, U, for inhomogeneous construction material is calculated by using the relation

$$U = \sum_{i=1}^{n} \frac{U_i A_i}{A} \quad ....(2.7)$$

where,

U_i is Heat transfer coefficient for area part i,

A_i is Surface area of part i,

A is Total area of the inhomogeneous surface.

Infiltration heat losses are calculated using the following equation:

$$Q_{inf} = (\rho C_p)_{air} * (q_h) * L\ (T_i - T_0)\ ....(2.8)$$

where,

ρC_p is Product of density and its specific heat of air

q_h is Infiltration rate, m^3/hr/m,

L is Crack length [m].

2.2 Sample of Calculation

In this section calculations of global ratios using Collares pereira model (Eqn. 1.2) will be presented in details. Radiation recieved at Amman during January will be taken as an example.

The altitude angle $\phi = 32^o.01'$

The mean day of January N=17

For the hour 11-12 $w=-7.5^o$ or -0.131 radians.

The declanation angle, δ, can be obtained using the following equation [21].

$$\delta = 23.45 \sin \left(360 \frac{284+N}{365}\right)$$

$$\delta = 23.45 \sin \left(360 \frac{301}{365}\right)$$

$$\delta = -20.92^0$$

The sunset angle is obtained by using Eqn. 1.14

$$w_s = \cos^{-1} [-\tan \phi \tan \delta]$$

$$w_s = \cos^{-1}[-\tan 32.01' \tan -20.92^0]$$

$$= 76.2^0 \text{ or } 1.33 \text{ radians.}$$

The consants a,b now can be calculated:

$$a=0.409 + 0.5016 \sin(w_s-1.047)$$

$$a=0.409 + 0.5016 \sin (1.33 - 1.047) = 0.549$$

$$b=0.6609-0.4767 \sin (w_s-1.047)$$

$$b=0.6609-0.4767 \sin (1.33-1.047) = 0.528$$

By substituting w, w_s, a, b in Eqn. 1.2, r_t is found to be 0.162.

Repeating the same calculation steps for each morning and afternoon hours the following calculated hourly global ratios would be obtained.

Hour	6.7	7-8	8-9	9-10	10-11	11-12
Global ratio, r_t	0.0	0.0216	0.065	0.108	0.142	0.162

In the other hand the actual measured global ratios for January (averages around solar noon are taken) are:

Hour	6-7	7-8	8-9	9-10	10-11	11-12
Global ratio, r_t	0.0	0.015	0.063	0.113	0.146	0.165

Error difference between measured and calculated ratios is obtained by using Eqn. 2.2.

Hour	6-7	7-8	8-9	9-10	10-11	11-12
Mean Error	0.0	-0.44	-0.032	0.044	0.027	0.018

Accordingly the monthly average daily mean error for January is -0.077.

CHAPTER THREE

AVAILABLE HOURLY RADIATION MODELS

CHAPTER THREE

AVAILABLE HOURLY RADIATION MODELS

In this research the available radiation models stated in chapter one were used to predict the solar radiation for both Amman and Aqaba. These predicted values were compared with the measured data and the error was calculated using equation 2.2. A Summary of monthly average daily mean errors obtained by examining existing models against all and averaged measured data around solar noon of global and diffuse radiation are presented in tables 3.1-3.8, while that for beam radiation are in table 3.9. It is noted that when all results are examined, the annual mean errors found to be too high. This occurs mainly because the early and late two hours are included in calculations. For example, the error incurred in calculating the radiation using Collares pereira model for the hour 6-7 rises up to 86.7% while for the hour 17-18 it rises up to 774.3%. This applies as well as for diffuse radiation.

3.1 Available hourly global radiation models

Liu and Jordan [1], Collares pereira [2] , Garg and Garg [3], Newell [4], and Al-Saad [6] hourly global models were tested against all and averaged measured data. Estimation of error between measured data and calculated values for these existing models was carried out. Monthly average daily mean error was also calculated for each month.

3.1.1 Comparison based on all data-Amman

Based on the calculated errors, the following observation can be made.

Collares pereira model shows lowest mean errors for months of January, April, September and November where its annual mean error is -0.244. Garg and Garg model represents the lowest mean errors for January, March , October and December where its annual mean error is -0.19. Al-Saad model shows lowest mean errors for four months too, but from May-August and its annual mean error is -0.972.

Considering the value of mean errors between 0-10% as an accepted and reasonable error we find that Collares Pereira and Garg and Garg models have reasonable results for months of February and April to August. Al-Saad model gives reasonable results for the months of April to August. Liu and Jordan and Newell models overestimate global radiation in general and do not give reasonable results, while their annual mean errors are -0.391 and -0.481 respectively.

3.1.2 Comparison based on averaged data-Amman

Based on the estimated errors, the following observation are made:

Collares Pereira model is the best for seven months from December to July except March. Garg and Garg model is the best for five months, only: March, August, and October to December. Collares pereira, Garg and Garg models fit the data reasonably for all months except october for the first and their annual mean error is 0.003. Liu and Jordan model fits reasonably the months from April to December and its annual mean error is -0.069. Newell model fits reasonably the months from May to July, October and November, Where its annual mean error is -0.106. Al-Saad model fits reasonably the months from April to September and its annual mean error is -0.664.

3.1.3. Comparison based on all data-Aqaba

Calculated errors yield the following observations:

Collares pereira model presents the lowset mean errors for six months: January, March to July and September except May, where the annual error is -0.189. Garg and Garg model is the lowset for four months: February and October to December, and its annual mean error is -0.074. The other two months: May and August are presented well using Al-Saad model where its annual mean error is -0.954.

Collares pereira model fits the data reasonably well for the months of January to August, except February. Garg and Garg model fits the months of January to October reasonably well, except September. Liu and Jordan model fits February and months of May to August reasonably well, where its annual mean error is -0.343. Finally Al-Saad model fits the months from April to August, reasonably well.

3.1.4 Comparison based on averaged data-Aqaba

Based on the calculated errors, the following observations are made:

Collares pereira model presents the lowest errors for the months of January, April to September and December, except June. The annual mean error is 0.027. Garg and Garg model fits February, March and November the best fit, where its annual mean error is 0.006. Garg and Garg model fits all months reasonably well. Collares pereira model fits measured data reasonably well for all months except February and October. Liu and Jordan model fits all data reasonably well, except for March, where its annual mean error is -0.042. Newell fits the months of February, May to August, October and November reasonably well. Its annual mean error is -0.077. Al-Saad model fits April to September reasonably well, where its annual mean error is -0.498.

Based on the above discussion Collares Pereira equation (1.2) and Garg and Garg equation (1.3) global radiation models are the most suitable for Jordan among existing models. A summary of obtained results based on both models is shown in table 3.10.

TABLE 3.1 COMPARISON BETWEEN MEAN ERRORS OF HOURLY GLOBAL RADIATION BASED ON EXISTING MODELS - AMMAN

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
COLLARES PERIERA	-0.207	-0.071	-0.173	-0.026	-0.083	-0.052	-0.051	-0.057	-0.231	-0.754	-0.803	-0.423	-0.244
LIU AND JORDAN	-0.354	-0.049	-0.345	-0.107	-0.153	-0.104	-0.108	-0.135	-0.398	-1.192	-1.096	-0.645	-0.391
GARG AND GARG	-0.207	-0.079	-0.158	-0.040	-0.083	-0.043	-0.047	-0.065	-0.232	-0.131	-0.808	-0.392	-0.190
NEWELL	-0.407	-0.188	-0.435	-0.147	-0.204	-0.145	-0.153	-0.188	-0.498	-1.473	-1.213	-0.718	-0.481
M. AL-SAAD	-1.628	-1.898	-0.479	-0.033	-0.056	-0.009	-0.015	-0.050	-0.408	-5.343	-0.948	-0.791	-0.972

TABLE 3.2 COMPARISON BETWEEN MEAN ERRORS OF HOURLY GLOBAL RADIATION BASED ON EXISTING MODELS - AMMAN (THE AVERAGE OF EACH TWO SIMILAR HOURS IS TAKEN)

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
COLLARES PERIERA	-0.077	-0.034	-0.025	-0.013	0.006	0.010	-0.001	-0.001	0.025	0.135	0.019	-0.003	0.003
LIU AND JORDAN	-0.187	-0.109	-0.141	-0.090	-0.043	-0.029	-0.048	-0.065	-0.056	0.074	-0.047	-0.091	-0.069
GARG AND GARG	-0.082	0.047	-0.002	-0.014	0.014	0.023	0.008	0.000	0.029	0.005	0.007	-0.003	0.003
NEWELL	-0.226	-0.139	-0.201	-0.129	-0.078	-0.060	-0.084	-0.108	-0.101	0.044	-0.072	-0.119	-0.106
M. AL-SAAD	-5.245	-1.242	-0.197	-0.018	0.040	0.055	0.037	0.013	-0.024	-0.106	-0.401	-0.876	-0.664

TABLE 3.3 COMPARISON BETWEEN MEAN ERRORS OF HOURLY GLOBAL RADIATION BASED ON EXISTING MODELS - AQABA

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
COLLARES FERIERA	-0.018	0.148	-0.085	-0.039	-0.035	0.005	0.012	-0.012	-0.127	-1.482	-0.390	-0.246	-0.189
LIU AND JORDAN	-0.102	0.088	-0.223	-0.125	-0.096	-0.037	-0.034	-0.080	-0.263	-2.274	-0.566	3.403	-0.343
GARG AND GARG	-0.022	0.078	-0.089	-0.050	-0.035	0.012	0.015	-0.020	-0.131	-0.068	-0.360	-0.219	-0.074
NEWELL	-0.132	0.078	-0.295	-0.178	-0.140	-0.069	-0.066	-0.126	-0.342	-2.760	-0.637	-0.459	-0.427
M. AL-SAAD	-0.961	-1.158	-0.299	-0.057	-0.008	0.045	0.047	-0.004	-0.265	-7.782	-0.421	-0.585	-0.954

TABLE 3.4 COMPARISON BETWEEN MEAN ERRORS OF HOURLY GLOBAL RADIATION BASED ON EXISTING MODELS - AQABA
(THE AVERAGE OF EACH TWO SIMILAR HOURS IS TAKEN)

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
COLLARES FERIERA	-0.003	0.154	-0.035	0.000	0.007	0.023	0.022	0.011	0.020	0.107	0.025	-0.010	0.027
LIU AND JORDAN	-0.082	0.097	-0.154	-0.074	-0.045	-0.016	-0.022	-0.051	-0.065	0.035	-0.034	-0.094	-0.042
GARG AND GARG	-0.014	-0.012	-0.014	0.001	0.014	0.034	0.030	0.013	0.024	-0.008	0.014	-0.016	0.006
NEWELL	-0.110	0.085	-0.216	-0.119	-0.081	-0.045	-0.053	-0.092	-0.112	-0.001	-0.056	-0.123	-0.077
M. AL-SAAD	-3.593	-0.868	-0.204	-0.007	0.037	0.064	0.058	0.023	-0.037	-0.116	-0.168	-1.165	-0.498

3.2 Available hourly diffuse radiation models

Liu and Jordan [1], Garg and Garg [3], Newell [4] and Orgill and Hollands [10] models have been tested against measured data. Errors between measured and calculated values based on these models are computed for each hour. The mean error for each month is calculated considering all data as well as averaged data.

3.2.1 Comparison based on all data-Amman

Based on obtained errors between measured and predicted data using these models, the following observations are made.

Liu and Jordan is the best for January, March, April, and September to December. Its annual mean error is -0.114. Garg and Garg presents the lowest mean errors for months May to August, where its annual mean error is -0.387.

Considering the value of mean error between 0-10% as an accepted error, Liu and Jordan and Newell models present reasonable results for months of January to September, except March for the latter, while Garg and Garg shows reasonable results for months April to September. Orgill and Hollands model showed disagreement with measured data.

3.2.2 Comparison based on averaged data-Amman

Based on estimated errors between measured and calculated data, it is observed that Garg and Garg model is the best for the months from May to October and its annual mean error is 0.019, while Liu and Jordan model presents the lowset mean errors for the months of January to March and December and its annual mean error is 0.033. Liu and Jordan, and Newell models fit measured data reasonably well except for October. Garg and Garg model fits all months reasonably well except for March and November.

3.2.3 Comparison based on all data-Aqaba

Considering the same models as in the Amman case, obtained errors yield the following observations:

Liu and Jordan model is the best for months March and september to December, where its annual mean error is -0.024. Garg and Garg model presents the lowest mean errors for February, and April to August, where its annual mean error is -0.149.

Liu and Jordan, Garg and Garg and Newell models fit Measured data reasonably for January to September, except one month each. Orgill and Hollands model overestimates hourly diffuse radiation for Aqaba as well as for Amman.

3.2.4 Comparison based on averaged data-Aqaba

Errors between measured and calculated values based on Liu and Jordan, Garg and Garg and Newell models are obtained. It is observed that all three models fit all months reasonably well except for February and October for Liu and Jordan and Newell models. Garg and Garg shows lowset mean errors for the months of January to october except March and its annual mean error is -0.003. The other three months fit well the Newell model, where its annual mean errors is 0.042.

From the above discussion it is clear that among existing models Liu and Jordan model equation (1.1) is the most suitable hourly diffuse model when all data are considered, while Garg and Garg model equation (1.15) is the most suitable hourly diffuse model when averaged data are considered. A summary of obtained results based on both models is shown in table 3.11.

3.3 Available hourly beam models

A study is performed by examining Turner and Mujahed [20] beam radiation model against measured data, where the corresponding constants for Amman and Aqaba are used.

Errors between measured and calculated values for both Amman and Aqaba are obtained. It is observed that estimated radiation values based on this model are less than those measured values. The annual mean error for Amman is 0.385, while for Aqaba is 0.217.

TABLE 3.5 COMPARISON BETWEEN MEAN ERRORS OF HOURLY DIFFUSE RADIATION BASED ON EXISTING MODELS - AMMAN

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
LIU AND JORDAN	-0.044	0.095	-0.067	0.000	0.041	0.050	0.051	0.047	0.004	-1.055	-0.236	-0.255	-0.114
GARG AND GARG	-0.132	-0.164	-0.185	-0.059	0.000	0.018	0.018	0.011	-0.066	-3.288	-0.363	-0.436	-0.387
NEWELL	-0.068	-0.011	-0.114	-0.023	0.028	0.046	0.046	0.036	-0.023	-1.325	-0.275	-0.294	-0.165
ORGILL AND HOLLANDS	-0.875	-0.925	-0.791	-0.746	-0.627	-0.880	-1.276	-0.907	-1.088	-1.241	-0.746	-0.990	-0.924

TABLE 3.6 COMPARISON BETWEEN MEAN ERRORS OF HOURLY DIFFUSE RADIATION BASED ON EXISTING MODELS - AMMAN (THE AVERAGE OF EACH TWO SIMILAR HOURS IS TAKEN)

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
LIU AND JORDAN	-0.011	0.007	-0.011	0.030	0.046	0.053	0.052	0.050	0.062	0.139	0.012	-0.030	0.033
GARG AND GARG	0.098	-0.080	-0.124	-0.022	0.009	0.026	0.024	0.017	0.012	0.058	0.139	0.068	0.019
NEWELL	-0.031	-0.008	-0.050	0.011	0.034	0.049	0.047	0.039	0.044	0.125	-0.004	-0.051	0.017

TABLE 3.7 COMPARISON BETWEEN MEAN ERRORS OF HOURLY DIFFUSE RADIATION BASED ON EXISTING MODELS - AQABA

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
LIU AND JORDAN	0.021	0.173	-0.018	0.037	0.034	0.051	0.047	0.031	-0.016	-0.365	-0.170	-0.107	-0.024
GARG AND GARG	-0.033	-0.042	-0.112	-0.006	-0.010	0.018	0.013	-0.012	-0.092	-1.031	-0.269	-0.213	-0.149
NEWELL	0.007	0.166	-0.053	0.019	0.017	0.045	0.039	0.015	-0.047	-0.468	-0.201	-0.135	-0.050
ORGILL AND HOLLANDS	-0.478	-0.342	-0.384	-0.115	-0.231	-0.403	-0.708	-0.543	-0.563	-0.563	-0.914	-0.719	-0.497

TABLE 3.8 COMPARISON BETWEEN MEAN ERRORS OF HOURLY DIFFUSE RADIATION BASED ON EXISTING MODELS - AQABA (THE AVERAGE OF EACH TWO SIMILAR HOURS IS TAKEN)

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP.	OCT	NOV	DEC	ANNUAL MEAN
LIU AND JORDAN	0.033	0.178	0.030	0.044	0.042	0.052	0.051	0.049	0.057	0.125	0.010	0.009	0.057
GARG AND GARG	-0.006	-0.015	-0.058	0.003	0.001	0.023	0.021	0.012	0.006	0.051	-0.026	-0.048	-0.003
NEWELL	0.020	0.171	0.001	0.028	0.027	0.046	0.043	0.036	0.038	0.110	-0.004	-0.008	0.042

TABLE 3.9 COMPARISON BETWEEN MEAN ERRORS OF HOURLY BEAM RADIATION BASED ON TURNER - MUJAHID MODEL

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
a) FOR AMMAN	0.585	0.570	0.466	0.327	0.256	0.234	0.252	0.251	0.299	0.419	0.407	0.551	0.385
b) FOR AQABA	0.165	0.152	0.277	0.100	0.150	0.145	0.174	0.171	0.212	0.253	0.340	0.468	0.217

Table 3.10 EVALUATION OF AVAILABLE HOURLY GLOBAL RADIATION MODELS

AMMAN ALL-DATA

MODEL	LOWEST MEAN ERRORS	REASONABLE ERRORS	ANNUAL MEAN ERROR
GARG & GARG	4 MONTHS	6 MONTHS	-0.190
COLLARES	4 MONTHS	6 MONTHS	-0.244

AMMAN-AVERAGED DATA

COLLARES	7 MONTHS	11 MONTHS	0.003
GARAG & GARG	5 MONTHS	12 MONTHS	0.003

AQABA-ALL DATA

GARAG & GARG	4 MONTHS	9 MONTHS	-0.074
COLLARES	6 MONTHS	7 MONTHS	-0.189

AQABA-AVERAGED DATA

COLLARES	7 MONTHS	10 MONTHS	0.027
GARAG & GARG	3 MONTHS	12 MONTHS	0.006

Table 3.11 EVALUATION OF AVAILABLE HOURLY DIFFUSE RADIATION MODELS

AMMAN-ALL DATA

MODEL	LOWEST MEAN ERRORS	REASONABLE ERRORS	ANNUAL MEAN ERROR
LIU & JORDAN	7 MONTHS	9 MONTHS	-0.114
GARG & GARG	4 MONTHS	6 MONTHS	-0.387

AMMAN-AVERAGED DATA

MODEL	LOWEST MEAN ERRORS	REASONABLE ERRORS	ANNUAL MEAN ERROR
GARG & GARG	6 MONTHS	10 MONTHS	0.019
LIU & JORDAN	4 MONTHS	11 MONTHS	0.003

AQABA-ALL DATA

MODEL	LOWEST MEAN ERRORS	REASONABLE ERRORS	ANNUAL MEAN ERROR
LIU & JORDAN	5 MONTHS	8 MONTHS	-0.024
GARG & GARG	6 MONTHS	8 MONTHS	-0.149

AQABA-AVERAGED DATA

MODEL	LOWEST MEAN ERRORS	REASONABLE ERRORS	ANNUAL MEAN ERROR
GARG & GARG	9 MONTHS	12 MONTHS	-0.003
NEWELL	3 MONTHS	10 MONTHS	0.042
LIU AND JORDAN	---	10 MONTHS	0.057

CHAPTER FOUR

DEVELOPED HOURLY RADIATION MODELS

CHAPTER FOUR

DEVELOPED HOURLY RADIATION MODELS

The measured data were processed as stated in chapter 2 and fitted to linear and polynomial regressions using least square approach. The following models are obtained:

4.1 Developed hourly global models

The hourly global models are obtained by examining the hourly global to monthly average daily ratio multiplied by the day length against the ratio from solar noon to sunset hours.

a. Models obtained by using all measured data-Amman are as follows:

(i) linear:

$$r_t * t_d = 1.955 - 1.889 \left(\frac{w}{w_s}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots(4.1)$$

(ii) second degree:

$$r_t * t_d = 1.783 - 0.839 \left(\frac{w}{w_s}\right) - 1.09\left(\frac{w}{w_s}\right)^2 \quad \ldots\ldots(4.2)$$

(iii) Third degree

$$r_t * t_d = 1.65\ 7 + 0.576\left(\frac{w}{w_s}\right) - 4.616\left(\frac{w}{w_s}\right)^2 + 2.39\left(\frac{w}{w_s}\right)^3 \ldots\ldots(4.3)$$

b. Models obtained by using averaged data-Amman are as follows

(i) linear:

$$r_t * t_d = 1.95 - 1.882 \left(\frac{W}{W_s}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots(4.4)$$

(ii) second degree:

$$r_t * t_d = 1.776 - 0.817 \left(\frac{W}{W_s}\right) - 1.107\left(\frac{W}{W_s}\right)^2 \quad \ldots.(4.5)$$

(iii) Third degree

$$r_t*t_d=1.651+0.585\left(\frac{W}{W_s}\right) - 4.595\left(\frac{W}{W_s}\right)^2+2.364\left(\frac{W}{W_s}\right)^3\ldots(4.6)$$

A summary of monthly averaged daily mean errors obtained by examining these models against all and averaged data for Amman are shown in tables 4.1 and 4.2.

c. Models obtained by using all measured data-Aqaba

(i) linear:

$$r_t * t_d = 1.932 - 1.848 \left(\frac{W}{W_s}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots(4.7)$$

(ii) second degree:

$$r_t * t_d = 1.753 - 0.771 \left(\frac{W}{W_s}\right) - 1.101\left(\frac{W}{W_s}\right)^2 \quad \ldots.(4.8)$$

(iii) Third degree

$$r_t*t_d=1.625+0.642\left(\frac{W}{W_s}\right) - 4.552\left(\frac{W}{W_s}\right)^2+2.295\left(\frac{W}{W_s}\right)^3\ldots(4.9)$$

d. Models obtained by using averaged data-Aqaba

(i) linear:

$$r_t * t_d = 1.931 - 1.846 \left(\frac{W}{W_s}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots(4.10)$$

(ii) second degree:

$$r_t*t_d=1.752-0.769\left(\frac{W}{W_s}\right) - 1.101\left(\frac{W}{W_s}\right)^2\ldots\ldots\ldots\ldots\ldots(4.11)$$

(iii) Third degree

$$r_t * t_d = 1.625 + 0.63 \left(\frac{W}{W_s}\right) - 4.521\left(\frac{W}{W_s}\right)^2 + 2.274\left(\frac{W}{W_s}\right)^3 \quad \ldots(4.12)$$

A summary of monthly averaged daily mean errors obtained by examining these models against all and averaged data for Aqaba are shown in tables 4.3 and 4.4.

4.2 Developed hourly diffuse models

The hourly diffuse models obtained by examinning hourly diffuse to hourly global ratio in terms of clearness index are as follows

a., Amman -all data

(i) Linear:

$$\frac{I_d}{I} = 0.613 - 0.611\ k_T \quad \ldots\ldots\ldots\ldots(4.13)$$

(ii) second degree:

$$\frac{I_d}{I} = 0.699 - 1.034\ k_T + 0.429\ k_T^2 \quad \ldots\ldots\ldots(4.14)$$

(iii) Third degree:

$$\frac{I_d}{I} = 0.51 + 0.768\ k_T - 3.778\ k_T^2 + 2.819\ k_T^3 \quad \ldots\ldots(4.15)$$

(iv) Segmented linear equations:

$$\frac{I_d}{I} = \begin{bmatrix} 0.646 - 0.68\ k_T & , & 0 \le k_T \le 0.492 \\ 0.658 - 0.704\ k_T & , & 0.492 \le k_T \le 0.75 \\ 0.13 & , & k_T \ge 0.75 \end{bmatrix} \quad \ldots\ldots(4.16)$$

TABLE 4.1 COMPARISON BETWEEN MEAN ERRORS OF HOURLY GLOBAL RADIATION BASED ON OBTAINED POLYNOMIAL & LINEAR EQUATIONS - AMMAN

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
LINEAR	-0.306	-0.109	-0.384	-0.077	-0.125	-0.079	-0.083	-0.111	-0.400	-2.645	-0.987	-0.602	-0.492
SECOND DEG. POLYN.	-0.158	-0.092	-0.022	-0.035	-0.124	-0.091	-0.090	-0.091	-0.185	-0.252	-0.751	-0.277	-0.181
THIRD DEG. POLYN.	-0.186	-0.073	-0.182	-0.031	-0.101	-0.068	-0.067	-0.074	-0.246	-0.894	-0.765	-0.379	-0.256

TABLE 4.2 COMPARISON BETWEEN MEAN ERRORS OF HOURLY GLOBAL RADIATION BASED ON OBTAINED POLYNOMIAL & LINEAR EQUATIONS - AMMAN (THE AVERAGE OF EACH TWO SIMILAR HOURS IS TAKEN)

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
LINEAR	-0.149	-0.068	-0.158	-0.061	-0.020	-0.007	-0.025	-0.043	-0.047	0.008	-0.014	-0.065	-0.054
SECOND DEGREE POLYN.	-0.043	-0.053	0.061	-0.021	-0.024	-0.020	-0.034	-0.029	0.035	-0.008	0.018	0.041	-0.006
THIRD DEGREE POLYN.	-0.064	-0.038	-0.034	-0.019	-0.008	-0.003	-0.016	-0.017	0.014	0.122	0.019	0.008	-0.003

TABLE 4.3 COMPARISON BETWEEN MEAN ERRORS OF HOURLY GLOBAL RADIATION BASED ON OBTAINED POLYNOMIAL & LINEAR EQUATIONS - AQABA

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
LINEAR	-0.075	-0.462	-0.274	-0.113	-0.074	-0.017	-0.014	-0.064	-0.286	-4.838	-0.516	-0.377	-0.593
SECOND DEG. POLYN.	-0.030	-0.034	-0.034	-0.074	-0.078	-0.031	-0.025	-0.052	-0.129	-0.188	-0.420	-0.232	-0.111
THIRD DEG. POLYN.	-0.024	0.091	-0.114	-0.063	-0.057	-0.013	-0.007	-0.035	-0.159	-2.202	-0.398	-0.244	-0.269

TABLE 4.4 COMPARISON BETWEEN MEAN ERRORS OF HOURLY GLOBAL RADIATION BASED ON OBTAINED POLYNOMIAL & LINEAR EQUATIONS - AQABA
(THE AVERAGE OF EACH TWO SIMILAR HOURS IS TAKEN)

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
LINEAR	-0.056	-0.336	-0.193	-0.061	-0.025	0.003	-0.003	-0.035	-0.069	-0.046	-0.010	-0.072	-0.075
SECOND DEGREE POLYN.	-0.016	-0.031	0.001	-0.032	-0.031	-0.011	-0.014	-0.026	0.009	-0.029	0.006	-0.010	-0.015
THIRD DEGREE POLYN.	-0.008	0.107	-0.059	-0.020	-0.012	0.007	0.004	-0.009	-0.001	0.085	0.018	-0.011	0.008

b., Amman, averaged data

(*i*) Linear:

$$\frac{I_d}{I} = 0.855 - 1.032\ k_T \qquad \text{...........(4.17)}$$

(*ii*) second degree:

$$\frac{I_d}{I} = 0.899 - 1.205\ k_T + 0.16\ k_T^2 \qquad \text{.........(4.18)}$$

(*iii*) Third degree:

$$\frac{I_d}{I} = 1.189 - 3.05\ k_T + 3.875\ k_T^2 - 2.386\ k_T^3 \qquad \text{.......(4.19)}$$

A summary of monthly averaged daily mean errors obtained by using these models against all and averaged data for Amman are shown in tables 4.5 and 4.6.

c., Aqaba-all data

(*i*) Linear:

$$\frac{I_d}{I} = 0.667 - 0.619\ k_T \qquad \text{...........(4.20)}$$

(*ii*) second degree:

$$\frac{I_d}{I} = 0.706 - 0.801\ k_T + 0.181\ k_T^2 \qquad \text{...........(4.21)}$$

(*iii*) Third degree:

$$\frac{I_d}{I} = 0.431 + 1.527\ k_T - 5.14\ k_T^2 + 3.635\ k_T^3 \qquad \text{..(4.22)}$$

(*iv*) Segmented linear equations:

$$\frac{I_d}{I} = \begin{cases} 0.635 - 0.48\ k_T, & 0 \le k_T \le 0.5 \\ 0.835 - 0.88\ k_T, & 0.5 \le k_T \le 0.75 \\ 0.175, & k_T \ge 0.75 \end{cases} \qquad \text{......(4.23)}$$

d. Aqaba- averaged data

(i) Linear:

$$\frac{I_d}{I} = 1.032 - 1.209\ k_T \quad \text{................(4.24)}$$

(ii) second degree:

$$\frac{I_d}{I} = 1.127 - 1.548\ k_T + 0.294\ k_T^2 \quad \text{.............(4.25)}$$

(iii) Third degree:

$$\frac{I_d}{I} = 1.383 - 3.014\ k_T + 3.031\ k_T^2 - 1.666\ k_T^3 \quad \text{......(4.26)}$$

A summary of monthly averaged daily mean errors obtained by using these models against all and measured data for Aqaba are shown in tables 4.7 and 4.8.

The hourly diffuse models obtained by examining hourly diffuse to hourly global ratio against clearness index using Orgill and Hollands approach are as follows:

a. Amman

(i) Linear:

$$\frac{I_d}{I} = 0.534 - 0.392\ k_T \quad \text{...........(4.27)}$$

(ii) second degree:

$$\frac{I_d}{I} = 0.582 - 0.682\ k_T + 0.29\ k_T^2 \quad \text{...........(4.28)}$$

(iii) Third degree:

$$\frac{I_d}{I} = 0.362 + 1.939\ k_T - 6.254\ k_T^2 + 4.362\ k_T^3 \quad \text{.....(4.29)}$$

(iv) Segmented linear equations:

$$\frac{I_d}{I} = \begin{cases} 0.344 + 1.454\ k_T, & 0 \le k_T \le 0.137 \\ 0.636 - 0.67\ k_T, & 0.137 \le k_T \le 0.785 \\ 0.11 & k_T \ge 0.785 \end{cases} \quad ......(4.30)$$

Table 4.9 shows comparison between mean errors obtained by using these models for Amman.

b. Aqaba

(i) Linear:

$$\frac{I_d}{I} = 0.591 - 0.543\ k_T \quad ....(4.31)$$

(ii) second degree:

$$\frac{I_d}{I} = 0.612 - 0.709\ k_T + 0.222\ k_T^2 \quad ....(4.32)$$

(iii) Third degree:

$$\frac{I_d}{I} = 0.526 + 0.647\ k_T - 4.287\ k_T^2 - 4.008\ k_T^3 \quad ......(4.33)$$

(iv) Segmented linear equations:

$$\frac{I_d}{I} = \begin{cases} 0.507 + 0.375\ k_T, & 0 \le k_T \le 0.11 \\ 0.597 - 0.45\ k_T, & 0.11 \le k_T \le 0.8 \\ 0.237, & k_T \ge 0.8 \end{cases} \quad ......(4.34)$$

Table 4.10 shows comparison between mean errors obtained by using these models for Aqaba.

The hourly diffuse models obtained by examining hourly diffuse to monthly average daily ratio multiplied by the day length against the ratio of hours from solar noon to sunset hours are as follows

a. Amman-all data

(i) Linear:

$$r_d * t_d = 1.648 - 1.245 \left(\frac{W}{W_s}\right) \quad ....(4.35)$$

(ii) second degree:

$$r_d * t_d = 1.378 + 0.403 \left(\frac{W}{W_s}\right) - 1.713\left(\frac{W}{W_s}\right)^2 \quad .....(4.36)$$

(iii) Third degree

$$r_d * t_d = 1.425 - 0.127\left(\frac{W}{W_s}\right) - 0.391\left(\frac{W}{W_s}\right)^2 - 0.896\left(\frac{W}{W_s}\right)^3 ...(4.37)$$

b. Amman-averaged data

(i) linear:

$$r_d * t_d = 1.647 - 1.245 \left(\frac{W}{W_s}\right) \quad ....(4.38)$$

(ii) second degree:

$$r_d * t_d = 1.378 + 0.403 \left(\frac{W}{W_s}\right) - 1.712\left(\frac{W}{W_s}\right)^2 \quad .....(4.39)$$

(iii) Third degree:

$$r_d * t_d = 1.426 - 0.136\left(\frac{W}{W_s}\right) - 0.371\left(\frac{W}{W_s}\right)^2 - 0.909\left(\frac{W}{W_s}\right)^3 ...(4.40)$$

A summary of monthly averaged daily mean errors obtained by using these models against all and averaged data for Amman are presented in tables 4.11 and 4.12.

c. Aqaba-all data

(i) Linear:

$$r_d * t_d = 1.601 - 1.163 \left(\frac{W}{W_s}\right) \quad ....(4.41)$$

(ii) second degree:

$$r_d * t_d = 1.287 + 0.727 \left(\frac{W}{W_s}\right) - 1.934\left(\frac{W}{W_s}\right)^2 \quad .....(4.42)$$

TABLE 4.5 COMPARISON BETWEEN MEAN ERRORS OF HOURLY DIFFUSE TO HOURLY GLOBAL RATIOS BASED ON OBTAINED POLYNOMIAL & LINEAR EQUATIONS - AMMAN

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
LINEAR	0.081	0.067	0.094	0.076	0.021	-0.278	-0.541	-0.256	-0.243	-0.233	0.073	0.003	-0.095
SECOND DEG. POLYN.	0.118	0.112	0.133	0.118	0.035	-0.323	-0.594	-0.283	-0.295	-0.262	0.054	0.032	-0.096
THIRD DEG. POLYN.	0.087	0.073	0.127	0.139	0.095	-0.244	-0.497	-0.205	-0.297	-0.212	0.019	0.019	-0.075
SEGM. LINEAR EQNS.	0.083	0.071	0.106	0.108	0.090	-0.173	-0.416	-0.153	-0.221	0.236	0.060	0.006	-0.017
THIRD DEG.-ORG. APPR.	0.065	0.044	0.116	0.140	0.126	-0.182	-0.422	-0.150	-0.274	-0.164	0.013	0.010	-0.057

TABLE 4.6 COMPARISON BETWEEN MEAN ERRORS OF HOURLY DIFFUSE TO HOURLY GLOBAL RATIOS BASED ON OBTAINED POLYNOMIAL & LINEAR EQUATIONS - AMMAN (THE AVERAGE OF EACH TWO SIMILAR HOURS IS TAKEN)

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANUAL MEAN
LINEAR	-0.044	-0.042	0.002	0.090	0.111	0.062	-0.103	0.027	-0.063	-0.084	-0.018	-0.164	-0.019
SECOND DEG. POLYN.	-0.038	-0.035	0.010	0.110	0.133	0.054	-0.105	0.019	-0.041	-0.044	0.047	-0.137	-0.002
THIRD DEG. POLYN.	-0.044	-0.036	0.006	0.086	0.098	0.067	-0.087	0.027	-0.076	-0.091	-0.015	-0.149	-0.018

TABLE 4.7 COMPARISON BETWEEN MEAN ERRORS OF HOURLY DIFFUSE TO HOURLY GLOBAL RATIOSN BASED ON OBTAINED POLYNOMIAL & LINEAR EQUATIONS - AQABA

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
LINEAR	-0.079	0.020	0.130	0.112	0.120	-0.077	-0.331	-0.134	-0.184	-0.126	-0.176	-0.016	-0.062
SECOND DEG. POLYN.	-0.073	0.028	0.140	0.112	0.125	-0.072	-0.327	-0.127	-0.188	-0.136	-0.182	-0.006	-0.059
THIRD DEG. POLYN.	-0.056	0.045	0.141	0.119	0.135	-0.053	-0.303	-0.108	-0.202	-0.165	-0.216	-0.007	-0.056
SEGM. LINEAR EQNS.	-0.061	0.031	0.099	0.150	0.128	-0.046	-0.286	-0.115	-0.152	-0.170	-0.212	-0.068	-0.058
THIRD DEG.-ORG. APPR.	-0.038	0.071	0.261	0.063	0.163	-0.072	-0.346	-0.092	-0.284	-0.271	-0.280	0.151	-0.056

TABLE 4.8 COMPARISON BETWEEN MEAN ERRORS OF HOURLY DIFFUSE TO HOURLY GLOBAL RATIOS BASED ON OBTAINED POLYNOMIAL & LINEAR EQUATIONS - AQABA (THE AVERAGE OF EACH TWO SIMILAR HOURS IS TAKEN)

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANUAL MEAN
LINEAR	-0.069	0.001	0.006	0.202	0.136	0.038	-0.175	-0.056	-0.068	-0.008	0.118	-0.144	-0.002
SECOND DEG. POLYN.	-0.067	0.004	0.007	0.199	0.138	0.038	-0.177	-0.055	-0.070	-0.015	0.160	-0.140	0.002
THIRD DEG. POLYN.	-0.071	0.000	0.002	0.200	0.135	0.035	-0.179	-0.059	-0.070	-0.005	-0.120	-0.141	-0.023

TABLE 4.9 COMPARISON BETWEEN MEASURED AND CALCULATED DATA BASED ON SEGMENTED AND POLYNOMIAL EQUATIONS USING ORGILL AND HOLLANDS METHOD (EQNS. 4.27 - 4.30) - AMMAN

MEAS. DATA	CLEARN. IND.	CAL. LINEAR	ERR. LINEAR	CAL. SECOND	ERR. SECOND	CAL. THIRD	ERR. THIRD	CAL. SEG.	ERR. SEGM.
0.200	0.025	0.524	-1.621	0.565	-1.826	0.407	-1.033	0.380	-0.902
0.632	0.075	0.505	0.202	0.532	0.157	0.474	0.250	0.453	0.283
0.639	0.125	0.485	0.241	0.501	0.216	0.515	0.194	0.526	0.177
0.561	0.175	0.465	0.170	0.472	0.159	0.533	0.050	0.519	0.075
0.599	0.225	0.446	0.256	0.443	0.260	0.531	0.113	0.485	0.190
0.464	0.275	0.426	0.081	0.416	0.103	0.513	-0.106	0.452	0.026
0.337	0.325	0.407	-0.024	0.391	0.015	0.481	-0.212	0.418	-0.054
0.400	0.375	0.387	0.033	0.367	0.082	0.440	-0.099	0.385	0.038
0.349	0.425	0.367	-0.053	0.345	0.013	0.391	-0.121	0.351	-0.006
0.320	0.475	0.348	-0.087	0.323	-0.011	0.339	-0.061	0.318	0.007
0.275	0.525	0.328	-0.193	0.304	-0.105	0.287	-0.045	0.284	-0.034
0.268	0.575	0.309	-0.151	0.286	-0.066	0.238	0.110	0.251	0.064
0.211	0.625	0.289	-0.370	0.269	-0.275	0.196	0.072	0.217	-0.030
0.161	0.675	0.269	-0.673	0.254	-0.576	0.163	-0.012	0.184	-0.141
0.156	0.725	0.250	-0.601	0.240	-0.538	0.143	0.085	0.150	0.037
0.129	0.775	0.230	-0.784	0.228	-0.765	0.139	-0.076	0.117	0.095
0.163	0.825	0.211	-0.292	0.217	-0.330	0.154	0.053	0.110	0.325
0.284	0.875	0.191	0.327	0.207	0.270	0.193	0.322	0.110	0.613
0.264	0.925	0.171	0.351	0.199	0.245	0.257	0.027	0.110	0.583
0.278	0.975	0.152	0.454	0.193	0.307	0.350	-0.260	0.110	0.604
MEAN ERROR			-0.137		-0.133		-0.038		0.038

TABLE 4.10 COMPARISON BETWEEN MEASURED AND CALCULATED DATA BASED ON SEGMENTED AND POLYNOMIAL EQUATIONS USING ORGILL AND HOLLANDS METHOD (EQNS. 4.31 - 4.34) - AQABA

MEAS. DATA	CLEARN. IND.	CAL. LINEAR	ERR. LINEAR	CAL. SECOND	ERR. SECOND	CAL. THIRD	ERR. THIRD	CAL. SEG.	ERR. SEG.
0.584	0.125	0.523	0.104	0.527	0.098	0.548	0.062	0.541	0.074
0.467	0.175	0.496	-0.062	0.495	-0.059	0.529	-0.134	0.518	-0.110
0.540	0.225	0.469	0.132	0.464	0.141	0.500	0.074	0.496	0.082
0.644	0.275	0.442	0.314	0.434	0.326	0.463	0.281	0.473	0.265
0.449	0.325	0.415	0.077	0.405	0.098	0.421	0.062	0.451	-0.004
0.435	0.375	0.387	0.109	0.377	0.133	0.377	0.133	0.428	0.016
0.359	0.425	0.360	-0.003	0.351	0.023	0.334	0.069	0.406	-0.130
0.447	0.475	0.333	0.255	0.325	0.272	0.296	0.339	0.383	0.143
0.350	0.525	0.306	0.126	0.301	0.140	0.264	0.246	0.361	-0.031
0.323	0.575	0.279	0.137	0.278	0.140	0.243	0.249	0.338	-0.047
0.249	0.625	0.252	-0.011	0.256	-0.026	0.234	0.059	0.316	-0.268
0.244	0.675	0.224	0.080	0.235	0.039	0.242	0.008	0.293	-0.202
0.208	0.725	0.197	0.051	0.215	-0.032	0.269	-0.294	0.271	-0.302
0.209	0.775	0.170	0.186	0.196	0.063	0.318	-0.523	0.248	-0.188
0.304	0.825	0.143	0.530	0.178	0.414	0.392	-0.291	0.237	0.220
MEAN ERROR			0.135		0.118		0.023		-0.032

(iii) Third degree

$$r_d * t_d = 1.325 + 0.31 \left(\frac{w}{w_s}\right) - 0.914\left(\frac{w}{w_s}\right)^2 - 0.678\left(\frac{w}{w_s}\right)^3 \quad ...(4.43)$$

d. Aqaba-averged data

(i) linear:

$$r_d * t_d = 1.601 - 1.163 \left(\frac{w}{w_s}\right) \quad ....(4.44)$$

(ii) second degree:

$$r_d * t_d = 1.287 + 0.727 \left(\frac{w}{w_s}\right) - 1.934\left(\frac{w}{w_s}\right)^2 \quad .....(4.45)$$

(iii) Third degree

$$r_d * t_d = 1.325 + 0.312\left(\frac{w}{w_s}\right) - 0.918\left(\frac{w}{w_s}\right)^2 - 0.675\left(\frac{w}{w_s}\right)^3 \quad ...(4.46)$$

A summary of monthly averaged daily errors obtained by examinig these models against all and averaged data for Amman are shown in tables 4.13 and 4.14.

4.3 Developed hourly beam models

Hourly beam models are obtained by examining hourly beam to hourly global ratio in terms of clearness index. The obtained correlations are as follows:

a. Amman-all data

(i) Linear:

$$\frac{I_b}{I} = 0.387 + 0.611\, k_T \quad ....(4.47)$$

(ii) second degree:

$$\frac{I_b}{I} = 0.301 + 1.034\, k_T - 0.429\, k_T^2 \quad \ldots\ldots\ldots\ldots(4.48)$$

(iii) Third degree:

$$\frac{I_b}{I} = 0.49 - 0.768\, k_T + 3.778\, k_T^2 - 2.819\, k_T^3 \quad \ldots\ldots(4.49)$$

b. Amman-averaged data

(i) Linear:

$$\frac{I_b}{I} = 0.145 + 1.032\, k_T \quad \ldots\ldots\ldots\ldots\ldots\ldots(4.50)$$

(ii) second degree:

$$\frac{I_b}{I} = 0.101 + 1.205\, k_T - 0.16\, k_T^2 \quad \ldots\ldots\ldots\ldots(4.51)$$

(iii) Third degree:

$$\frac{I_b}{I} = -0.189 + 3.05\, k_T - 3.875\, k_T^2 + 2.386\, k_T^3 \quad \ldots\ldots(4.52)$$

A summary of monthly averaged daily errors obtained by examinig these models against all and averaged data for Amman are shown in table 4.15 and 4.16.

c. Aqaba-all data

(i) Linear:

$$\frac{I_b}{I} = 0.333 + 0.619\, k_T \quad \ldots\ldots\ldots\ldots\ldots\ldots(4.53)$$

(ii) second degree:

$$\frac{I_b}{I} = 0.294 + 0.801\, k_T - 0.181\, k_T^2 \quad \ldots\ldots\ldots\ldots(4.54)$$

(iii) Third degree:

$$\frac{I_b}{I} = 0.569 - 1.527\, k_T + 5.14\, k_T^2 - 3.635\, k_T^3 \quad \ldots(4.55)$$

TABLE 4.11 COMPARISON BETWEEN MEAN ERRORS OF HOURLY DIFFUSE TO MONTHLY AVERAGE DAILY RATIOS BASED ON OBTAINED POLYNOMIAL AND LINEAR EQUATIONS - AMMAN

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
LINEAR	-0.226	-0.045	-0.497	-0.101	0.024	0.058	0.054	0.020	-0.162	-11.857	-0.484	-0.708	-1.160
SECOND DEG. POLYN.	-0.128	-0.038	-0.220	-0.060	0.012	0.040	0.038	0.021	-0.071	-3.268	-0.357	-0.422	-0.371
THIRD DEG. POLYN.	-0.123	-0.042	-0.192	-0.061	0.009	0.037	0.034	0.018	-0.065	-1.931	-0.356	-0.401	-0.256

TABLE 4.12 COMPARISON BETWEEN MEAN ERRORS OF HOURLY DIFFUSE TO MONTHLY AVERAGE DAILY RATIOS BASED ON OBTAINED POLYNOMIAL AND LINEAR EQUATIONS - THE AVERAGE OF EACH TWO SIMILAR HOURS IS TAKEN - AMMAN

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
LINEAR	-0.164	-0.042	-0.347	-0.049	0.032	0.061	0.056	0.025	-0.040	-0.166	-0.079	-0.251	-0.080
SECOND DEG. POLYN.	-0.085	-0.036	-0.136	-0.021	0.019	0.042	0.039	0.024	0.010	0.058	-0.040	-0.120	-0.021
THIRD DEG. POLYN.	-0.081	-0.040	-0.113	-0.021	0.015	0.040	0.036	0.021	0.014	0.094	-0.039	-0.109	-0.015

TABLE 4.13 COMPARISON BETWEEN MEAN ERRORS OF HOURLY DIFFUSE TO MONTHLY AVERAGE DAILY RATIOS BASED ON OBTAINED POLYNOMIAL AND LINEAR EQUATIONS - AQABA

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
LINEAR	-0.070	-1.178	-0.373	-0.034	0.006	0.058	0.047	-0.010	-0.228	-3.677	-0.347	-0.346	-0.513
SECOND DEG. POLYN.	-0.036	-0.099	-0.155	-0.012	-0.005	0.036	0.029	-0.009	-0.116	-1.163	-0.280	-0.227	-0.170
THIRD DEG. POLYN.	-0.038	0.010	-0.145	-0.014	-0.009	0.033	0.025	-0.013	-0.114	-0.943	-0.284	-0.227	-0.143

TABLE 4.14 COMPARISON BETWEEN MEAN ERRORS OF HOURLY DIFFUSE TO MONTHLY AVERAGE DAILY RATIOS BASED ON OBTAINED POLYNOMIAL AND LINEAR EQUATIONS - THE AVERAGE OF EACH TWO SIMILAR HOURS IS TAKEN - AQABA

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
LINEAR	-0.050	-0.799	-0.254	-0.022	0.018	0.059	0.051	0.015	-0.065	-0.155	-0.054	-0.128	-0.115
SECOND DEG. POLYN.	-0.020	-0.011	-0.082	-0.002	0.006	0.038	0.033	0.014	-0.005	-0.027	-0.039	-0.067	-0.014
THIRD DEG. POLYN.	-0.022	0.050	-0.075	-0.005	0.002	0.034	0.029	0.011	-0.005	0.054	-0.042	-0.068	-0.003

d., Aqaba-averaged data

(i) Linear:

$$\frac{I_b}{I} = -0.032 + 1.209\ k_T \qquad \text{................(4.56)}$$

(ii) second degree:

$$\frac{I_b}{I} = -0.127 + 1.548\ k_T - 0.294\ k_T^2 \qquad \text{............(4.57)}$$

(iii) Third degree:

$$\frac{I_b}{I} = -0.383 + 3.014\ k_T - 3.031\ k_T^2 + 1.666\ k_T^3 \qquad \text{......(4.58)}$$

A summary of monthly averaged daily errors obtained by examinig these models against all and averaged data for Aqaba are shown in tables 4.17 and 4.18.

TABLE 4.15 COMPARISON BETWEEN MEAN ERRORS OF HOURLY BEAM RADIATION BASED ON OBTAINED POLYNOMIAL AND LINEAR EQUATIONS - AMMAN

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
LINEAR	-0.133	-0.098	-0.073	-0.055	-0.049	0.034	0.071	0.033	0.035	0.052	-0.087	0.000	-0.023
SECOND DEG. POLYN.	-0.137	-0.115	-0.083	-0.074	-0.051	0.039	0.075	0.035	0.052	0.066	-0.054	-0.002	-0.021
THIRD DEG. POLYN.	-0.120	-0.081	-0.080	-0.074	-0.056	0.035	0.069	0.030	0.065	0.061	-0.063	-0.004	-0.018

TABLE 4.16 COMPARISON BETWEEN MEAN ERRORS OF HOURLY BEAM RADIATION BASED ON OBTAINED POLYNOMIAL AND LINEAR EQUATIONS - THE AVERAGE OF EACH TWO SIMILAR HOURS IS TAKEN - AMMAN

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
LINEAR	0.004	0.012	-0.002	-0.032	-0.053	-0.012	0.026	-0.004	-0.005	0.003	-0.052	0.081	-0.003
SECOND DEG. POLYN.	0.007	0.012	-0.003	-0.034	-0.054	-0.011	0.027	-0.004	-0.006	-0.001	-0.056	0.081	-0.004
THIRD DEG. POLYN.	0.015	0.012	-0.003	-0.032	-0.051	-0.013	0.023	-0.005	-0.003	0.004	-0.055	0.075	-0.003

TABLE 4.17 COMPARISON BETWEEN MEAN ERRORS OF HOURLY BEAM RADIATION BASED ON OBTAINED POLYNOMIAL AND LINEAR EQUTIONS - AQABA

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
LINEAR	0.013	-0.023	-0.147	-0.115	-0.088	-0.011	0.065	0.014	0.033	0.047	0.077	-0.010	-0.012
SECOND DEG. POLYN.	0.010	-0.027	-0.153	-0.116	-0.091	-0.013	0.063	0.012	0.036	0.051	0.082	-0.009	-0.013
THIRD DEG. POLYN.	0.008	-0.030	-0.146	-0.110	-0.087	-0.013	0.059	0.010	0.048	0.073	0.082	-0.024	-0.011

TABLE 4.18 COMPARISON BETWEEN MEAN ERRORS OF HOURLY BEAM RADIATION BASED ON OBTAINED POLYNOMIAL AND LINEAR EQUATIONS - THE AVERAGE OF EACH TWO SIMILAR HOURS IS TAKEN - AQABA

MEAN ERROR/MONTHS	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
LINEAR	0.013	-0.024	-0.031	-0.112	-0.071	-0.025	0.040	0.012	0.025	0.037	0.043	0.099	0.001
SECOND DEG. POLYN.	0.013	-0.025	-0.027	-0.111	-0.072	-0.026	0.040	0.011	0.024	0.036	0.041	0.097	0.000
THIRD DEG. POLYN.	0.013	-0.024	-0.023	-0.111	-0.071	-0.025	0.041	0.012	0.025	0.037	0.043	0.097	0.001

CHAPTER FIVE

RESULTS AND DISCUSSION

5.1 Hourly global radiation

Plots of measured hourly global radiation against local solar time for Amman and Aqaba are shown in Figures 5.1 to 5.4.

Figures 5.1 and 5.2 for Amman, show that variation of hourly global radiation is symmetrical around solar noon for all months. The absolute amount of hourly global radiation varies between 0.0 and 971.75 W/m^2 over all hours. Maximum values of hourly global radiation vary from 383.25 W/m^2 in December to 971.25 W/m^2 in June. Figures 5.3 and 5.4 for Aqaba, show same behaviour for hourly global radiation around solar noon, the absolute amount of hourly global radiation varies between 0.0 and 920 W/m^2 over all hours of the year. Maximum values of hourly global radiation vary between 500 W/m^2 in December and 920 W/m^2 in July. Data for Amman and Aqaba are in the same range of values except for winter season, where values of hourly global radiation for Amman are lower than those for Aqaba which reflects the fact that in winter Amman region is covered with clouds, but not Aqaba region.

The variation of hourly global to monthly average daily ratio with sunset hour angle is shown in figures 5.5 and

5.6 for Amman and Aqaba, respectively.

From figure 5.5 we can see that hourly global to monthly average daily ratio for Amman varies from 0.001 to 0.171, while figure 5.6 shows that this ratio varies between 0.0 and 0.168 for Aqaba throughout the year. It is also observed that these ratios are lower in the morning and afternoon hours, and higher around the solar noon hours for all months of the year.

5.1.1 Developed hourly global radiation models

Hourly global to monthly average daily ratio multiplied by the day length in terms of hours from solar noon to sunset angle ratio is studied. Errors between measured and calculated data are obtained along with monthly average daily mean errors. It is noted that when all data are examined, the annual mean errors are found to be high. This occurs mainly due to the inclusion of the early and late two hours in calculations which results normally in high mean errors. For example mean error obtained using equation 4.2 for the hour 16-17 in November is 606%. This applies to global as well as to diffuse radiation.

5.1.1.1 Comparison based on all data-Amman

The obtained linear, second and third degree regressions are shown in figures 5.7 to 5.9. Errors between measured and predicted data using the developed models are obtained using Eqn. 2.2. The following observations can be made:

Third degree polynomial (Eqn. 4.3) presents the lowest mean errors for the months of February and April to August, where the annual mean error is -0.256. The second degree polynomial (Eqn. 4.2) is the best for the months of January, March and September to December, and its annual mean error is -0.181.

The second degree polynomial (Eqn. 4.2) fits reasonably six months from February to April and June to August. Third degree polynomial (Eqn. 4.3) fits reasonably well five months February, April, and June to August. Linear (Eqn. 4.1) fits reasonably April, June and July with an annual mean error of -0.492.

5.1.1.2 Comparison based on averaged data-Amman

Obtained linear, second and third degree regressions are shown in figures 5.10 to 5.12. Based on the calculated errors between measured and predicted values the following observation are made:

Third degree polynomial (Eqn. 4.6) represents the lowest mean errors for nine months: February to September and December, where its annual mean error is -0.003. Second degree polynomial (Eqn. 4.5) is the best only for January and October, and its annual mean error is -0.006. Linear regression (Eqn. 4.4) represents minimum errors for the months: October and November, Where its annual mean error is -0.054. The second degree polynomial fits all months reasonably well.Third degree polynomial (Eqn. 4.6) fits all months reasonably well too except October. Finally, linear regression (Eqn. 4.4) fits all months reasonably well, except January and March.

5.1.1.3 Comparison based on all data-Aqaba

Linear, second and third regressions are obtained and shown in figures 5.13 to 5.15. Based on obtained errors between measured and calculated values the following observations can be made:

Third degree polynomial (Eqn. 4.9) is the best for seven months of January, April to August and November, where the annual mean error is -0.269. Second degree polynomial (Eqn. 4.8) represent lowest mean errors for five months of February,March, September,October and December, where the annual mean error is -0.111.

The second degree polynomial fits January to August data reasonably well. Third degree polynomial fits the same months reasonably too, except March. Linear regression (Eqn. 4.7) fits January and May to August reasonably well, and the annual mean error is -0.593.

5.1.1.4 Comparison based on averaged data-Aqaba

Linear, second and third degree regressions are obtained as shown in figures 5.16 to 5.18. Errors between measured and calculated data offers the following observations: Third degree polynomial (Eqn. 4.12) is the best for five months, January, April, May, August and September, where the annual mean error is 0.008. Second degree polynomial (eqn 4.11) is the best for five months also, but February, March and October to December, and the annual mean error is -0.015. Linear regression (Eqn. 4.10) is the best only for June and July, with an annual mean error equal to -0.075.

The second degree Polynomial fits all months of the year reasonably well. Third degree fits all months reasonably well, except for February, while linear regression fits all months reasonably well, too, except for February and March.

Based on the above discussion second degree polynomials equation (4.2) and equation (4.8) are the most suitable among the developed global models, when all data are considered. In the other hand third degree polynomials equation (4.6) and equation (4.12) are the suitable ones when averaged data are considered for both Amman and Aqaba respectively. A summary of obtained results using these models is shown in table 5.1.

Table 5.1 EVALUATION OF DEVELOPED HOURLY GLOBAL RADIATION MODELS

AMMAN-ALL DATA

MODEL	THE LOWEST MEAN ERRORS	REASONABLE ERRORS	ANNUAL MEAN ERROR
SECOND DEGREE POLY. (EQN 4.2)	6 MONTHS	6 MONTHS	-0.181
THIRD DEGREE POLY. (EQN. 4.3)	5 MONTHS	5 MONTHS	-0.256

AMMAN-AVERAGED DATA

MODEL	THE LOWEST MEAN ERRORS	REASONABLE ERRORS	ANNUAL MEAN ERROR
THIRD DEGREE POLY. (EQN. 4.6)	9 MONTHS	11 MONTHS	-0.003
SECOND DEGREE POLY. (EQN. 4.5)	2 MONTHS	12 MONTHS	-0.054

AQABA-ALL DATA

MODEL	THE LOWEST MEAN ERRORS	REASONABLE ERRORS	ANNUAL MEAN ERROR
SECOND DEGREE POLY. (EQN. 4.8)	5 MONTHS	8 MONTHS	-0.111
THIRD DEGREE POLY. (EQN. 4.9)	7 MONTHS	7 MONTHS	-0.269

AQABA-AVERAGED DATA

MODEL	THE LOWEST MEAN ERRORS	REASONABLE ERRORS	ANNUAL MEAN ERROR
THIRD DEGREE POLY. (EQN. 4.12)	5 MONTHS	11 MONTHS	0.008
SECOND DEGREE POLY. (EQN. 4.11)	5 MONTHS	12 MONTHS	-0.015

5.2 Hourly diffuse radiation

Plots of measured hourly diffuse radiation against local solar time are shown in figures 5.19 to 5.22. Figures 5.19 and 5.20 for Amman show the variation of hourly diffuse radiation around solar noon hours for the months July to December is less than for the months January to June. The absolute amounts of hourly diffuse radiation varies between 0.00 and 181 $\frac{W}{m^2}$ over all hours, while for middle six hours around the solar noon, are between 74 and 114 $\frac{W}{m^2}$. Values interference is observed too. Maximum values of diffuse radiation vary between 84 $\frac{W}{m^2}$ in July and 181 W/m^2 in March. The higher diffuse radiation in March could be due to special type of clouds contribution as some type of clouds are more scattering than others [6].

From figures 5.21 and 5.22 for Aqaba, almost same result can be observed except that absolute values of hourly diffuse radiation for Aqaba are higher than those for Amman. The absolute amount of hourly diffuse radiation is between 0.00 and 212 W/m^2 over all hours and between 95 and 212 W/m^2 for the middle six hours. Maximum value ranges between 116 W/m^2 in November and 212 W/m^2 in May. The higher values of diffuse radiation for Aqaba compared with Amman of diffuse values could be due to the contribution of dust, humidity and reflection from the surface of sea water.

For Amman the annual diffuse to the annual global ratio is found to be 0.28 while for Aqaba is 0.304. From figure 5.23 we can see that hourly diffuse to monthly averaged daily ratios vary from 0.002 to 0.156 for Amman, while figure 5.24 shows that this ratio varies from 0.001 to 0.168 for Aqaba throughout the year. It is also observed that hourly diffuse to monthly average daily ratios are lower in the morning and afternoon hours, while they are higher around solar noon hours for all months of the year.

5.2.1 Developed hourly diffuse models

5.2.1.1 Amman-all data

Four models obtained for $\frac{I_d}{I} = f(k_T)$, equations 4.13 to 4.16 and three models obtained for $r_d * t_d = f(\frac{W}{W_s})$, equations 4.35 to 4.37 have been investigated. In addition to these models four correlations equations 4.27 to 4.30 obtained by using Orgill and Hollands approach are also investigated. Equation 4.29 found to have the lowest mean error along other correlations obtained using this approaches as shown in table 4.9.

Plots of these models are shown in figures 5.25 to 5.33. Based on obtained errors between measured and calculated data using these models, the following observations can be made:

The third degree polynomial (Eqn. 4.37) based on $r_d * t_d = f(\frac{W}{W_s})$, shows lowest mean errors for five months from May to September and its annual mean error is -0.256. The third degree polynomial using Orgill and Hollands approach, (Eqn. 4.29) is the best for three months of January, October and November, where its annual mean error is -0.057. The linear regression (Eqn. 4.13) based on $\frac{I_d}{I} = f(k_T)$, represents lowest mean errors for March and December and its annual mean error is -0.095 . The second degree polynomial based on $r_d * t_d = f(\frac{W}{W_s})$, (Eqn. 4.36) is the best for February and April, where its annual mean error is -0.371.

The third and second degree polynomials based on $r_d * t_d = f(\frac{W}{W_s})$ each fits reasonably seven months of February and April to September. The linear regression (Eqn. 4.13) based on $\frac{I_d}{I} = f(k_T)$ fits also reasonably well seven months of January to May, November and December. The third degree polynomial (Eqn. 4.15) and segmented linear regressions (Eqn. 4.16) based on $\frac{I_d}{I} = f(k_T)$ each fits reasonably well five months of January, February, May, November and December. The linear regression (Eqn. 4.35) based on $r_d * t_d = f(\frac{W}{W_s})$ fits also reasonably well five months of February and May to August, where its annual mean error is -1.16. The third degree polynomial obtained by using Orgill and Hollands approach fits reasonably well four months of January, February, November and December. Finally the second degree polynomial (Eqn. 4.14) based on $\frac{I_d}{I} = f(k_T)$ fits reasonably well three months of May, November and December, where its annual mean error is -0.096.

5.2.1.2 Amman-averaged data

Obtained linear, second and third degree polynomials, equations 4.17 to 4.19 and 4.38 to 4.40 based on $\frac{I_d}{I} = f(k_T)$ and $r_d * t_d = f(\frac{W}{W_s})$ are tested against measured data.

Plots of these models are shown in figures 5.34 to 5.39. The following observations can made:

The third degree polynomial based on $r_d*t_d = f(\frac{W}{W_s})$, equation (4.40) represents lowest mean errors for six months of April to August and December, where its annual mean error is -0.015. The second degree polynomial based on $\frac{I_d}{I} = f(k_T)$, equation (4.18) is the best for January, February and October and its annual mean error is -0.002. The second degree polynomial based on $r_d*t_d=f(\frac{W}{W_s})$, equation (4.39) is the best for April and September and its annual mean error is -0.021. Third degree polynomial based on $\frac{I_d}{I} = f(k_T)$, equation 4.19 shows lowest mean errors for November and its annual mean error is -0.018, while linear regression based on $\frac{I_d}{I} = f(k_T)$, equation (4.17) fits March the best and its annual mean error is -0.019.

The third degree polynomial (eqn. 4.19) based on $\frac{I_d}{I} = f(k_T)$ fits reasonably well eleven months of January to November. The second and third degree polynomials (Eqn. 4.39) and (Eqn. 4.40) based on $r_d*t_d= f(\frac{W}{W_s})$ each fits reasonably well ten months of January to November except March. The linear regression (Eqn. 4.17) based on $\frac{I_d}{I} = f(k_T)$, fits reasonably well nine months of January to April, June and August to November. The second degree polynomial (Eqn. 4.18) based on $\frac{I_d}{I} = f(k_T)$ fits reasonably well eight months from January to March, June and

August to November, while the linear regression Eqn.4.38) based on $r_d * t_d = f(\frac{W}{W_s})$ also fits eight months reasonably well but February, April to September and November and its annual mean error is -0.08.

From the above it is obvious that the third degree polynomials based on $r_d * t_d = f(\frac{W}{W_s})$, (Eqn. 4.37) and (Eqn. 4.40) are the most suitable for Amman, when all and averaged data are examined. A summary of obtained results based on these models is shown in Table 5.2.

5.2.1.3 Aqaba-all data

Four models obtained based on $\frac{I_d}{I} = f(k_T)$, equations 4.20 to 4.23 and three models obtained based on $r_d * t_d = f(\frac{W}{W_s})$, equations 4.41 to 4.43 have been investigated. In addition to these four correlations, equations 4.31 to 4.34 obtained by using Orgill and Hollands approach are investigated too. Equation 4.33 found to have the lowest mean error along other correlations obtained using this approach as shown in table 4.10.

Plots of these models are shown in figures 5.40 to 5.48. The following observation can be made:

The third degree polynomial based on $r_d * t_d = f(\frac{W}{W_s})$ equation (4.43) shows lowest mean errors for four months of February, June, July and September, where its annual mean error is -0.143. The second degree polynomial based on $r_d * t_d = f(\frac{W}{W_s})$, equation (4.42) also fits four months of January, April, May and August, where its annual mean error is -0.17. The linear regression based on $\frac{I_d}{I} = f(k_T)$ equation (4.20) is the best for two months of October and November and its annual mean error is -0.062. The segmented

linear equations (4.23) based on $\frac{I_d}{I} = f(k_T)$ is the best for March and its annual mean error is -0.058, while the second degree polynomial based on $\frac{I_d}{I} = f(k_T)$, equation (4.21) fits December and its annual mean error is -0.059. The second and third degree polynomials (Eqn. 4.42) and (Eqn.4.43) based on $r_d*t_d=f(\frac{W}{W_s})$ each fits seven months reasonably of January, February and April to August. The linear regression (Eqn. 4.41) based on $r_d*t_d = f(\frac{W}{W_s})$ fits six months reasonably of January and April to August. The segmented linear equations (Eqn. 4.23) based on $\frac{I_d}{I}= f(k_T)$ fits reasonably five months of January to March, June and December. The third degree polynomial obtained by using Orgill and Hollands approach (Eqn. 4.33) fits also reasonably five months of January, February, April, June and August, where its annual mean error is -0.056. The linear, second and third degree regressions (Eqns. 4.20 to 4.22) based on $\frac{I_d}{I} = f(k_T)$ each fits four months reasonably of January, February, June and December.

5.2.1.4 Aqaba-averaged data

Obtained linear, second and third degree polynomials, equations 4.24 to 4.26 and 4.44 to 4.46 based on $\frac{I_d}{I} = f(k_T)$ and $r_d*t_d = f(\frac{W}{W_s})$ are tested against measured data. Plots of these models are shown in figures 5.49 to 5.54. The following observations can be made:

The third degree polynomial based on $r_d*t_d = f(\frac{W}{W_s})$, equation (4.46) represents lowest mean errors for five months of May to September and its annual mean error is -0.003. The second degree polynomial based on $r_d*t_d = f(\frac{W}{W_s})$, equation (4.45) is the best for four months of January, April, November and December, where its annual mean error is -0.014. The third degree polynomial based on $\frac{I_d}{I} = f(k_T)$, equation (4.26) shows lowest mean errors for months of February, March and October, where its annual mean error is -0.023.

The second and third degree polynomials (Eqn. 4.45) and (Eqn. 4.46) based on $r_d*t_d=f(\frac{W}{W_s})$ each fits reasonably all months of the year. The linear regression (Eqn. 4.44) based on $r_d*t_d = f(\frac{W}{W_s})$ fits reasonably eight months of January, April to September and November where its annual mean error is -0.115. The linear, second and third degree polynomials (Eqns. 4.24 to 4.26) based on $\frac{I_d}{I} = f(k_T)$ each fits reasonably seven months of January to March, June and August to October, where their annual mean errors are -0.002, 0.002 and -0.023 respectively.

From the above it is clear that the third degree polynomial based on $r_d*t_d=f(\frac{W}{W_s})$, equations (4.43) and (4.46) are the most suitable for Aqaba when all and averaged data are tested. A summary of obtained results based on these models is shown in table 5.2.

Table 5.2 EVALUATION OF DEVELOPED HOURLY GLOBAL RADIATION MODELS

MODEL	LOWEST MEAN ERRORS	REASONABLE ERRORS	ANNUAL MEAN ERROR
AMMAN-ALL DATA			
THIRD DEGREE POLY. (EQN.4.37)	5 MONTHS	7 MONTHS	-0.256
SEGMENTED LINEAR EQUATIONS (EQN 4.29)	3 MONTHS	4 MONTHS	-0.057
LINEAR REGRESSION (EQN. 4.13)	2 MONTHS	7 MONTHS	-0.095
AMMAN-AVERAGED DATA			
THIRD DEGREE POLY. (EQN.4.40)	6 MONTHS	10 MONTHS	0.015
SECOND DEGREE POLY. (EQN. 4.39)	2 MONTHS	10 MONTHS	0.021
THIRD DEGREE POLY. (EQN. 4.19)	1 MONTHS	11 MONTHS	-0.018
AQABA-ALL DATA			
THIRD DEGREE POLY. (EQN. 4.43)	4 MONTHS	7 MONTHS	-0.143
SECOND DEGREE POLY. (EQN. 4.42)	4 MONTHS	7 MONTHS	-0.170
LINEAR REGRESSION (EQN. 4.20)	2 MONTHS	6 MONTHS	-0.062
AQABA-AVERAGED DATA			
THIRD DEGREE POLY. (EQN. 4.46)	5 MONTHS	12 MONTHS	-0.003
SECOND DEGREE POLY. (EQN. 4.45)	4 MONTHS	12 MONTHS	-0.014

5.3 Hourly beam radiation

Measured hourly beam radiation data are plotted against local solar time for Amman and Aqaba as shown in figures 5.55 to 5.58. Figures 5.55 and 5.56 for Amman show the variation of hourly beam radiation is almost symmetrical around solar noon. Beam radiation values from January to June are in the same range of values from July to December. The absolute amounts of beam radiation vary between 0.0 and 881.75 W/m^2. Maximum value of beam radiation varies between 305 W/m^2 in December and 881.75 $\frac{W}{m^2}$ in July which is normally expected. Similarly for Aqaba figures 5.57 and 5.58 show almost same behavior of beam radiation around solar noon as for Amman. Beam radiation values from January to June are in the same range compared with the other six months except for December where lower values are recorded. The absolute values of beam radiation vary between 0.0 and 789 W/m^2. Maximum value of beam radiation varies between 361 W/m^2 in December and 789 W/m^2 in July which is normally expected too.

5.3.1 Developed hourly beam radiation models

5.3.1.1 Comparison based on all data-Amman

Figures 5.59 to 5.61 represent linear,second and third degree regressions obtained by examining $\frac{I_b}{I}$ against k_T. Based on the calculated errors between measured and predicted data using these models the following observation can be made:

The Linear regression (Eqn. 4.47) shows lowest mean errors for months March to June, September, October and December, where its annual mean error is -0.023. Third degree polynomial (Eqn. 4.49) shows the lowest mean errors for the months: January, February, July and August where its annual mean error is -0.018.

The Linear and Third degree regressions show reasonable mean errors for all months except January, while February is added to the second degree polynomial (Eqn. 4.48).

5.3.1.2 Comparison based on averaged data-Amman.

Figures 5.62 to 5.64 represent obtained linear, second and third degree regressions. Based on the errors between measured and predicted data obtained using these models the following observations can be made:

Linear regression (Eqn. 4.50) represents lowest mean errors for six months, namely January to April, August and November, where its annual mean error is -0.003. Third degree polynomial (Eqn. 4.52) fits February, April, May, July, September and December, where its annual mean error is -0.003. Second degree polynomial (Eqn. 4.51) is the best for February, June, August and October, where its annual mean error is -0.004.

All developed models represent measured data reasonably for all months all over the year.

5.3.1.3 Comparison based on all data-Aqaba

Obtained linear, second and third degree regressions are shown in figures 5.65 to 5.67. Obtained errors between measured and calculated data using these models offer the following observations:

Linear regression (Eqn. 4.53) shows lowest mean errors for February, June and September to November, where its annual mean error is -0.012. Third degree polynomial, (Eqn. 4.55) is the best for January, March to May, July and August, where its annual mean error is -0.011.

All models represent measured data reasonably except for months March and April.

5.3.1.4 Comparison based on averaged data-Aqaba

Obtained linear, second and third degree regressions are shown in figures 5.68 to 5.70. Based on the errors between measured and predicted data obtained using these models the following observations can be made: The second degree polynomial (Eqn. 4.57) presents lowest mean errors for months of January, April and July to December where its annual mean error is 0.0. Third degree polynomial (Eqn. 4.58) is the best for January to June and December, where its annual mean error is 0.001. Linear regression (Eqn. 4.56) fits months of January February and May to July, where its annual mean error is 0.001.

All models fit measured data reasonably except for April.

From the above discussion it is obvious that all developed beam models are adequate, mainly linear regressions equation (4.47) and equation (4.50) when all and averaged data are considered for Amman. Concerning Aqaba, all models would be suitable too, mainly linear regression equation (4.53) and second degree polynomial equation (4.57) when all and averaged data are examined. A summary of results obtained based on these models is shown in table 5.3.

5.4 Comparison with previous works

5.4.1 Hourly global radiation models

Comparing the results obtained by using the best models among the available and developed ones the following observations can be made:

5.4.1.1 Amman-all data

The second degree polynomial (Eqn. 4.2) presents the lowest mean errors for months of January, March, September, November and December with annual mean error -0.181. Garg and Garg model presents lowest mean error for October only with an

Table 5.3 EVALUATION OF DEVELOPED HOURLY BEAM RADIATION MODELS

AMMAN-ALL DATA

MODEL	LOWEST MEAN ERRORS	REASONABLE ERRORS	ANNUAL MEAN ERROR
LINEAR REGRESSION (EQN.4.47)	7 MONTHS	11 MONTHS	-0.023
THIRD DEGREE POLYNOMIAL (EQN.4.49)	4 MONTHS	11 MONTHS	-0.018
AMMAN-AVERAGED DATA			
LINEAR REGRESSION (EQN.4.50)	6 MONTHS	12 MONTHS	-0.003
THIRD DEGREE POLYNOMIAL (EQN.4.52)	6 MONTHS	12 MONTHS	-0.003
AQABA-ALL DATA			
LINEAR REGRESSION (EQN.4.53)	5 MONTHS	10 MONTHS	-0.012
THIRD DEGREE POLYNOMIAL (EQN.4.55)	5 MONTHS	10 MONTHS	-0.011
AQABA-AVERAGED DATA			
SECOND DEGREE POLYNOMIAL (EQN.4.57)	8 MONTHS	11 MONTHS	0.000
THIRD DEGREE POLYNOMIAL (EQN.4.58)	7 MONTHS	11 MONTHS	0.001

annual mean error -0.19. Both models present six months reasonably well.

5.4.1.2 Amman-averaged data

Collares pereira presents four months with lowest mean errors, namely February, April, May and July while Third degree polynomial (Eqn. 4.6) presents only June and September. Both models present eleven months reasonably well with an annual mean error ±0.003.

5.4.1.3 Aqaba-all data

Garg and Garg model presents October, November and December with lowest mean errors and nine months reasonably well and its annual mean error is -0.074. The second degree polynomial (Eqn. 4.8) presents February and March with lowest mean errors and eight months reasonably well with an annual mean error -0.111.

5.4.1.4 Aqaba-averaged data

The third degree polynomial (Eqn. 4.12) presents August and September with lowest mean errors and all months reasonably well with an annual mean error 0.008. Collares pereira presents January, April, May and December with lowest mean errors and ten months reasonably well and its annaul mean error is 0.027.

From the above it is obvious that developed models compared with the available ones yield an improved and equal annual mean errors for all cases except for Aqaba-all data where the difference is 0.037. Also, it is observed that developed models are of simple forms, easy to calculate with and give reasonable results.

5.4.2 Hourly diffuse radiation models

5.4.2.1 Amman-all data

Liu and Jordan presents lowest mean errors for January, March, April and September and nine months reasonably well with an annual mean error -0.114. The third degree polynomial (Eqn. 4.37) presents seven months reasonably well with an annual mean error -0.256.

5.4.2.2 Amman - averaged data

Garg and Garg model presents lowest mean errors for four months of May to August. It fits the data reasonably well for all months, except March and November with an annual mean error 0.019. Third degree polynomial (Eqn. 4.37) also fits the data reasonably well for all months, except March and December and its annual mean error is -0.015.

5.4.2.3 Aqaba-all data

Liu and Jordan model shows lowest mean errors for three months of March, September and November, while presents eight months reasonably well from January to September except February with an annual mean error -0.024. The third degree polynmomial (Eqn. 4.40) presents lowest mean error for February only and present reasnonably well seven months from January to August except March, with an annual mean error -0.143.

5.4.2.4 Aqaba-averaged data

Garg and Garg model presents lowest mean errors for four months of January, May, June and July. Also it presents all months of the year reasonably well with an annual mean error -0.003. The third degree polynomial Eqn. 4.46 presents lowest mean errors for August and September and present all months of the year reasonably well with an annual mean error -0.003.

From the above we notice that developed models compared with the available ones yield an improved and equal annual mean errors when averaged data are investigated. Also as for the golbal radiation case the developed models are of simple forms, easy to calculate with and give reasonable results.

In other hand it is noticed that all developed models in the form of $\frac{I_d}{I} = f(k_T)$ have low annual mean errors compared with developed models in the form of $(\frac{W}{W_s})$ and the other available models tested.

Figure 5.71 shows the comparison of diffuse radiation, calculated by using the devloped linear model (Eqn. 4.13) and Orgill and Hollands model (Eqn. 1.16), with the measured data as well as comparison amongst themselves. It is obvious that Orgill and Hollands model over estimates the diffuse radiation for Amman. Similar results can be observed for Aqaba too.

5.4.3 Hourly Beam radiation models

All developed models for both Amman and Aqaba yield better results than Turner and Mujahid model. Further details are indicated in 3.3 and 5.3.1.

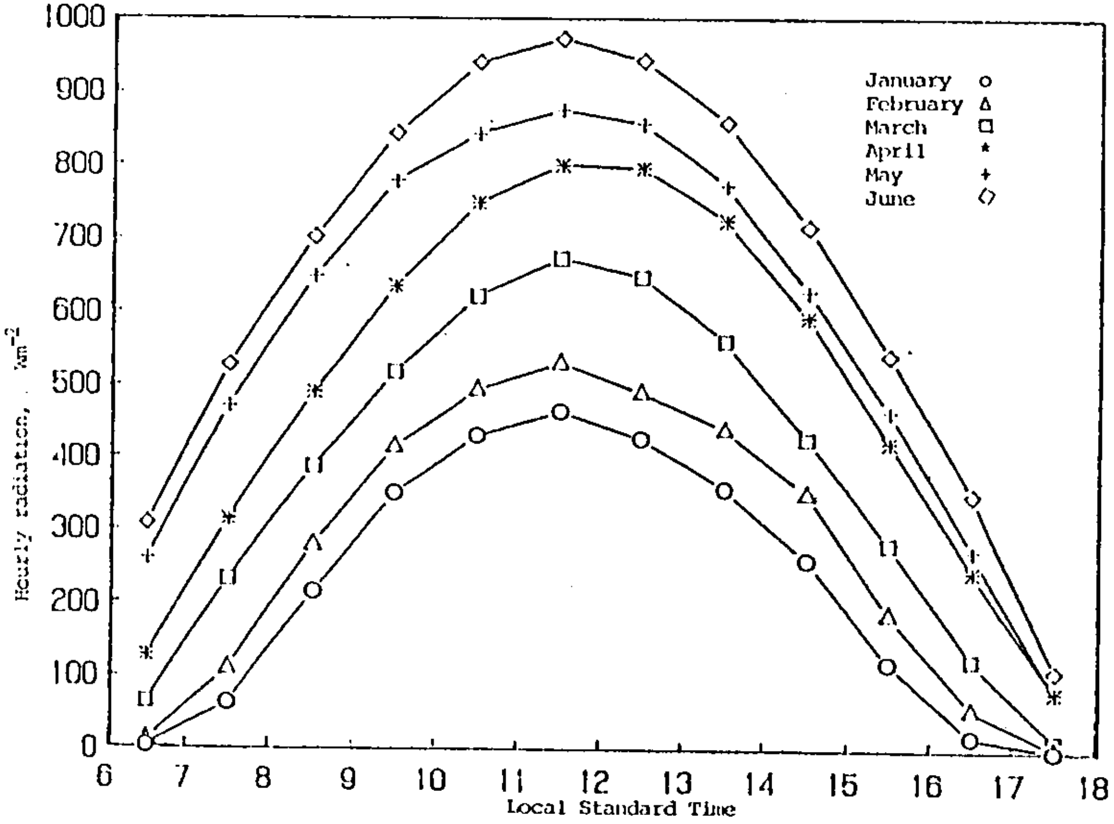

Fig 5.1 variation of hourly global radiation for the months of Jan,- June for Amman

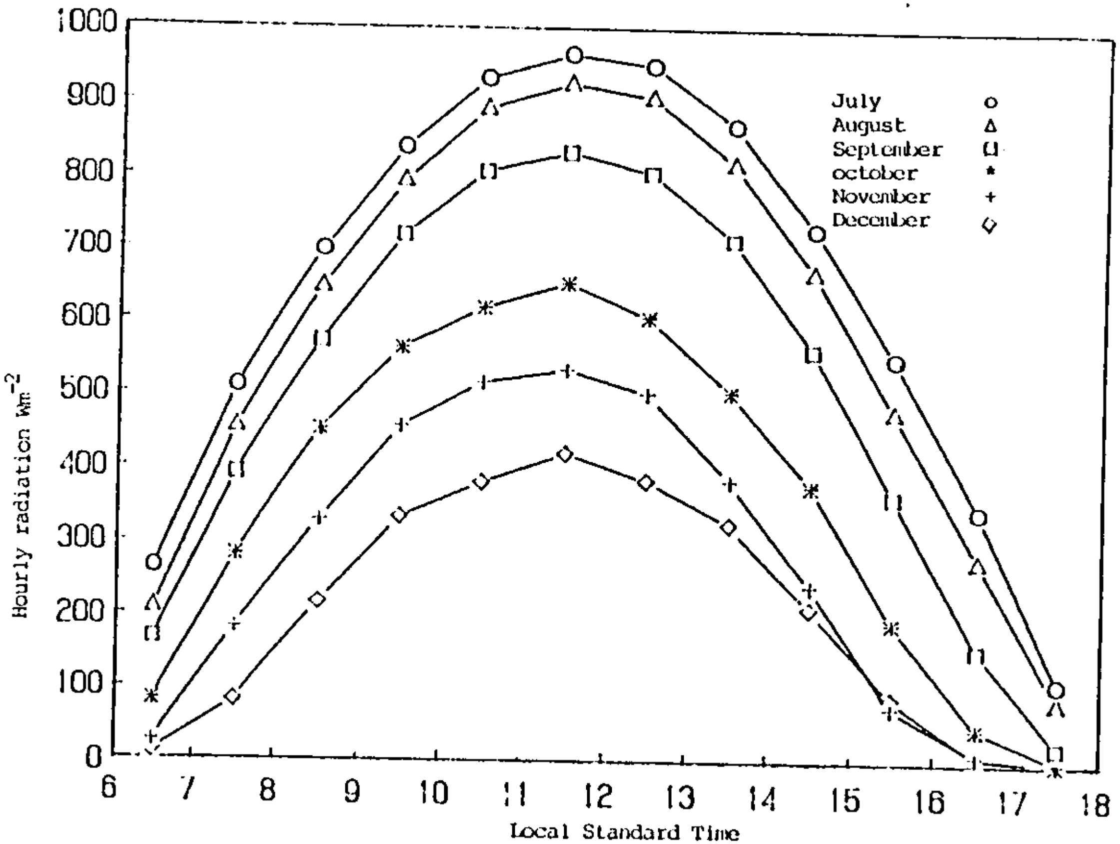

Fig 5.2 variation of hourly global radiation for the months of July - December for Amman.

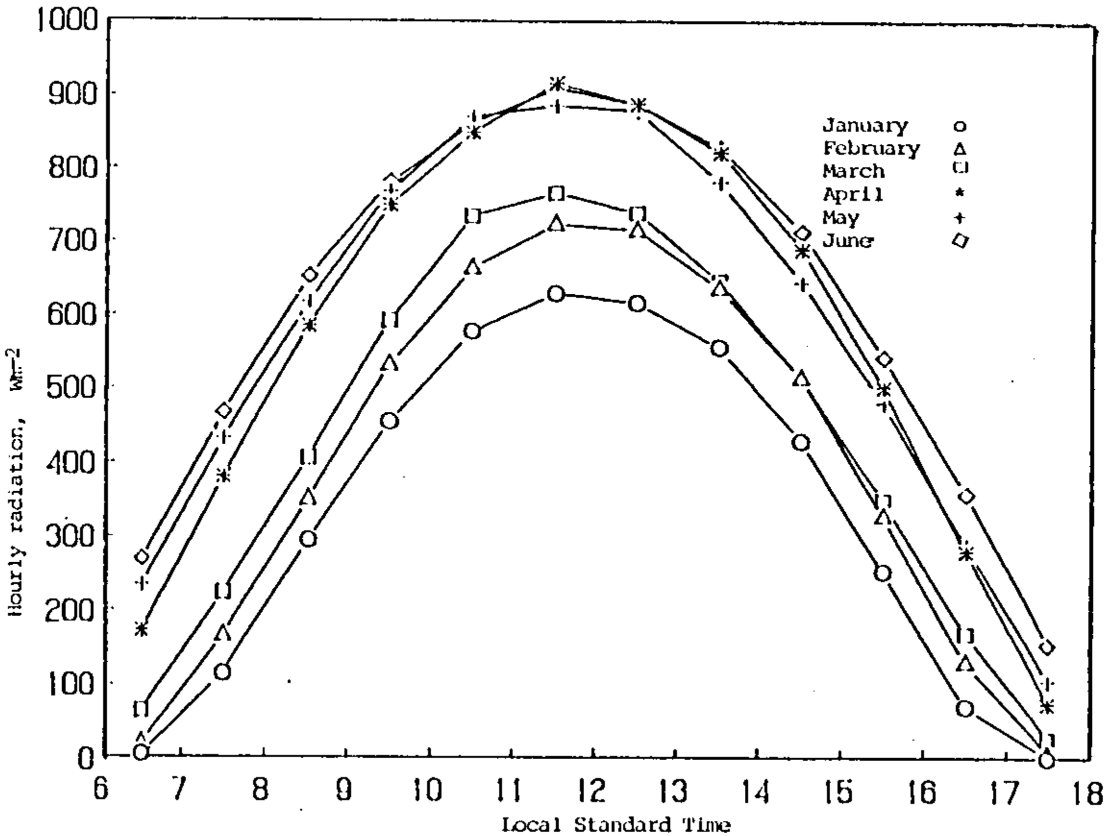

Fig 5.3 variation of hourly global radiation for the months of Jan - June to Aqaba

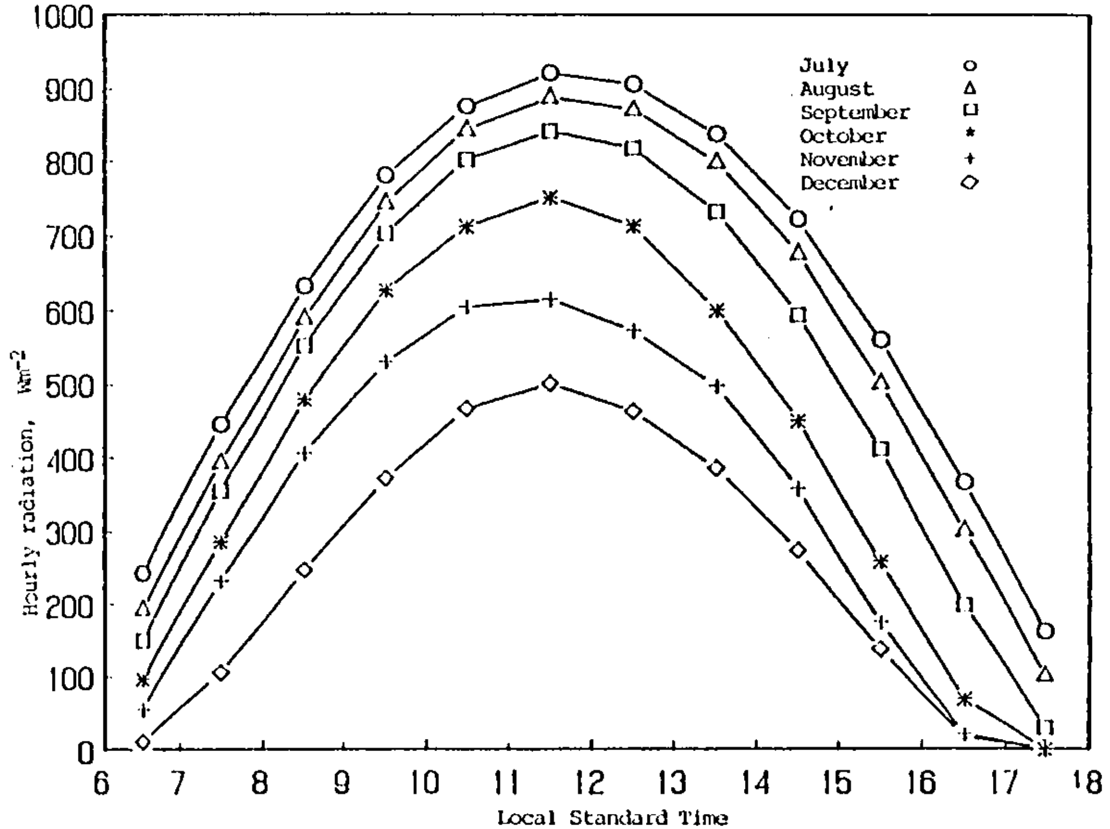

Fig 5.4 , variation of hourly global radiation for the months of July - December for Aqaba.

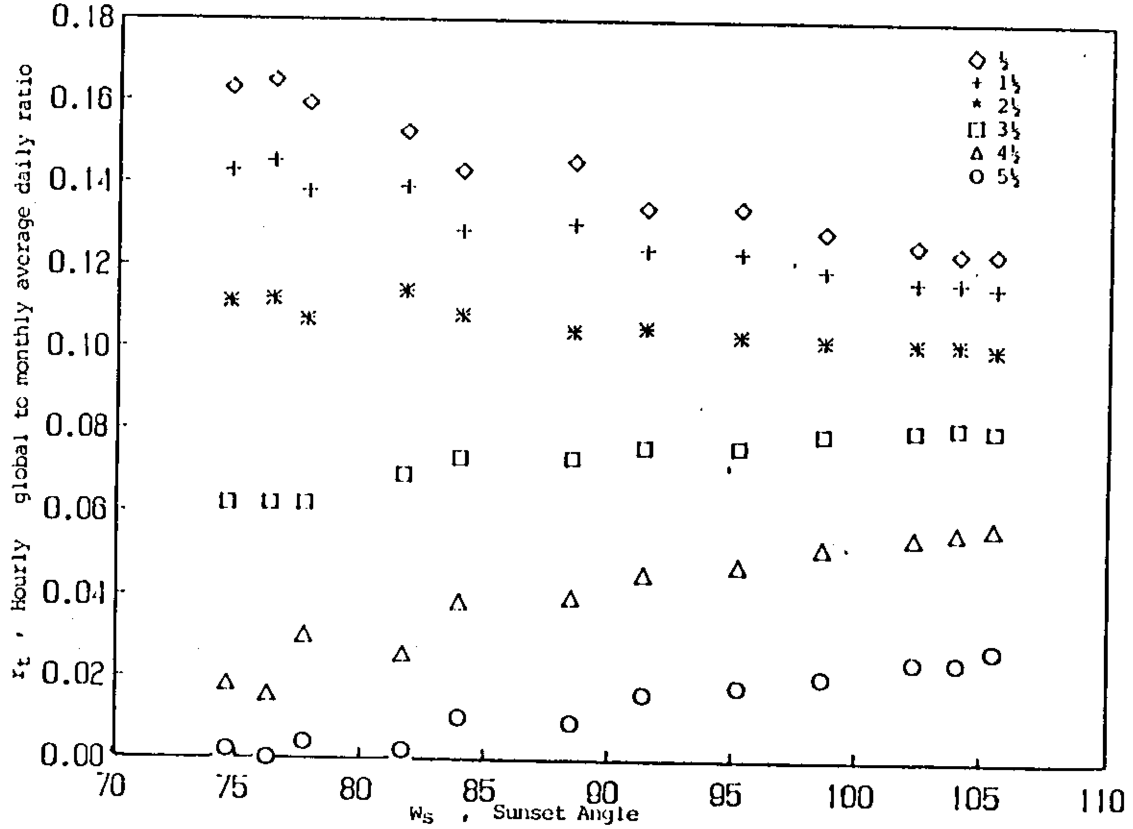

Fig 5.5. Hourly global to monthly average daily ratio versus sunset angle - Amman .

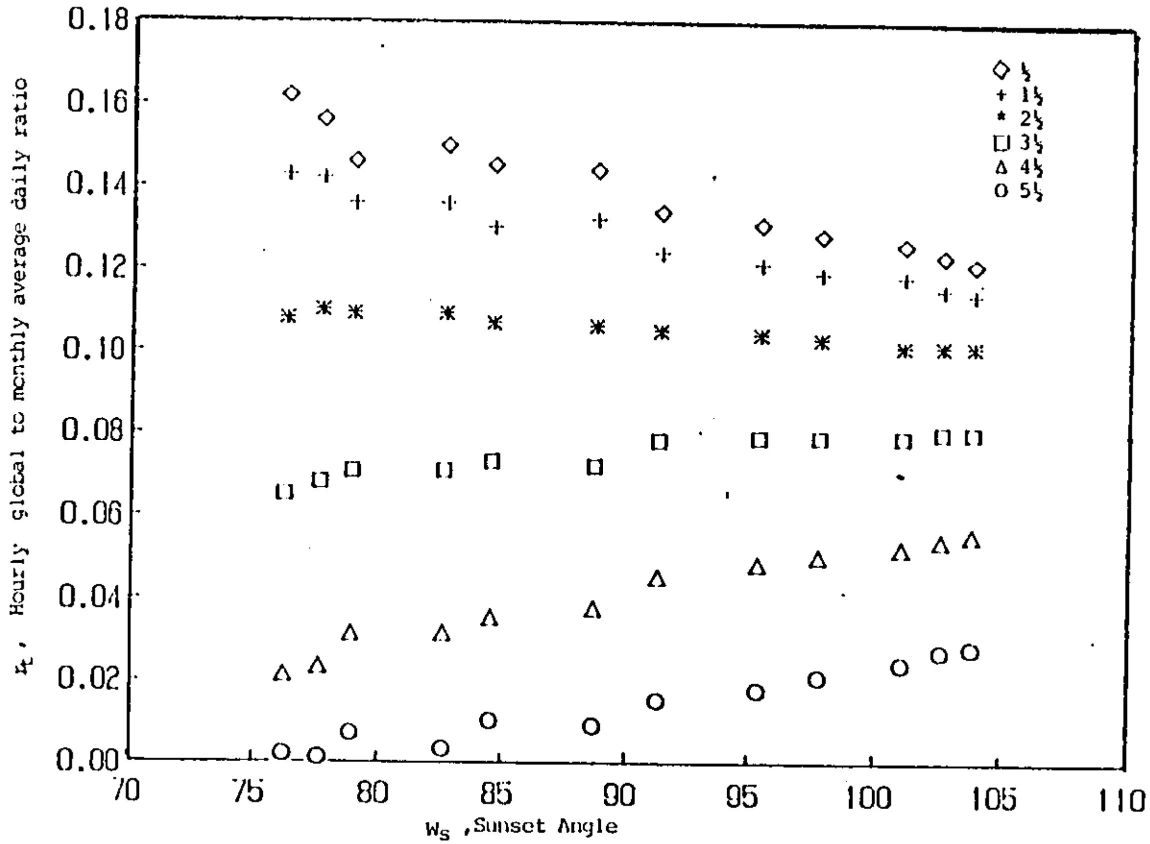

Fig 5.6 Hourly Global to monthly average daily ratio versus sunset angle - Aqaba .

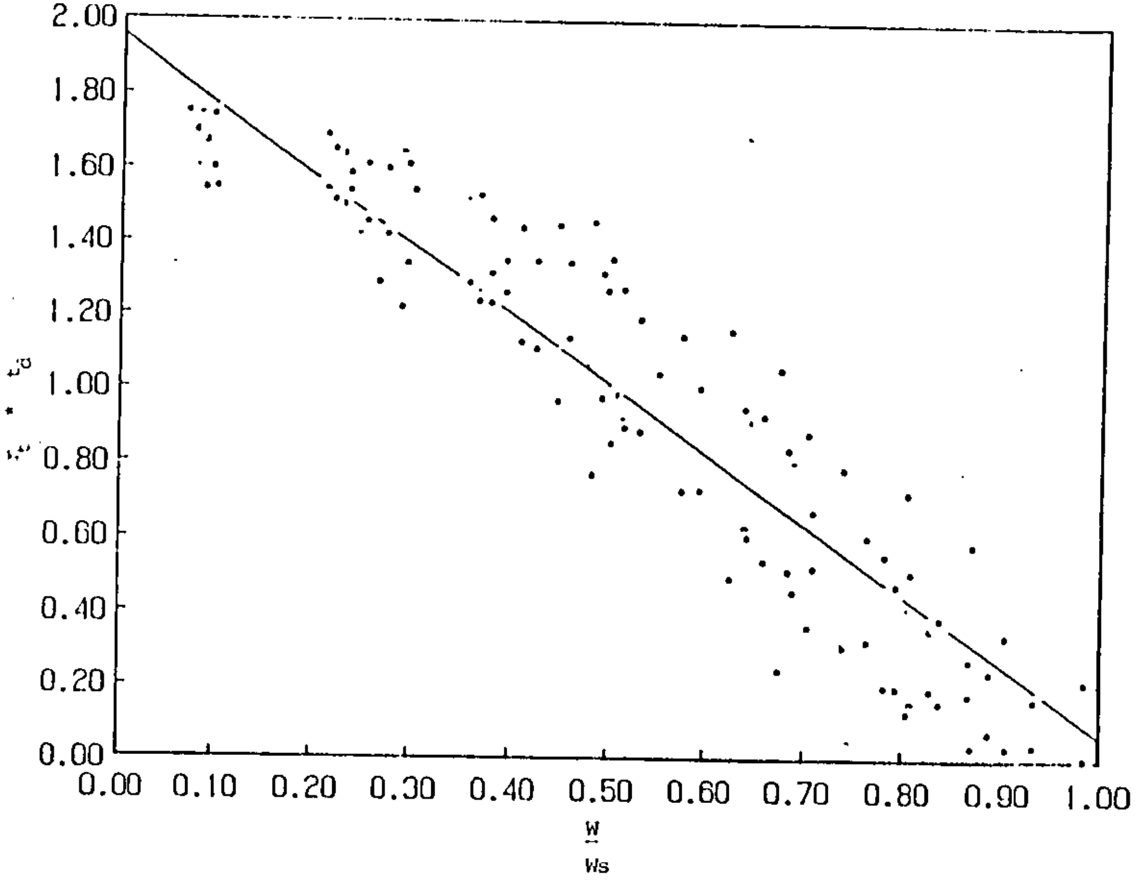

Figure 5.7 , Hourly Global to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on obtained linear equation - Amman . Eqn. (4.1).

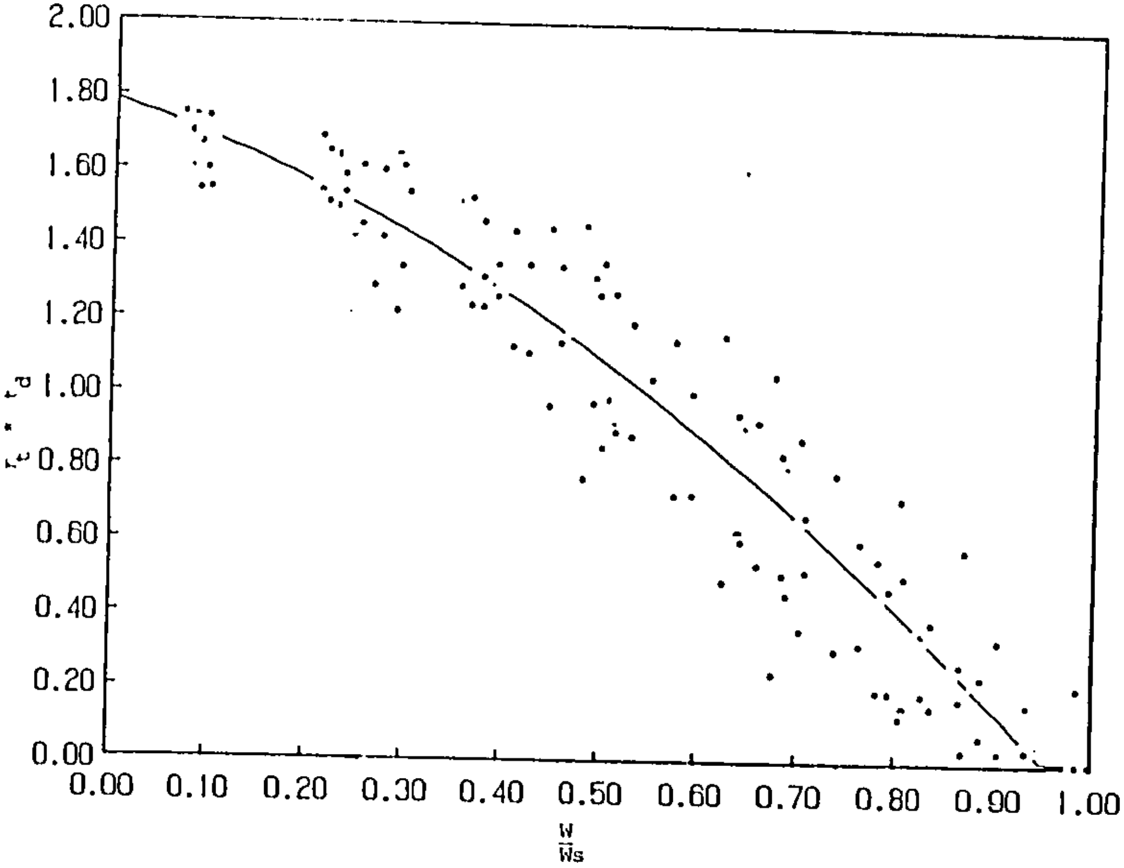

Figure 5.8 , Hourly Global to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on obtained second degree euation - Amman . Eqn. (4.2).

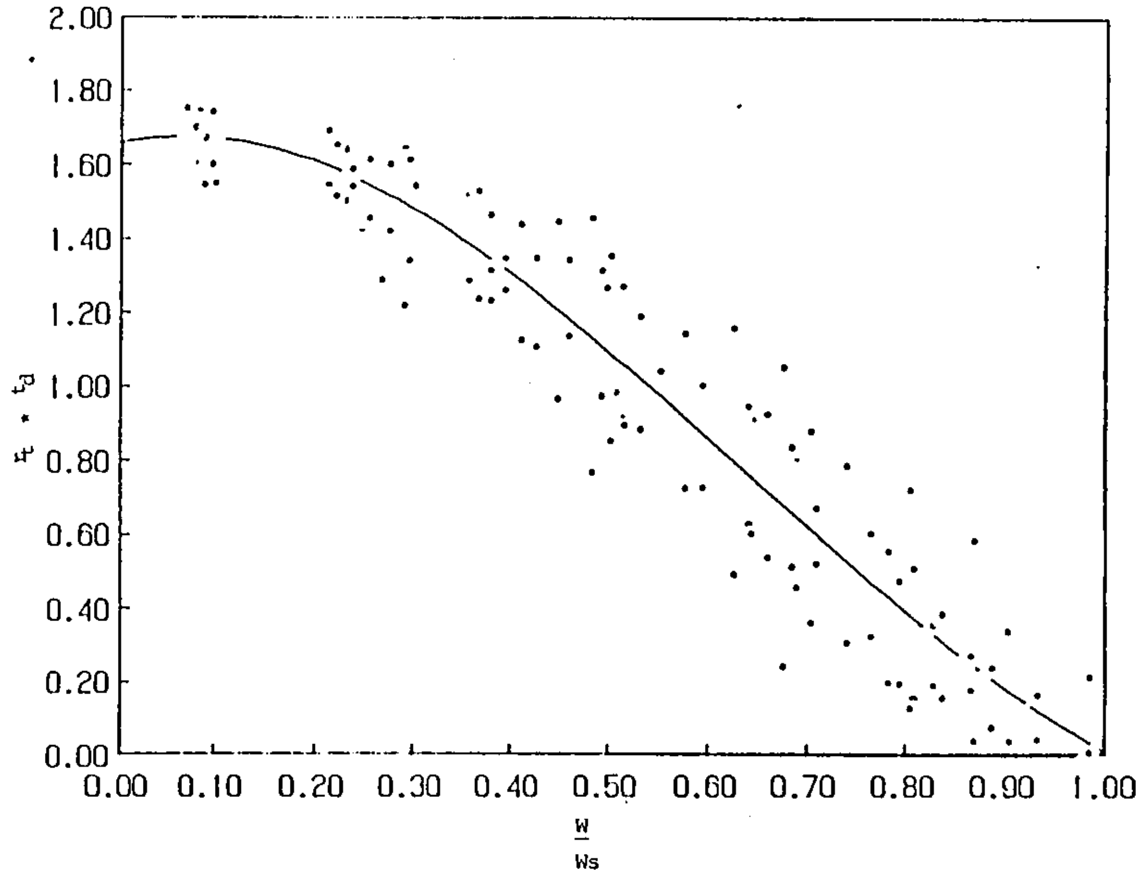

Figure 5.9 , Hourly Global to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on obtained third degree equation - Amman . Eqn. (4.3)

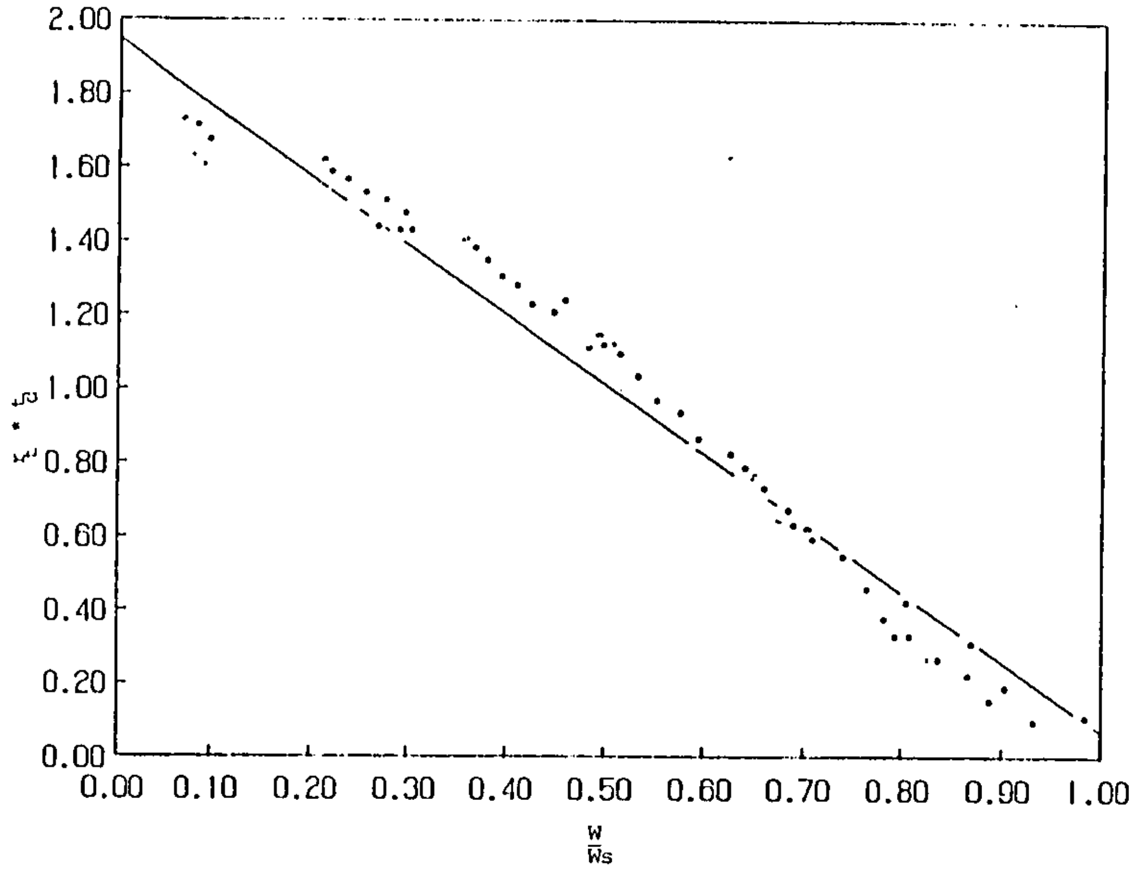

Figure 5.10 Hourly Global to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on obtained Linear Equation – Amman . Eqn. (4.4)

The average data around solar noon is taken.

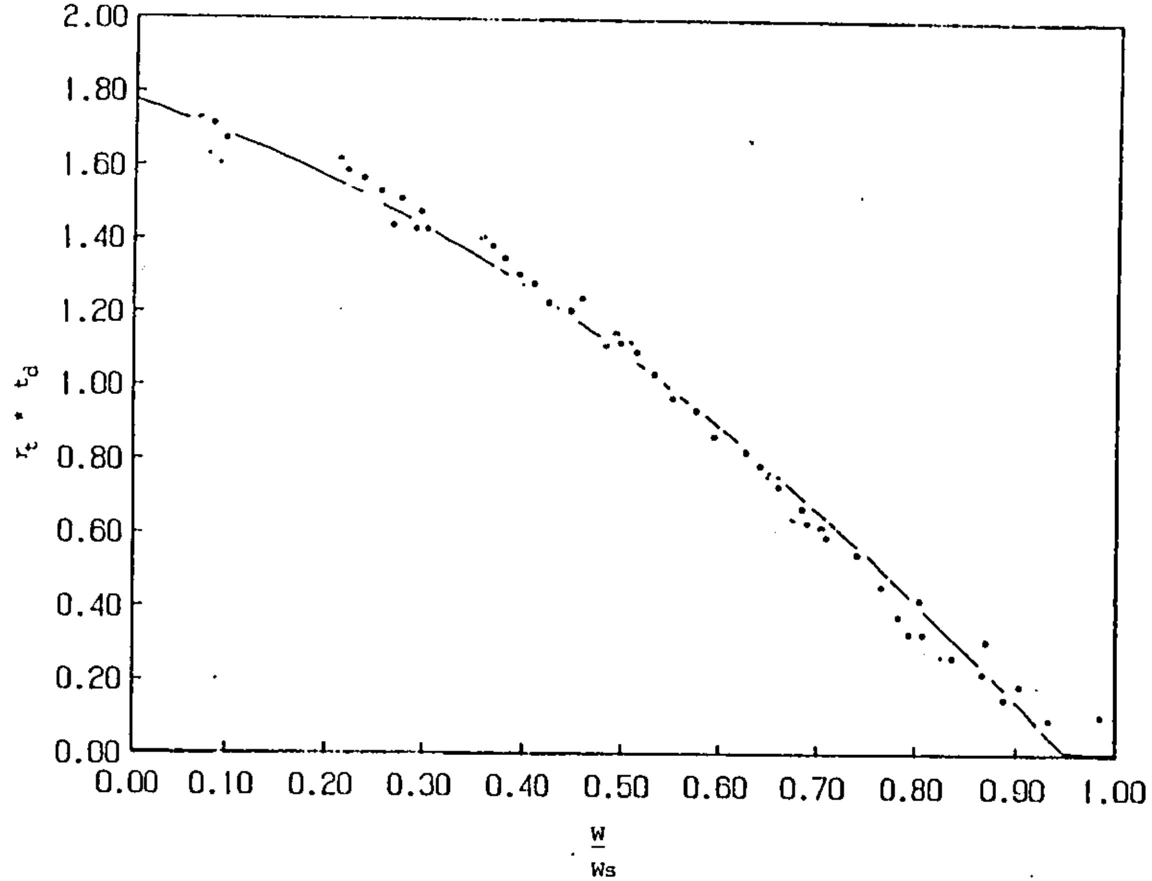

Figure 5.11 Hourly Global to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on obtained second degree equation - Amman .Eqn. (4.5).
The average data around Solar noon is taken.

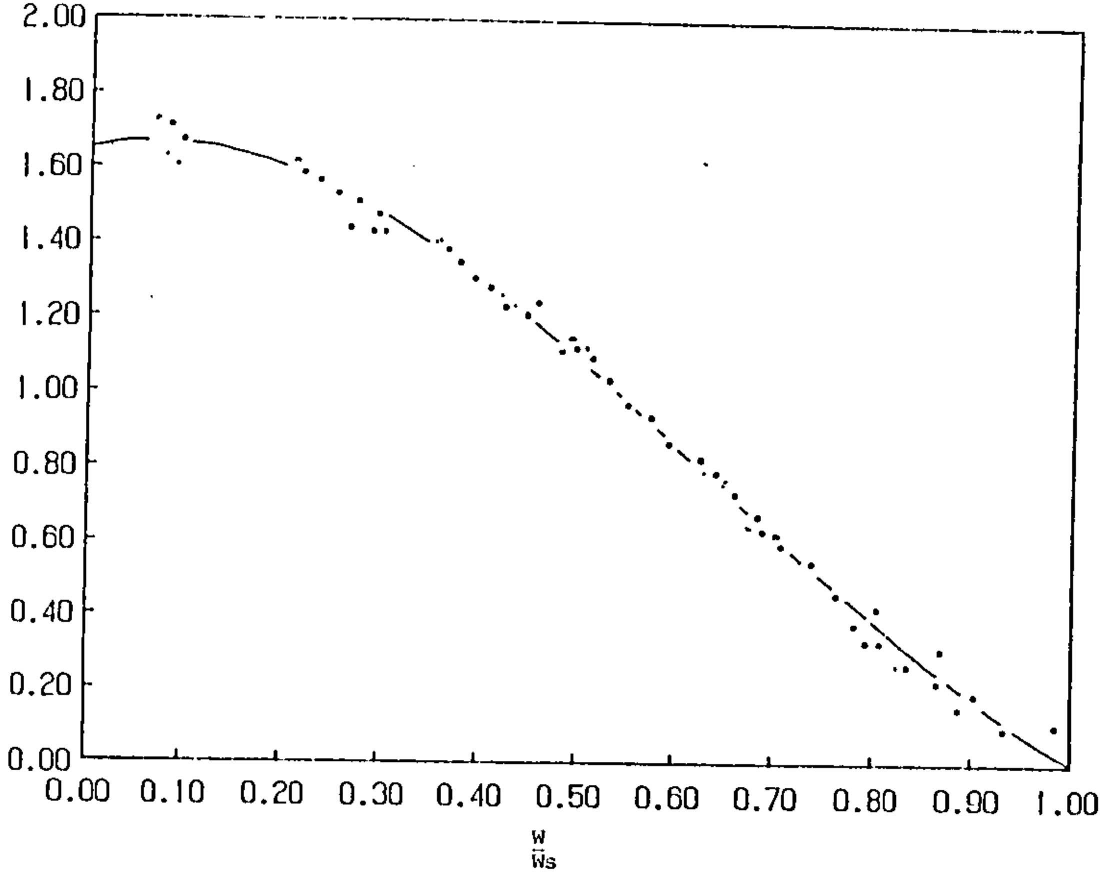

Figure 5.12 Hourly Global to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on obtained Third Degree equation - Amman. Eqn. (4.6) .
The average data around solar noon is taken.

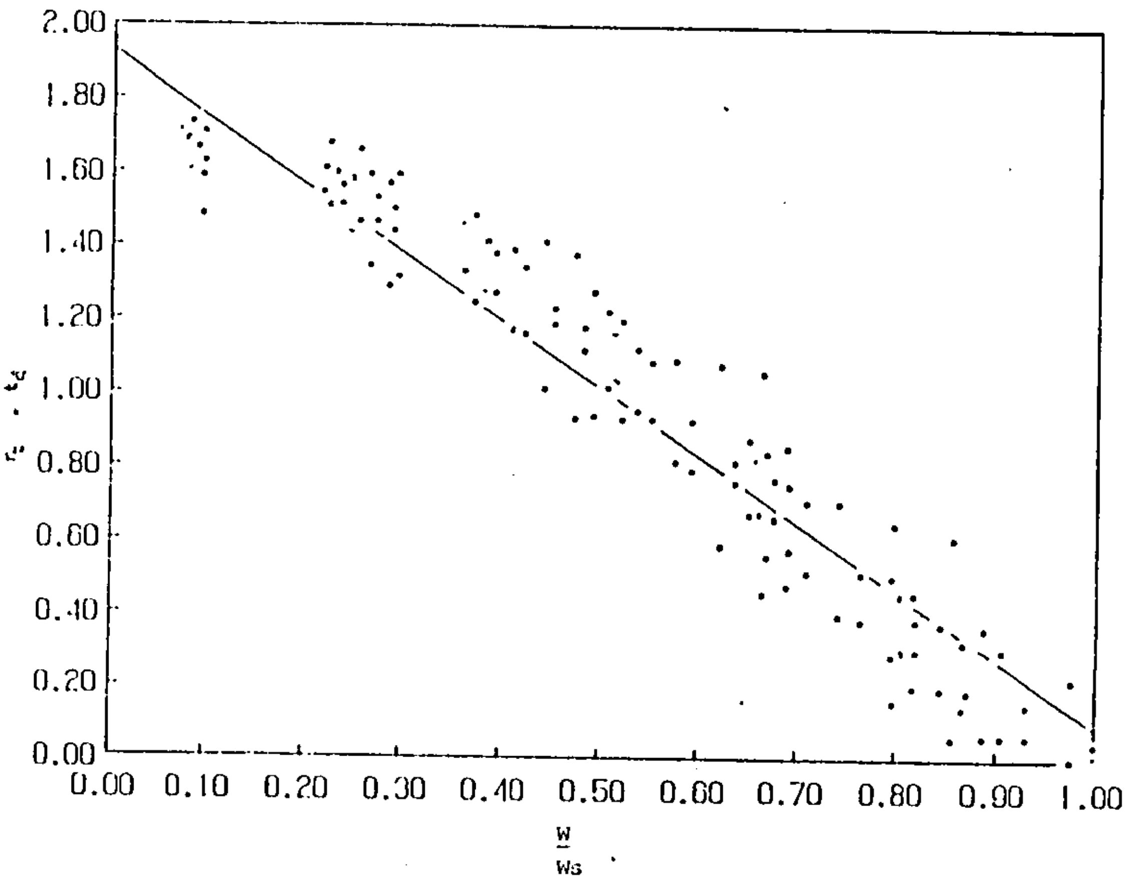

Figure 5.13, Hourly Global to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on obtained linear Equation – Aqaba. Eqn. (4.7).

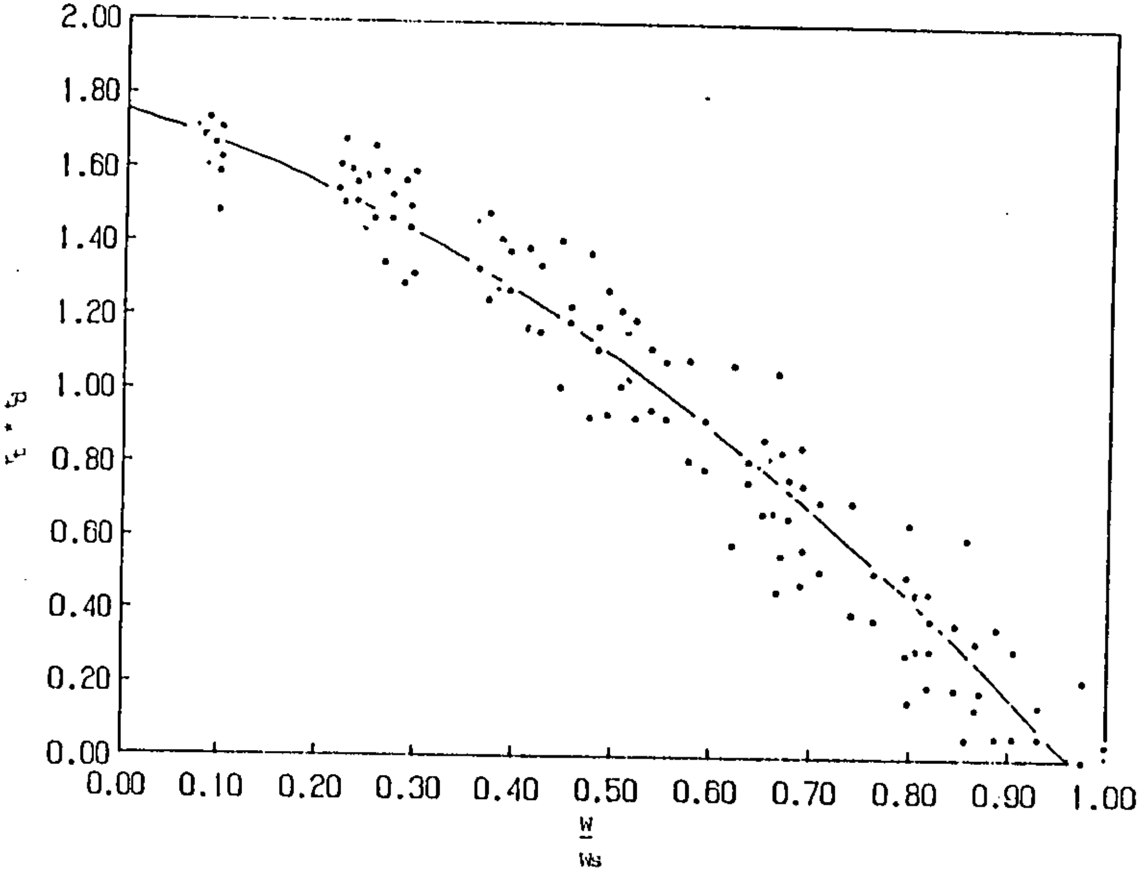

Figure 5.14 Hourly Global to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on obtained Second Degree Equation - Eqn. (4.8). Aqaba.

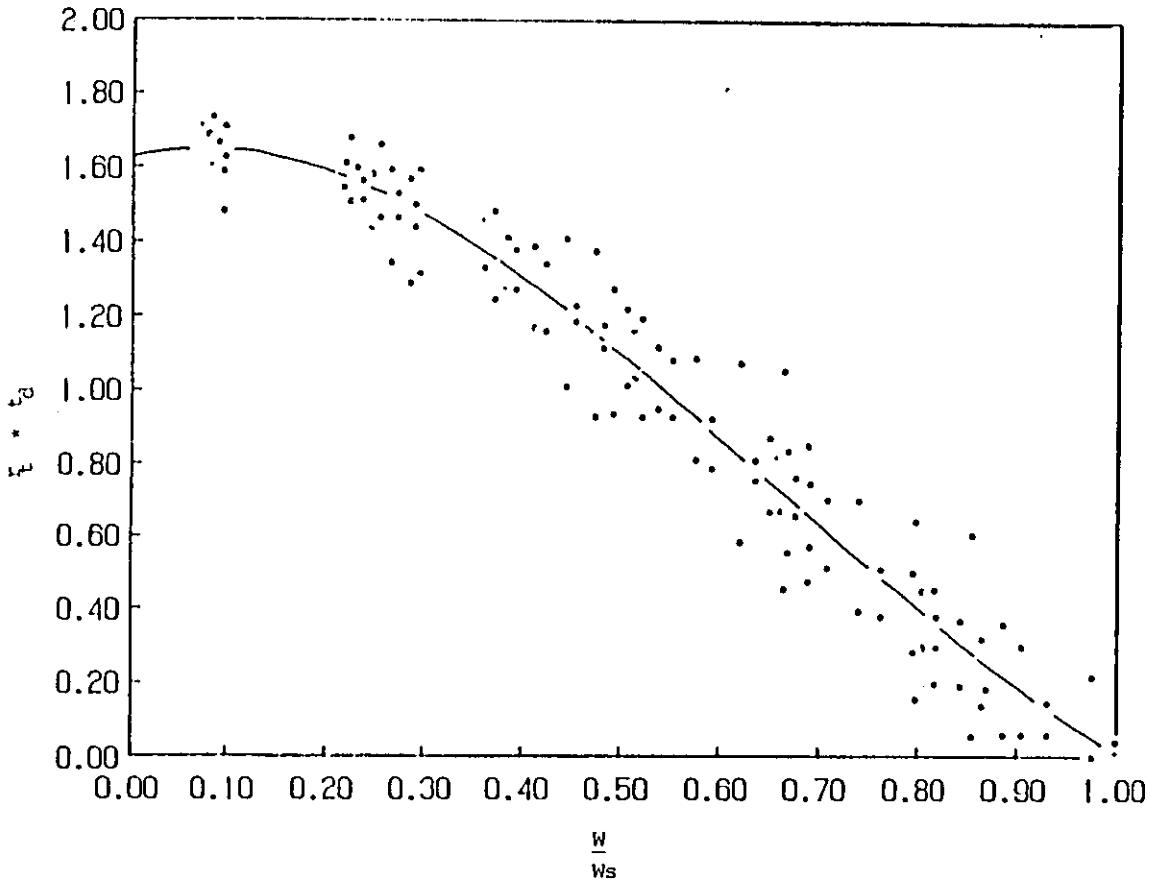

Figure 5.15 Hourly Global to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on obtained Third Degree Equation - Aqaba .Eqn. (4.9).

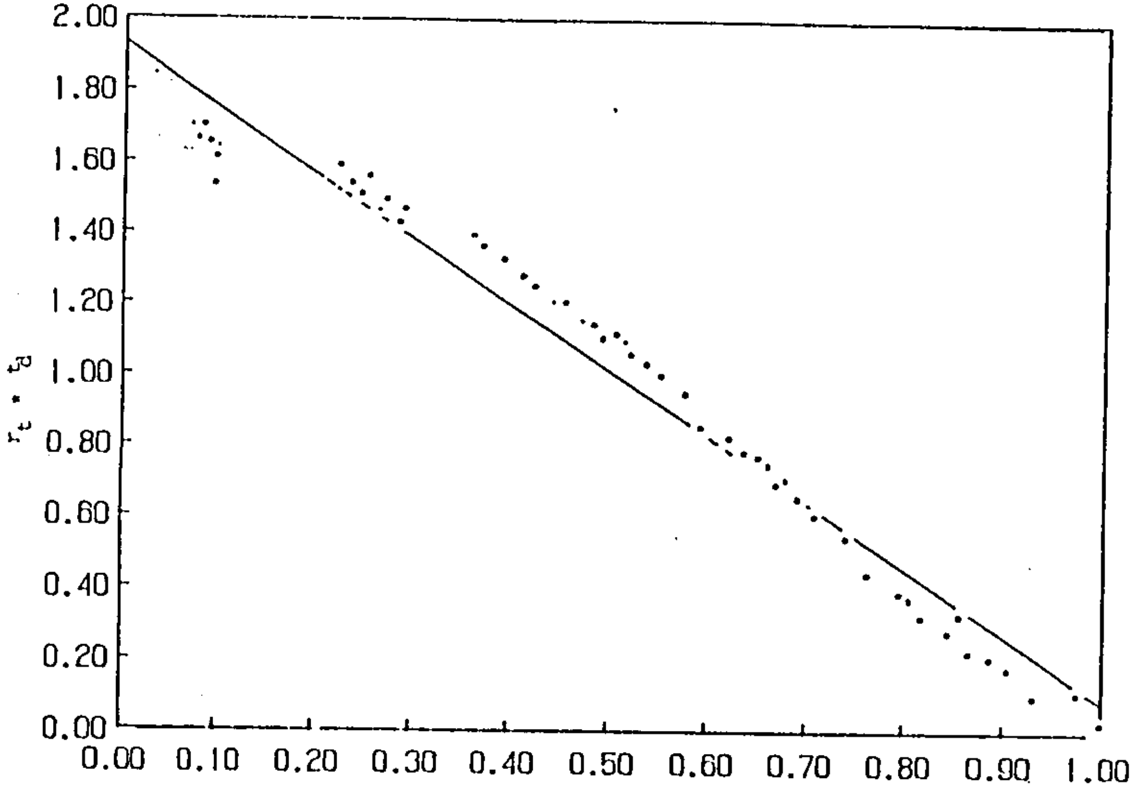

Figure5.16, Hourly Global to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on obtained Linear Equation - Aqaba. Eqn. (4.10).
The average data around solar noon is taken.

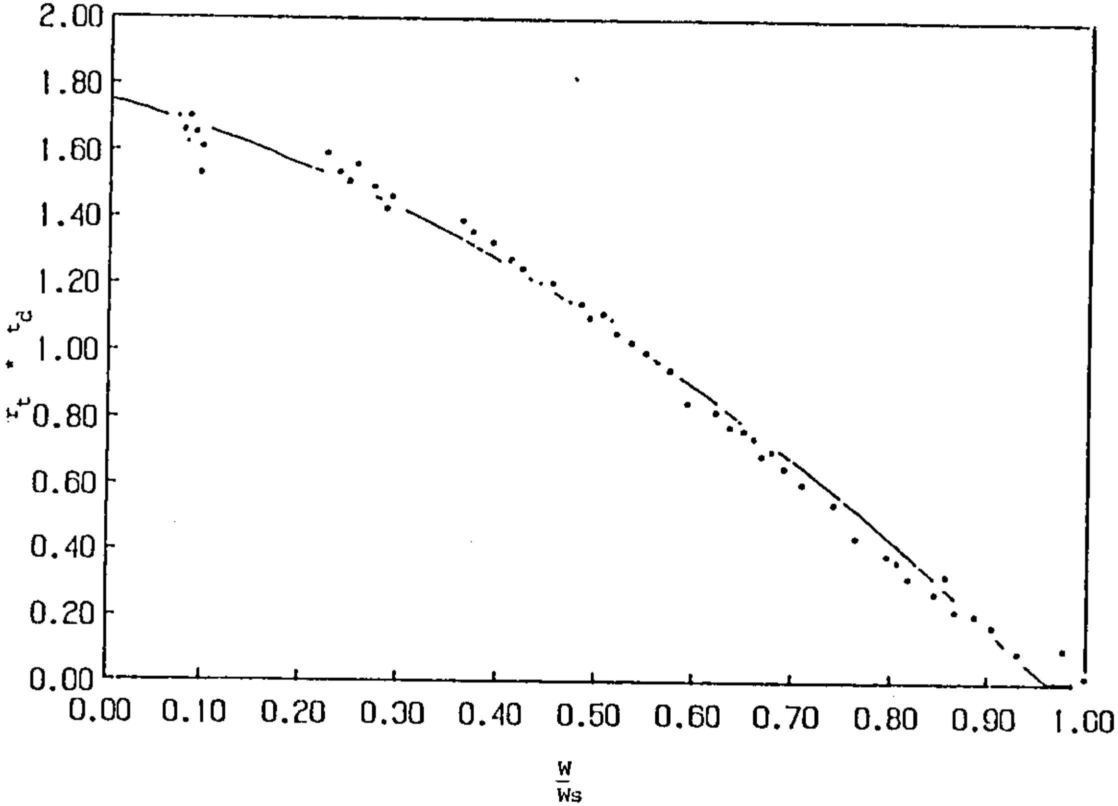

Figure 5.17 Hourly Global to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on obtained Second Degree Equation - Aqaba. Eqn. (4.11).

The average data around solar noon is taken .

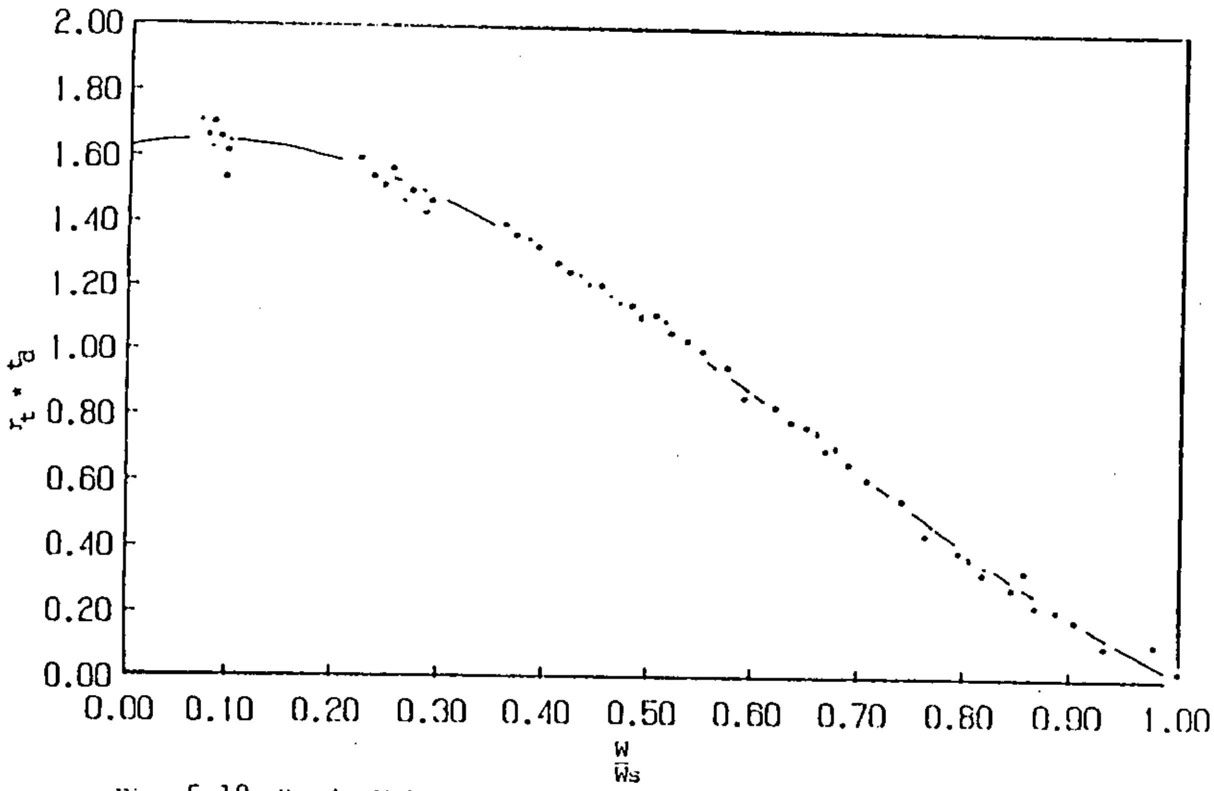

Figure5.18, Hourly Global to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on obtained third degree equation - Aqaba .Eqn.(4.12).
The average data around Solar Noon is taken.

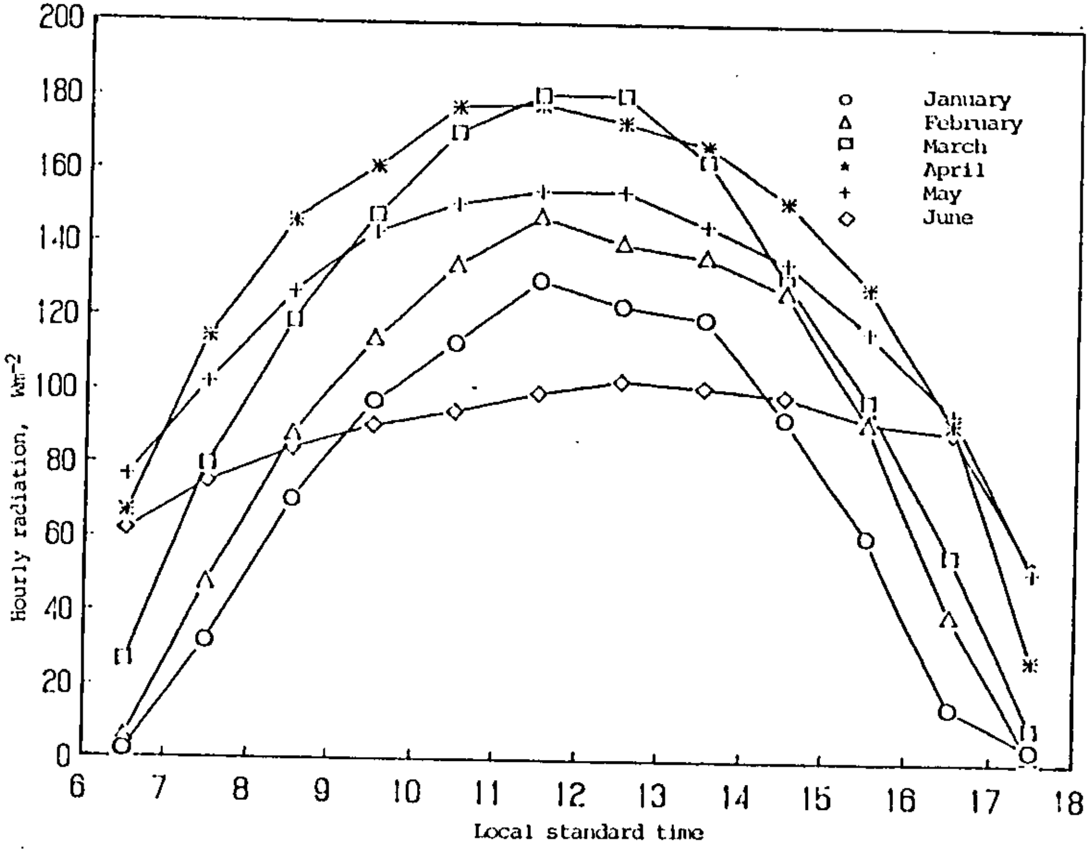

Fig5.19 variation of hourly Diffuse radiation for the months of Jan - June for Amman.

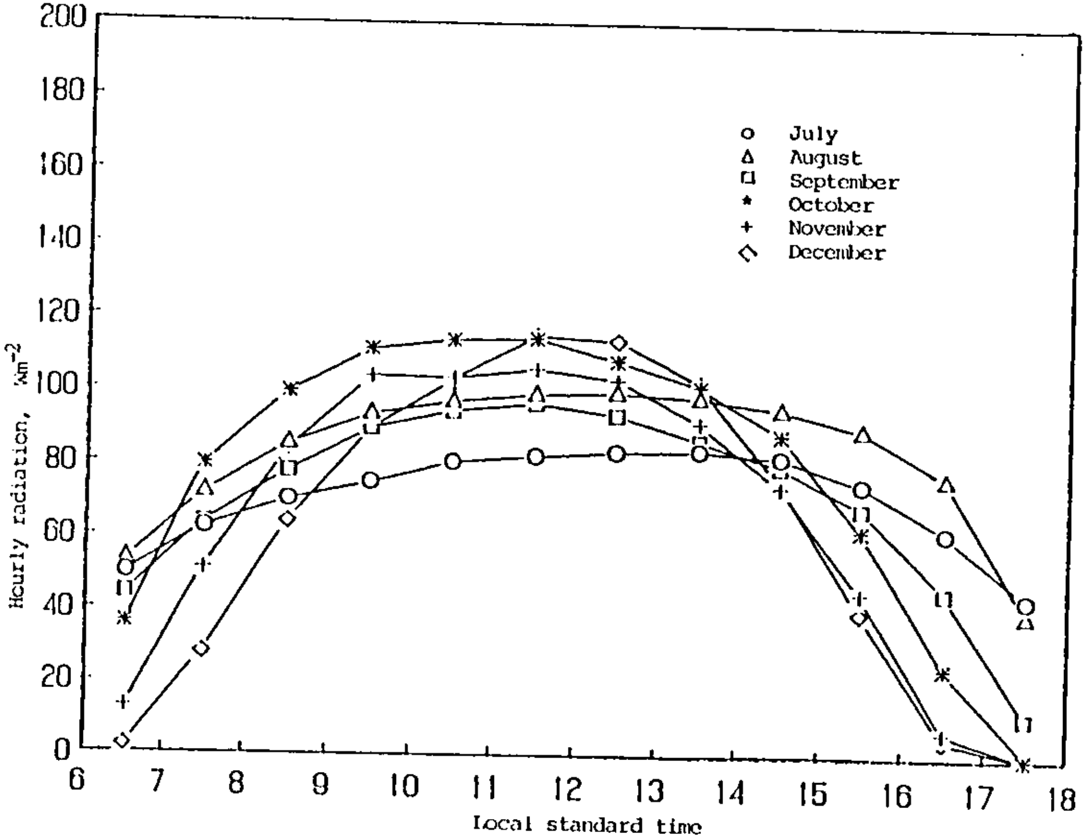

Fig5.20 variation of hourly diffuse radiation for the months of July - December for Amman.

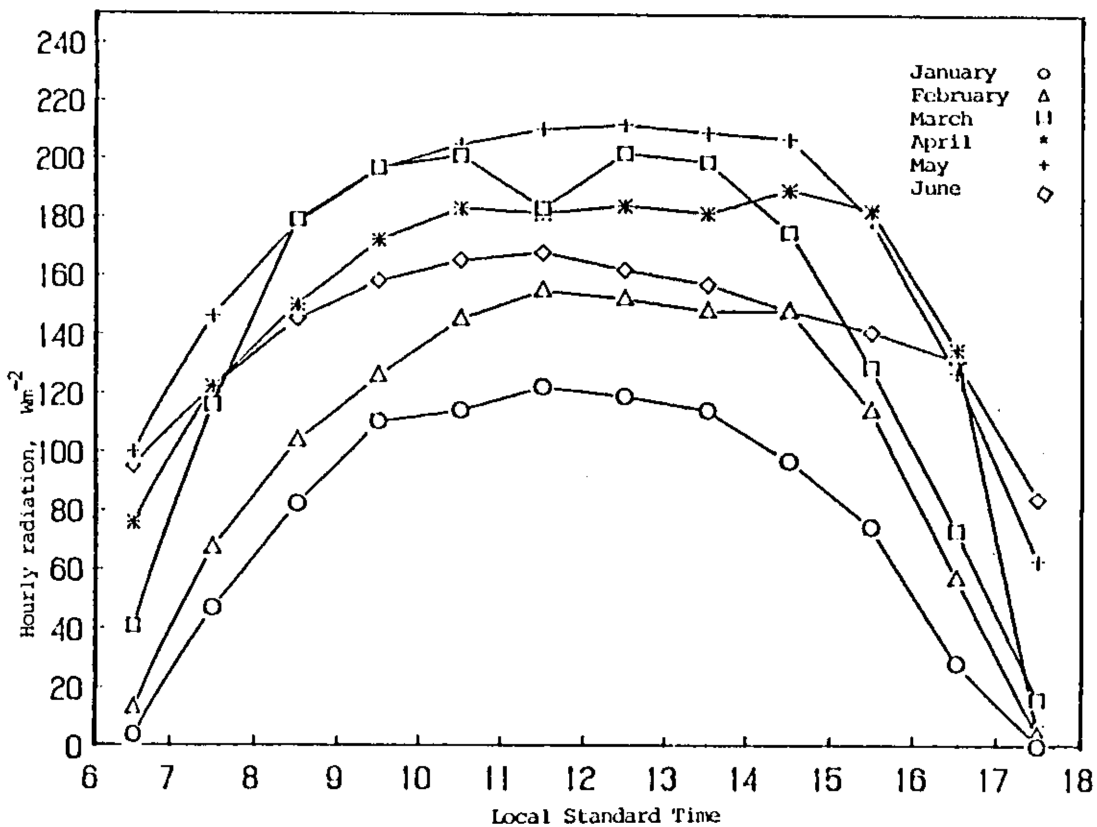

Fig.5.21 variation of hourly diffuse radiation for the months of Jan - June for Aqaba.

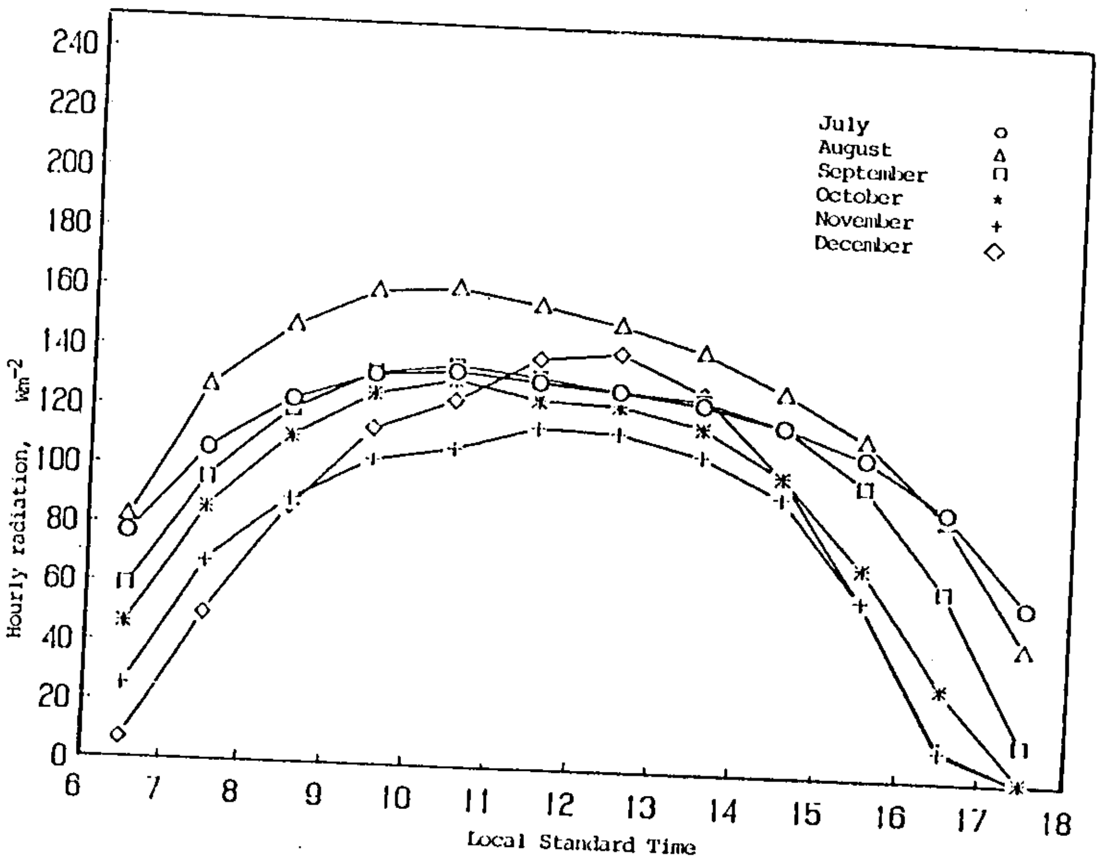

Fig. 5.22, variation of hourly diffuse radiation for the months of July - December for Aqaba.

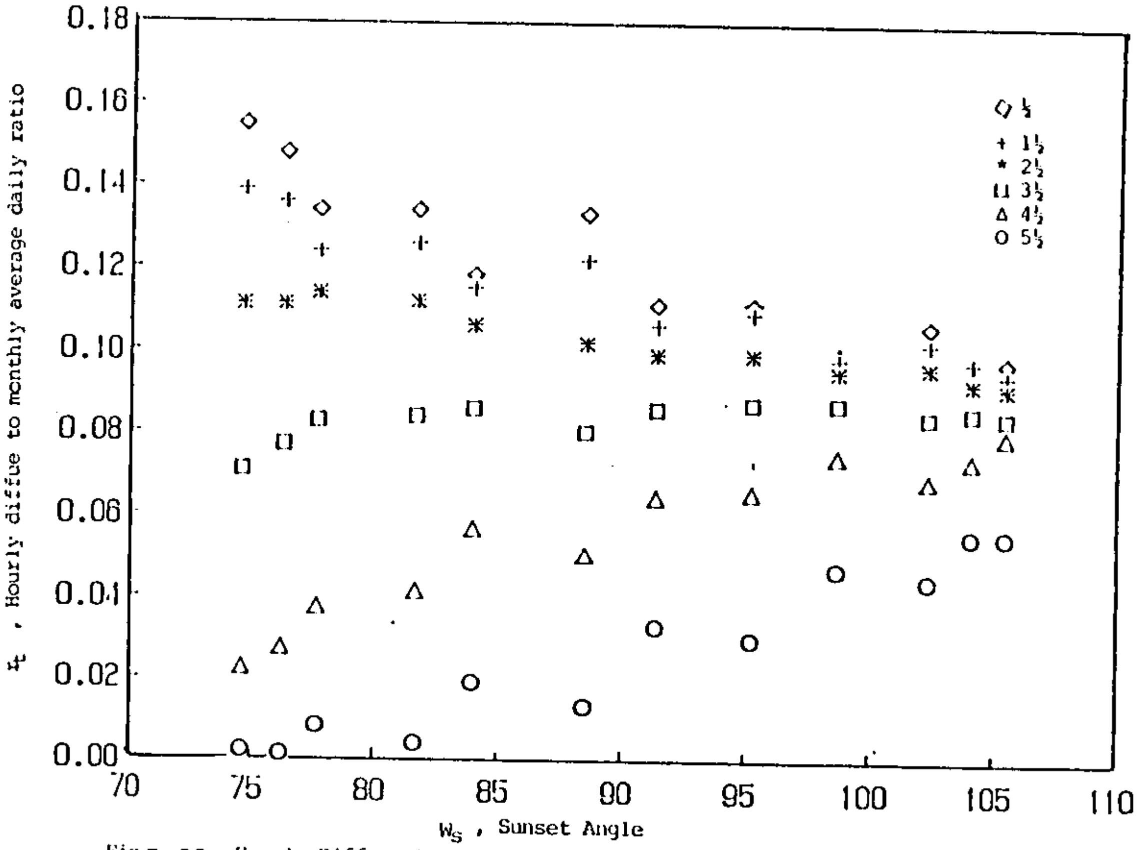

Fig.5.23 Hourly Diffuse to monthly average daily ratio versus sunset angle - Amman.

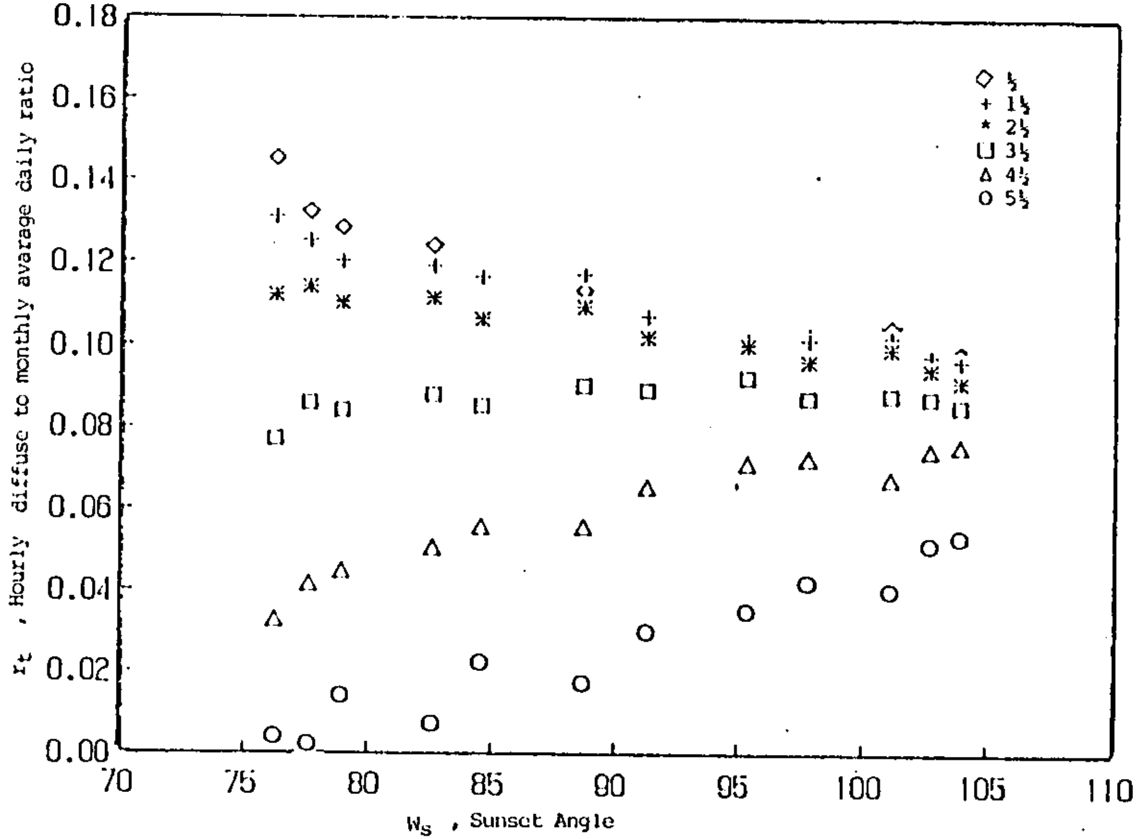

Fig.5.24 Hourly diffuse to monthly average daily ratio versus sunset angle - Aqaba .

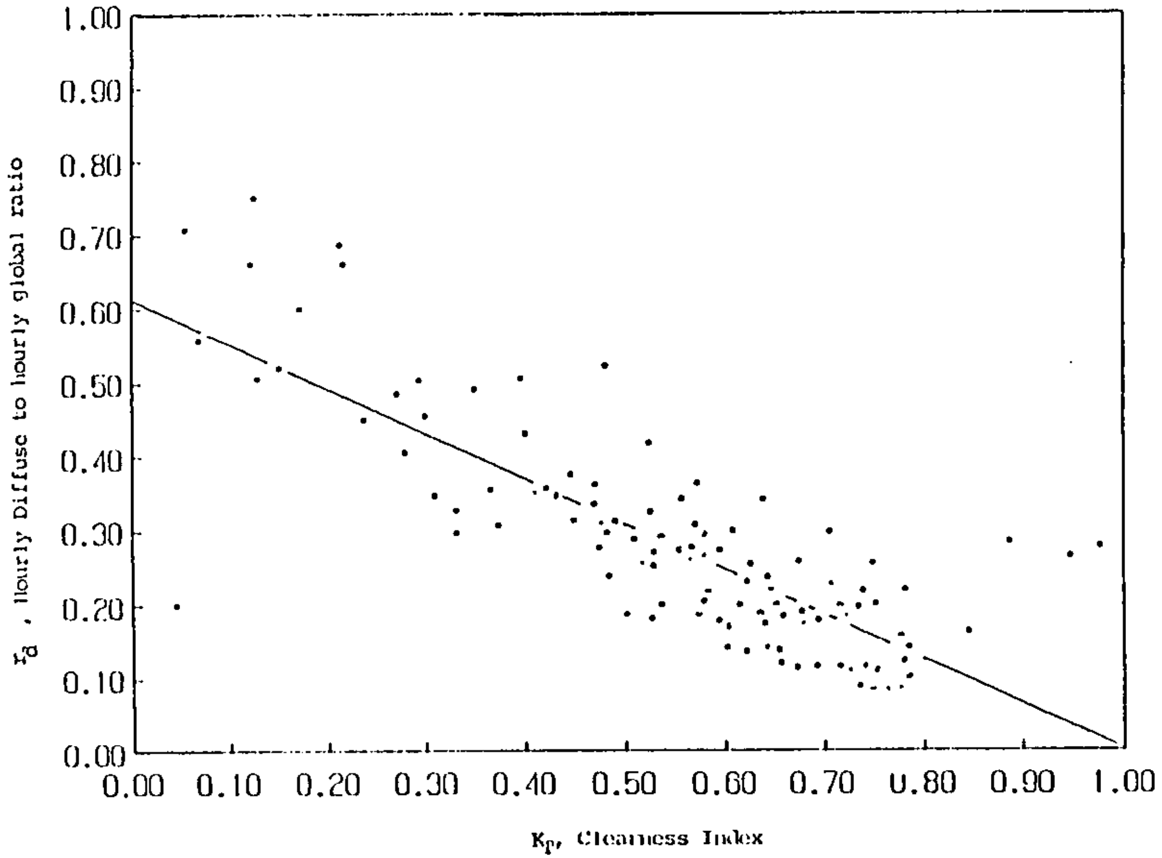

Figure 5.25 Hourly diffuse to hourly global ratio versus clearness index based on obtained Linear Equation. Amman. Eqn. (4.13).

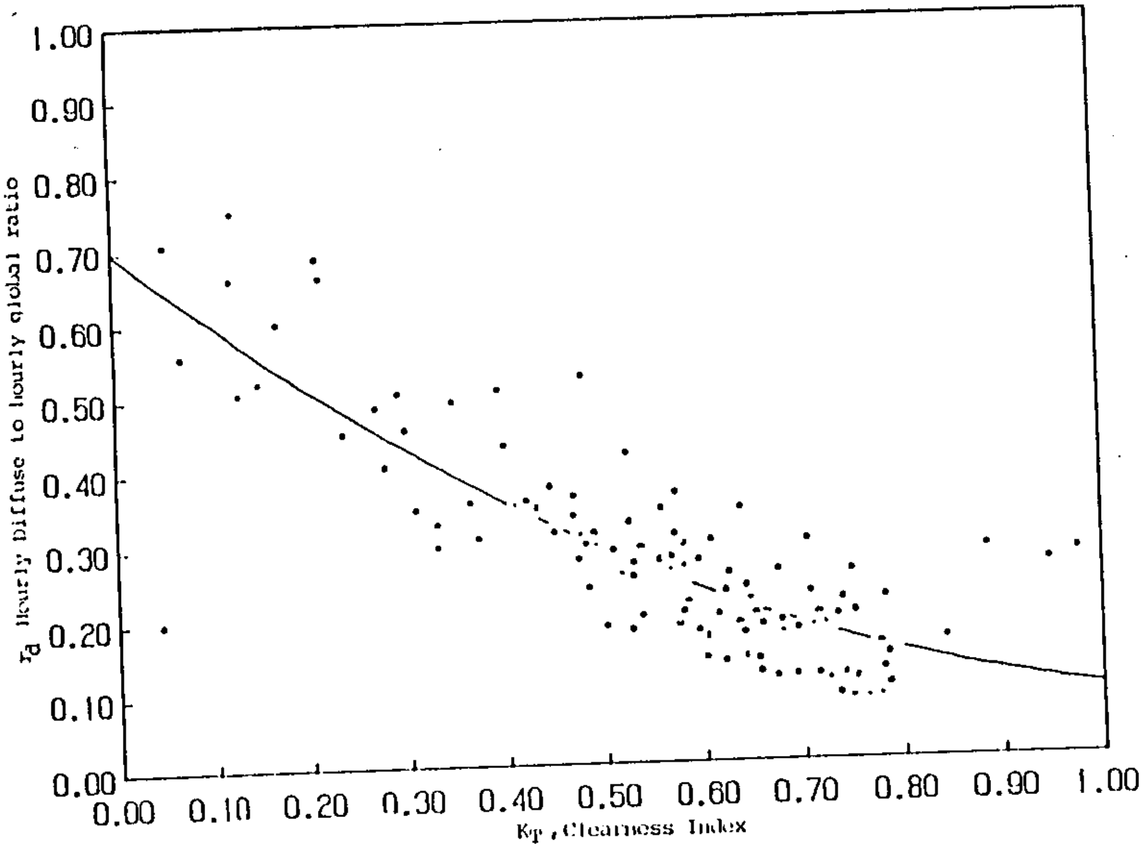

Figure 5.26 Hourly diffuse to hourly global ratio versus clearness index based on obtained Second Degree Equation-Amman.Eqn. (4.14).

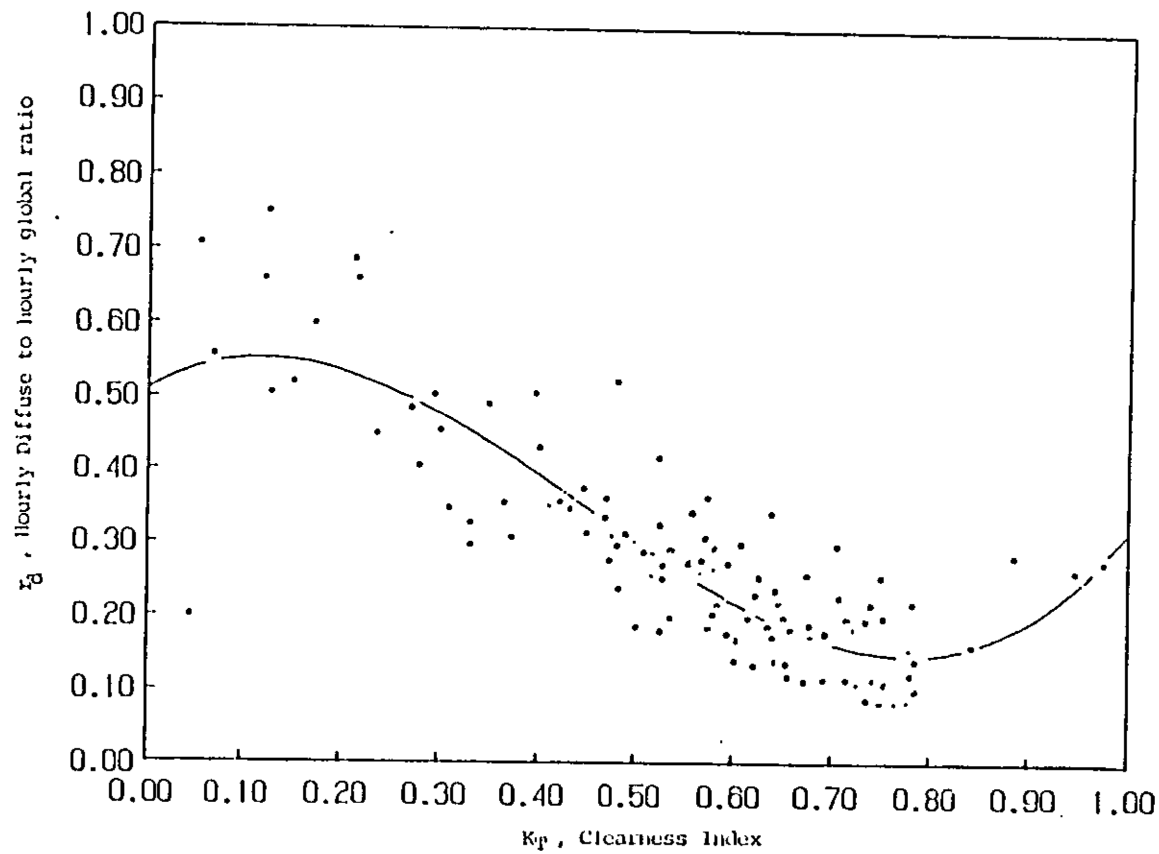

Figure 5.27 Hourly diffuse to hourly global ratio versus clearness index based on obtained Third degree Equation-Amman Eqn. (4.15)

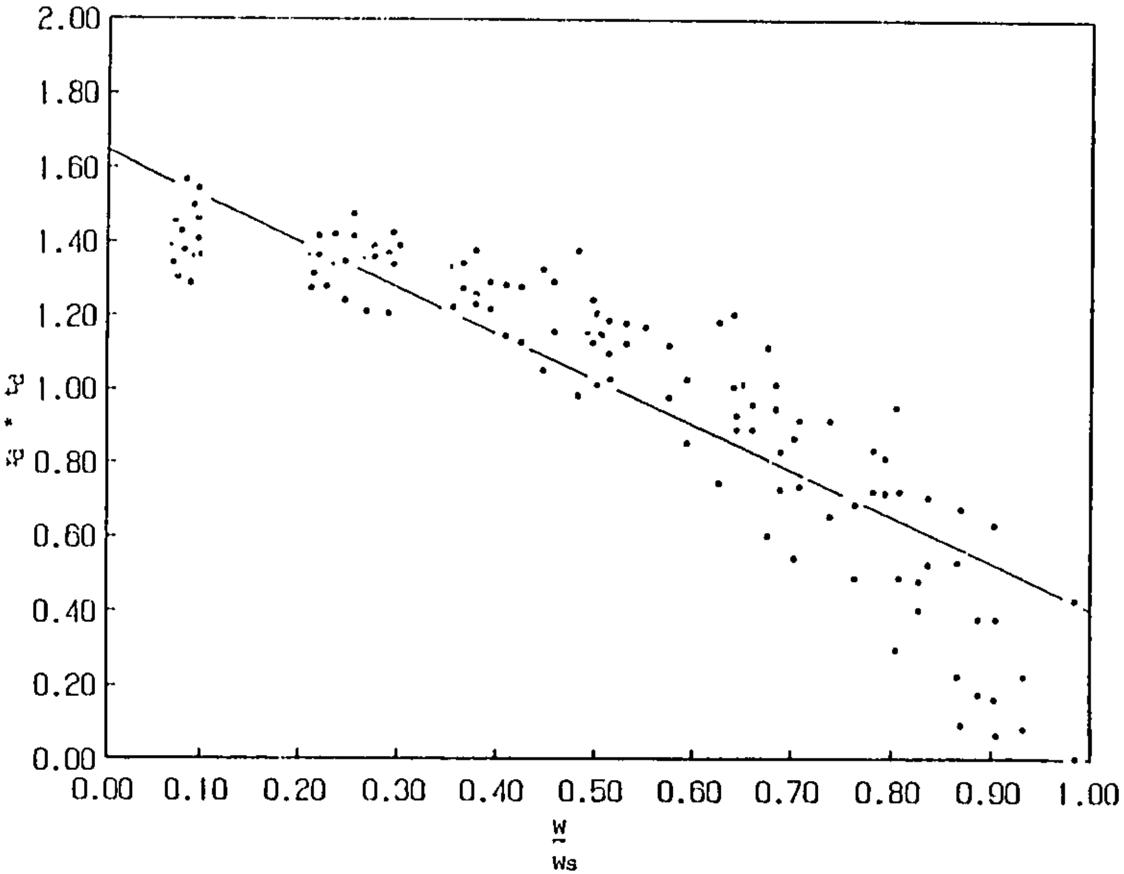

Figure 5.28 Hourly Diffuse to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on Linear Equation - Amman .Eqn. (4.35)

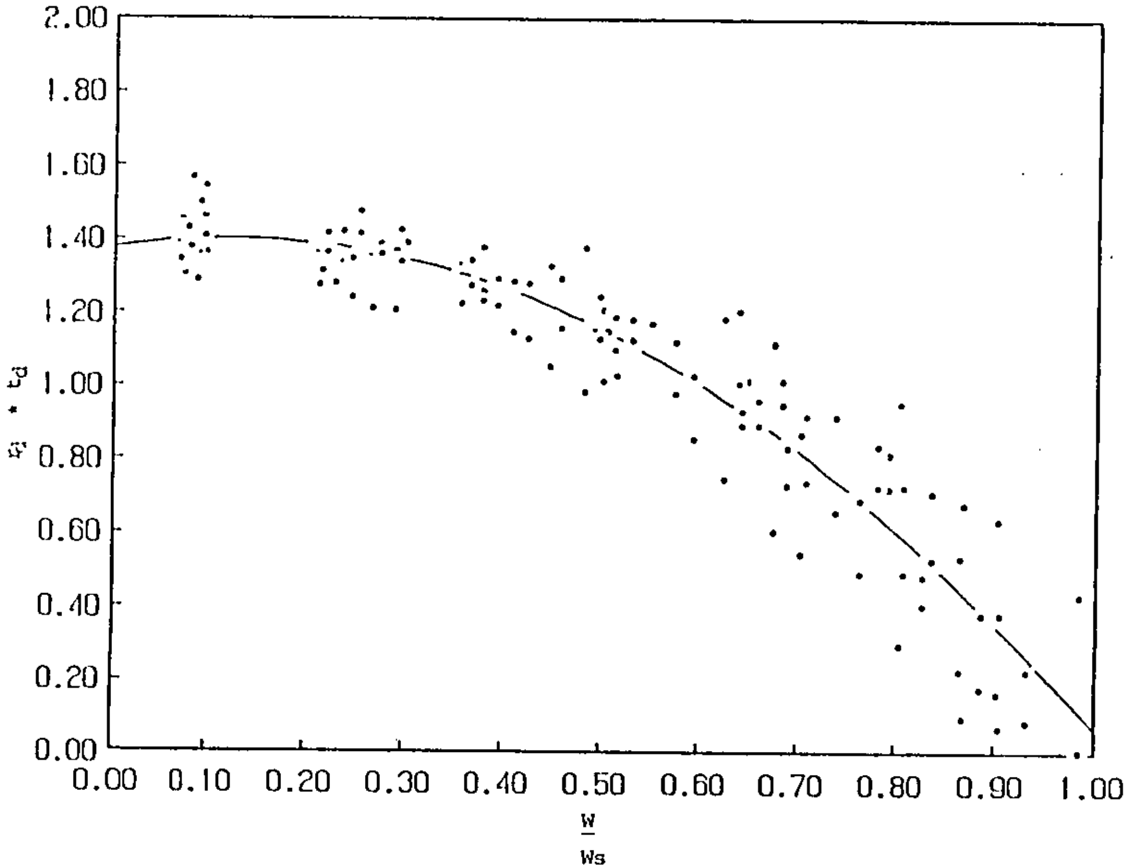

Figure5.29 , Hourly Diffuse to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on Second Degree Equation - Amman . Eqn (4.36)

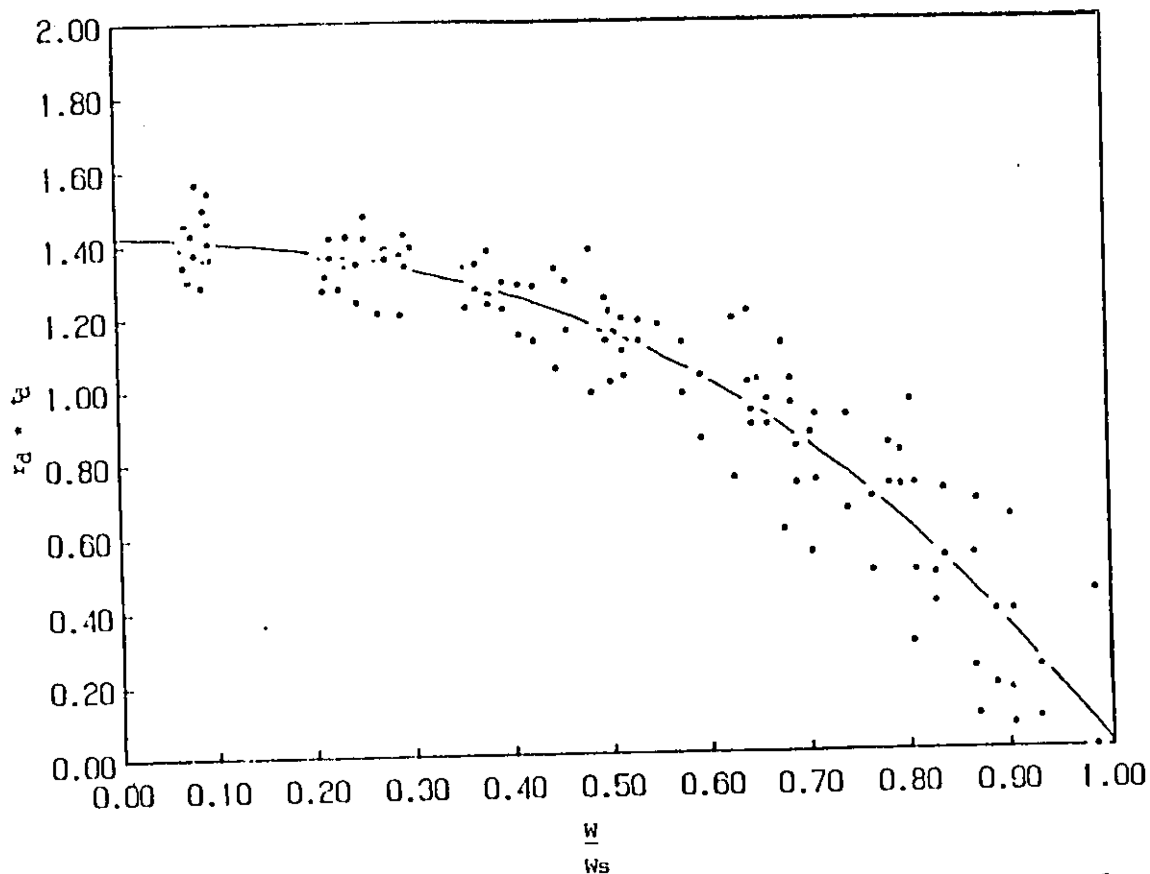

Figure 5.30, Hourly Diffuse to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on Third Degree Equation Amman . Eqn. (4.37)

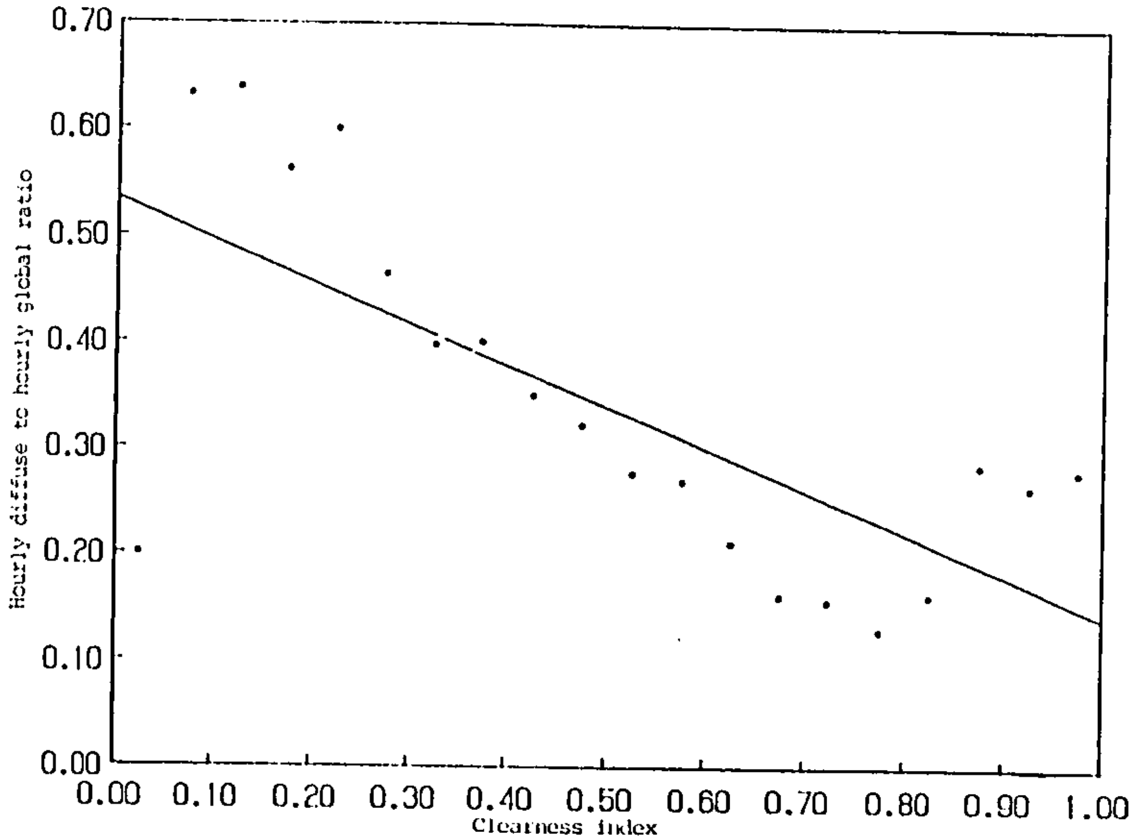

Fig 5.31 Hourly diffuse to hourly global ratio versus clearness index based on obtained Linear equation (using orgill and Hollands method)-Amman.Eqn. (4.27)

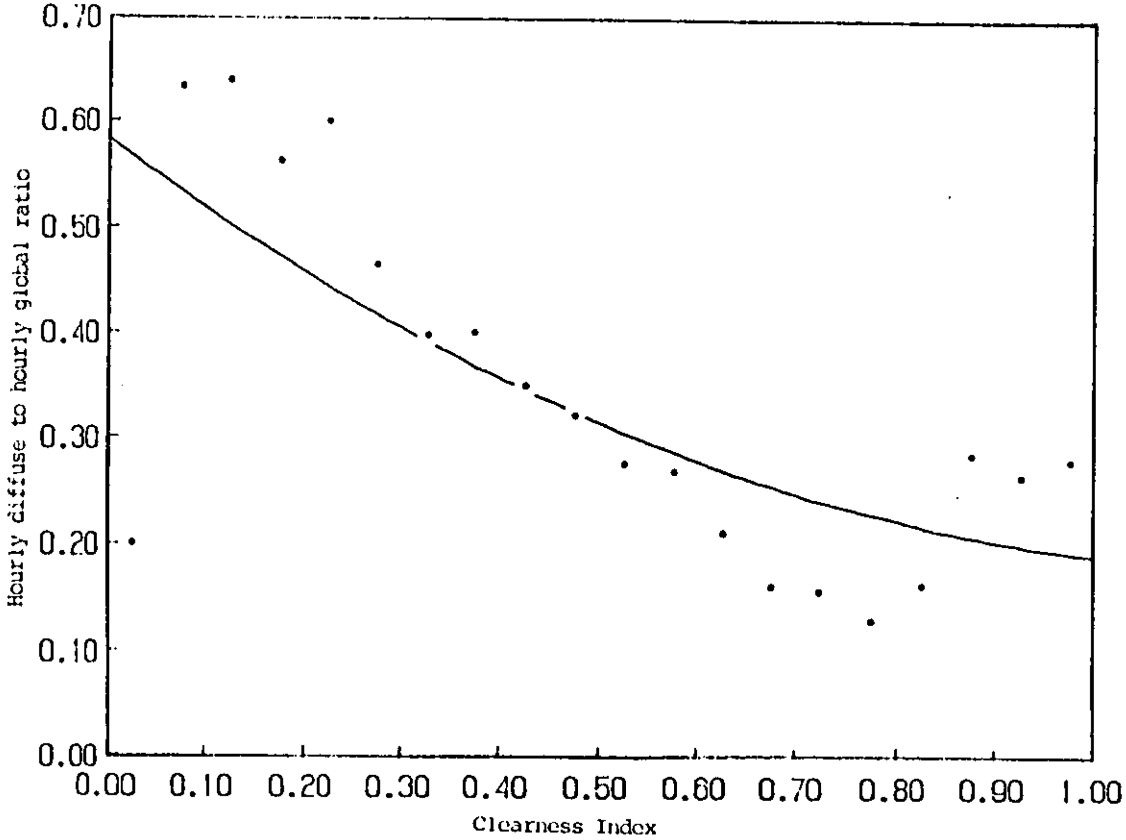

Fig 5.32 Hourly diffuse to hourly global ratio versus clearness index based on obtained second degree equation (using orgill and Hollands method) - Amman . Eqn. (4.28)

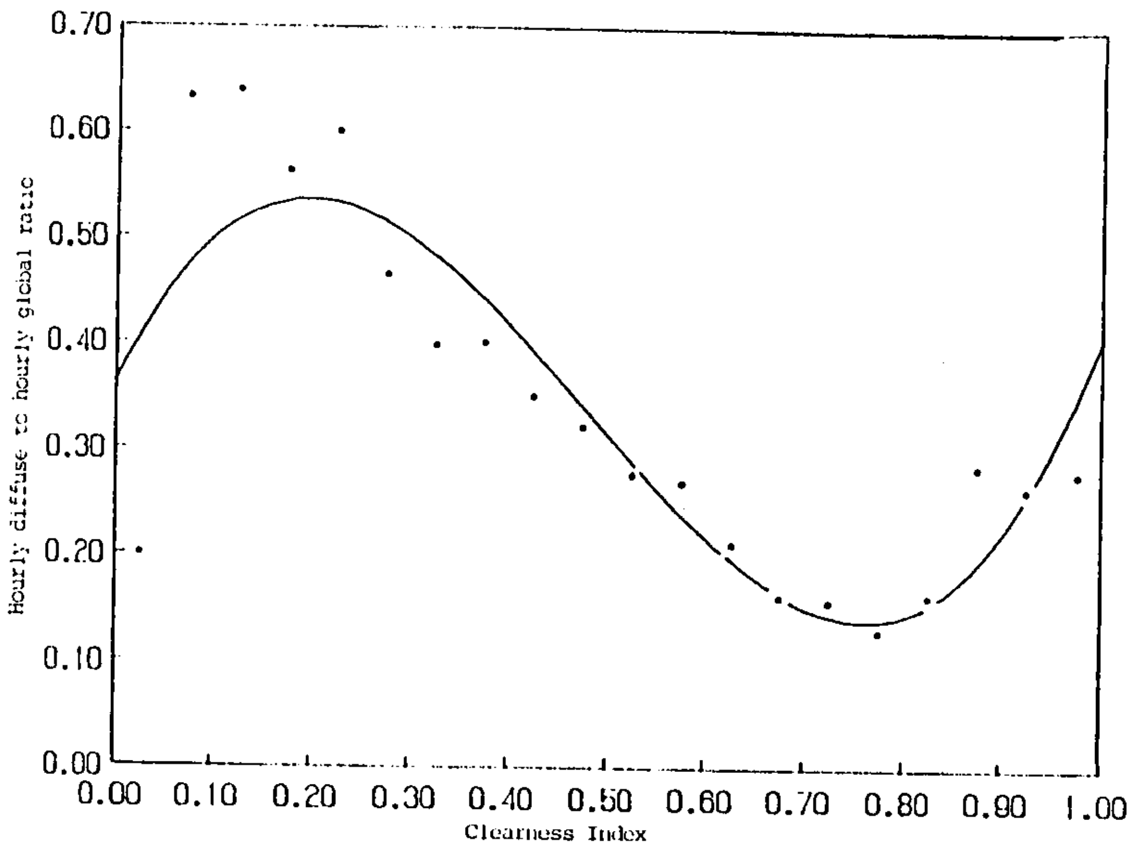

Fig. 5.33 Hourly diffuse to hourly global ratio versus clearness index based on obtained third degree equation (using orgill and hollands method) - Amman. Eqn. (4.29)

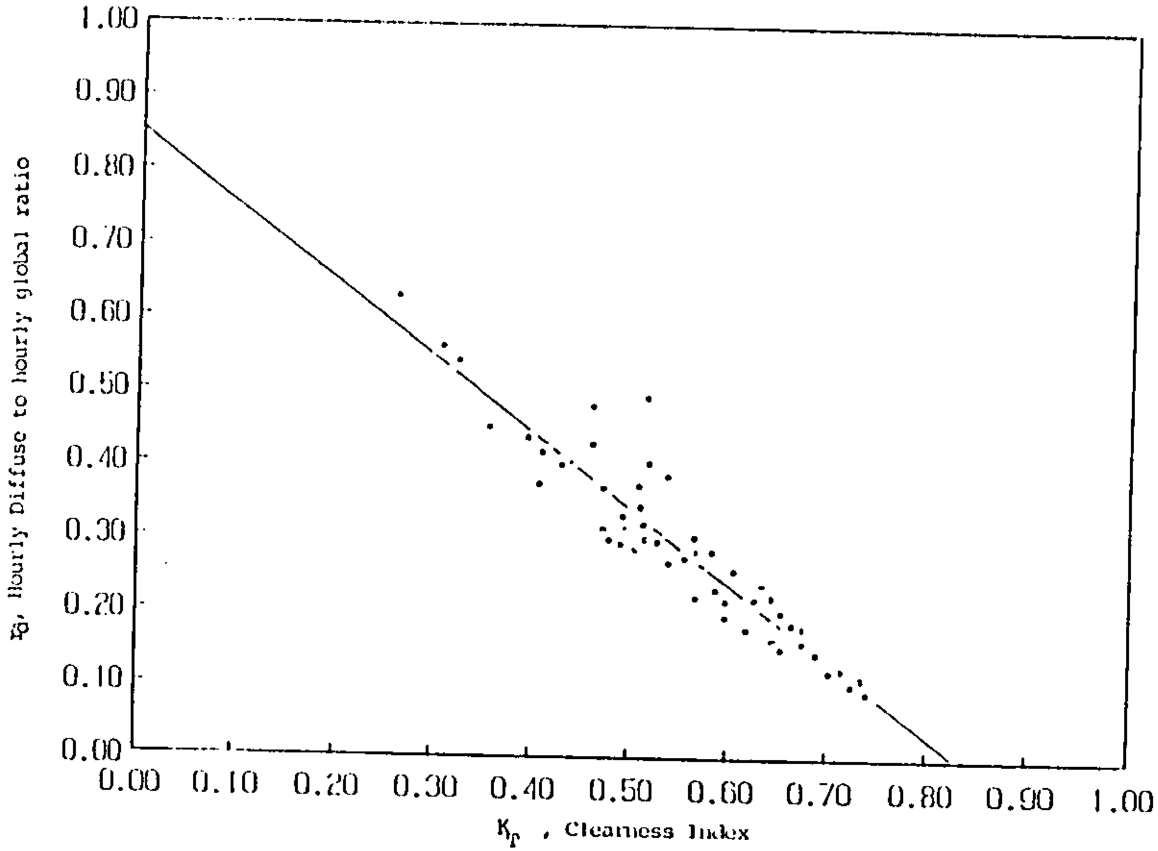

Figure 5.34 Hourly diffuse to hourly global ratio versus clearness index based on obtained Linear Equation - Amman. The average data around Solar-noon is taken . Eqn. (4.17)

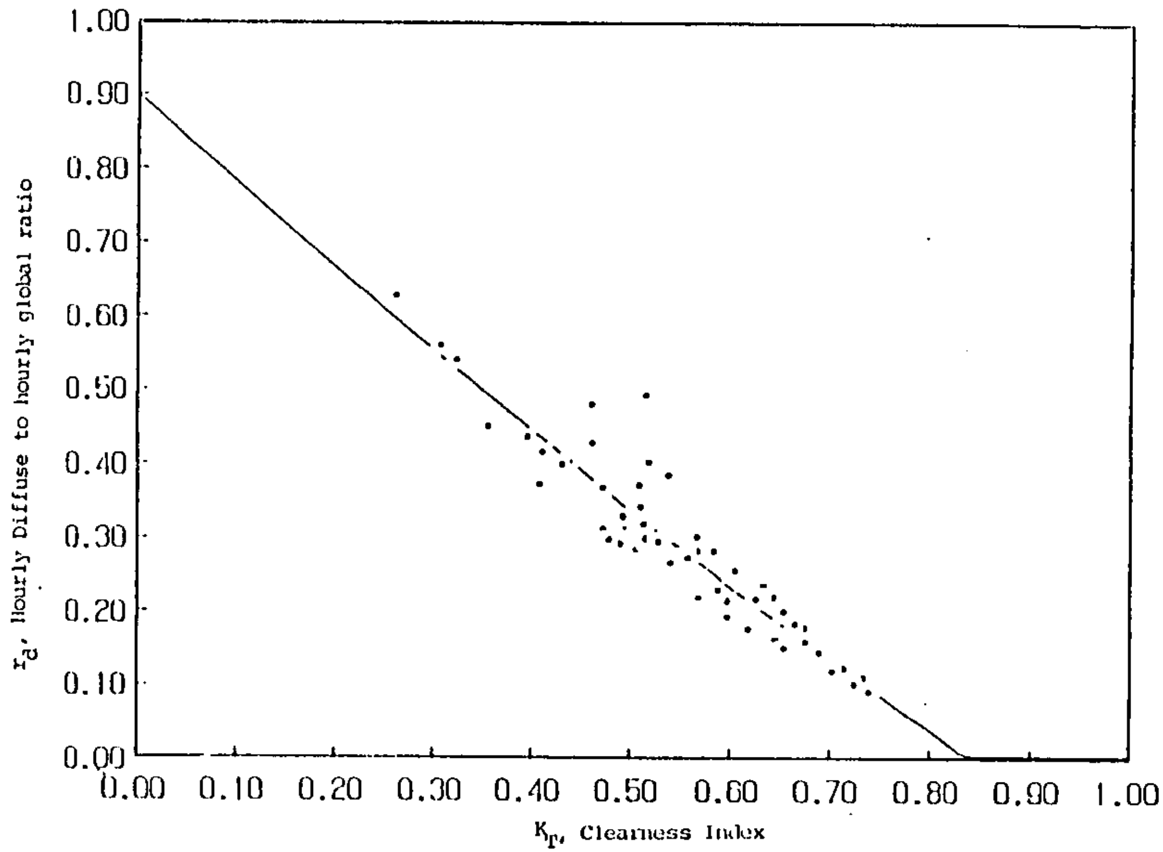

Figure 5.35 Hourly diffuse to hourly global ratio versus clearness index based on obtained second degree equation-Amman. The average data around Solar-noon is taken . Eqn. (4.18)

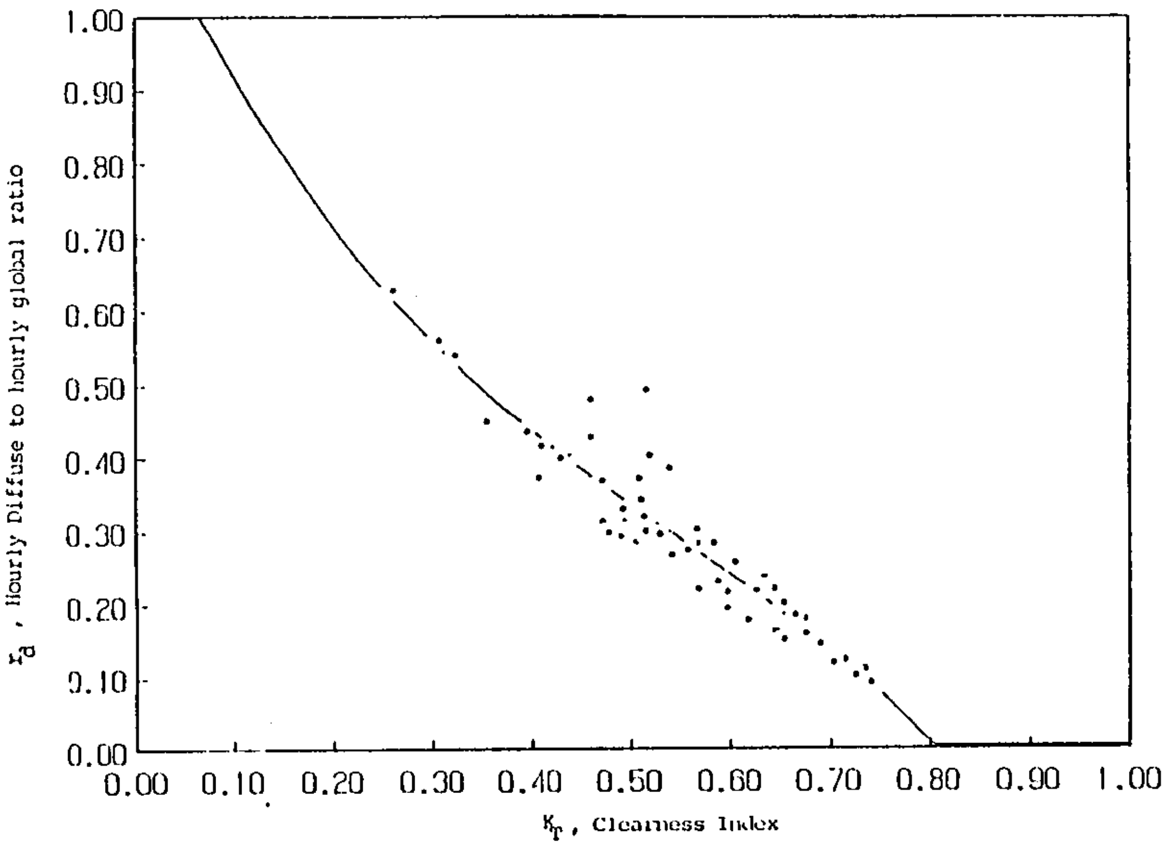

Figure 5.36 Hourly diffuse to hourly global ratio versus clearness index based on obtained third degree equation Amman. The average data around Solar-noon is taken . Eqn. (4.19)

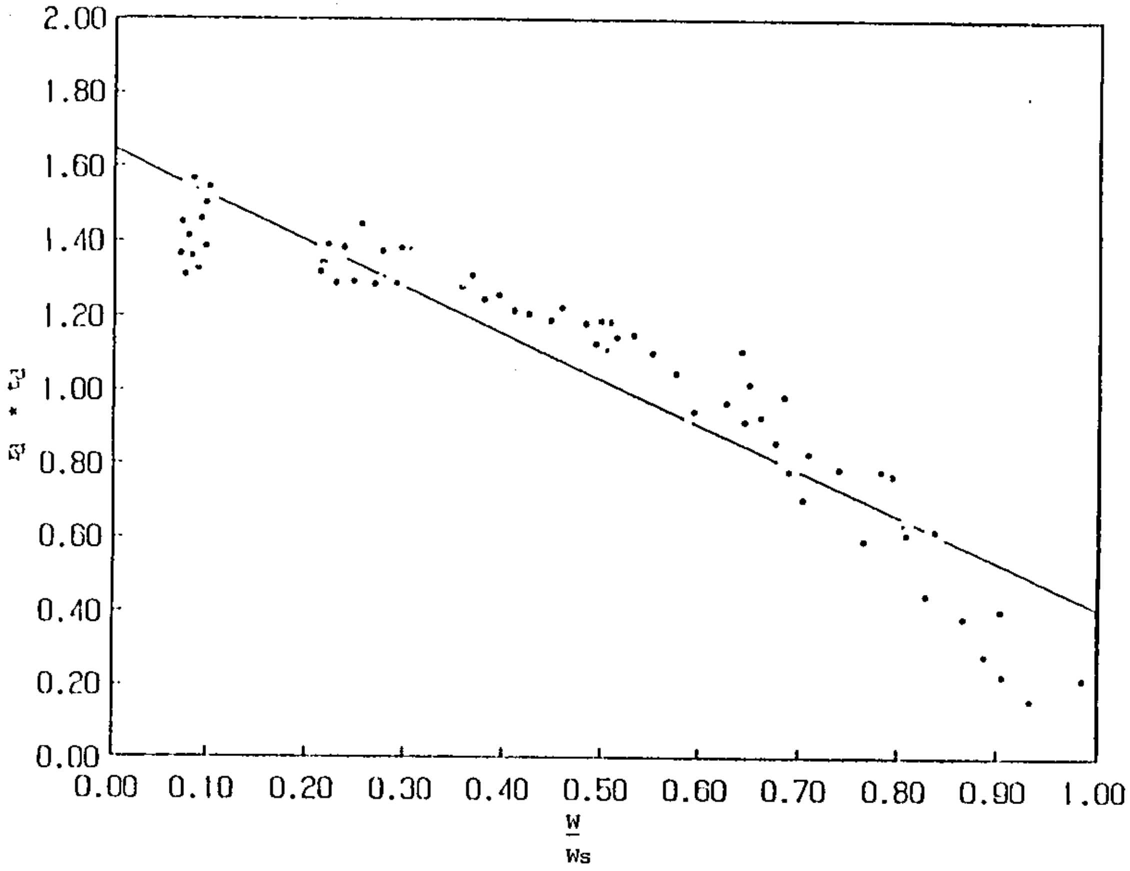

Figure 5.37 , Hourly Diffuse to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on Linear Equation ~ Amman. Eqn. (4.38)

The average data around Solar Noon is taken .

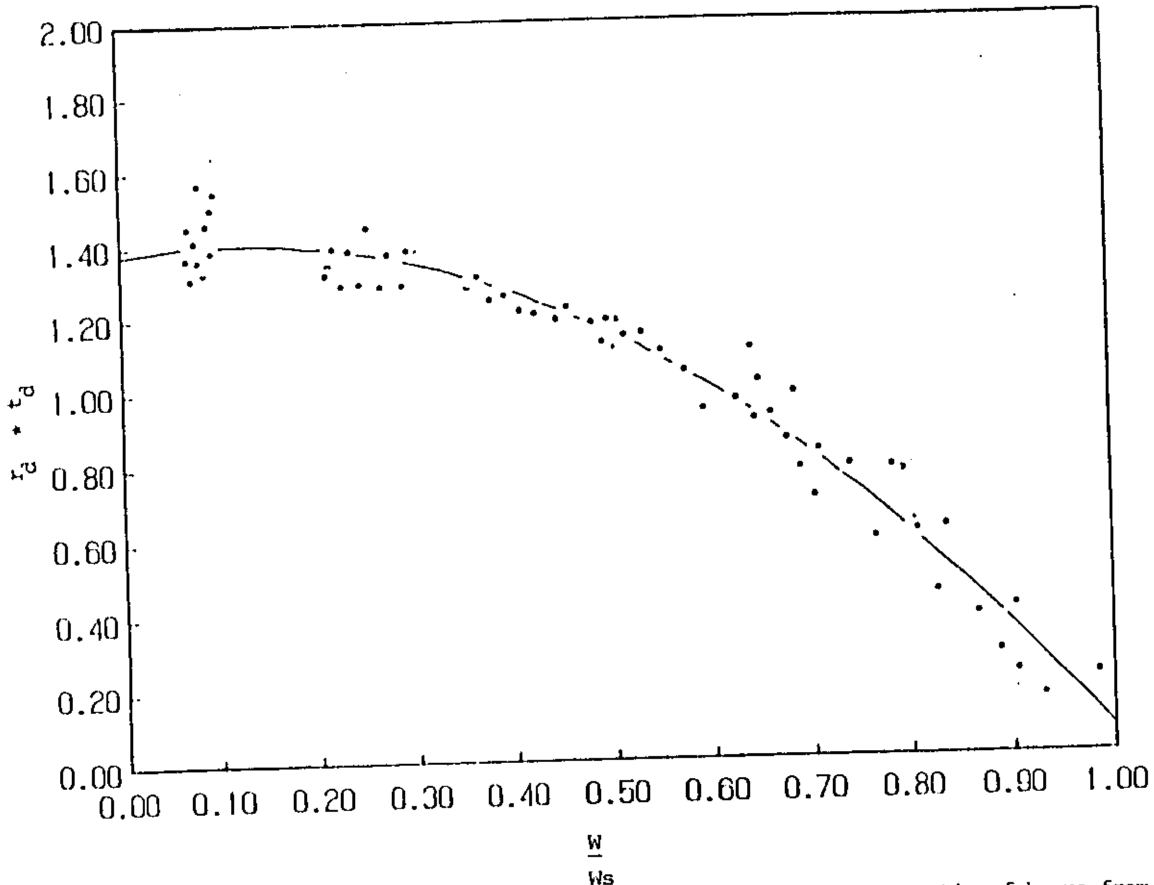

Figure 5.38, Hourly Diffuse to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on Second Degree Equation - Amman. Eqn. (4.39)

The average data around Solar Noon is taken .

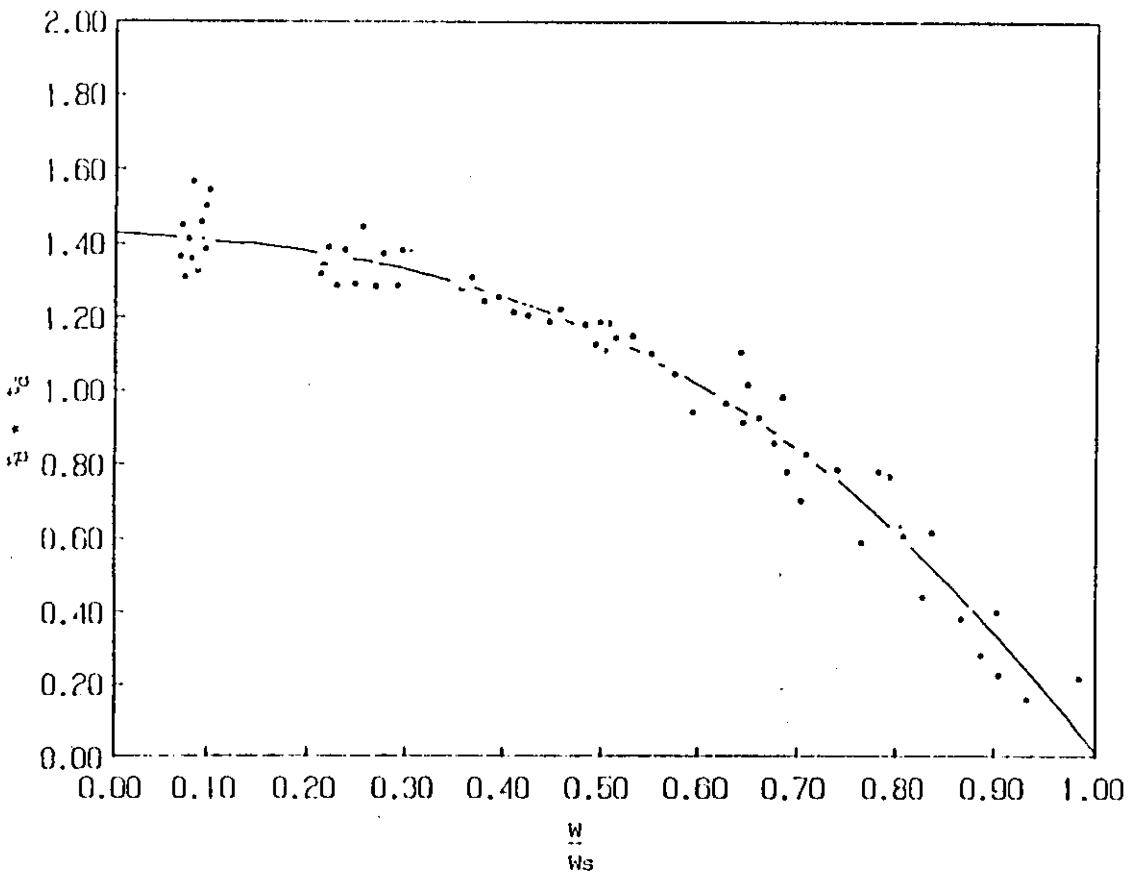

Figure 5.39. Hourly Diffuse to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on Third Degree Equation Amman. Eqn. (4.40)

The average data around Solar Noon is taken.

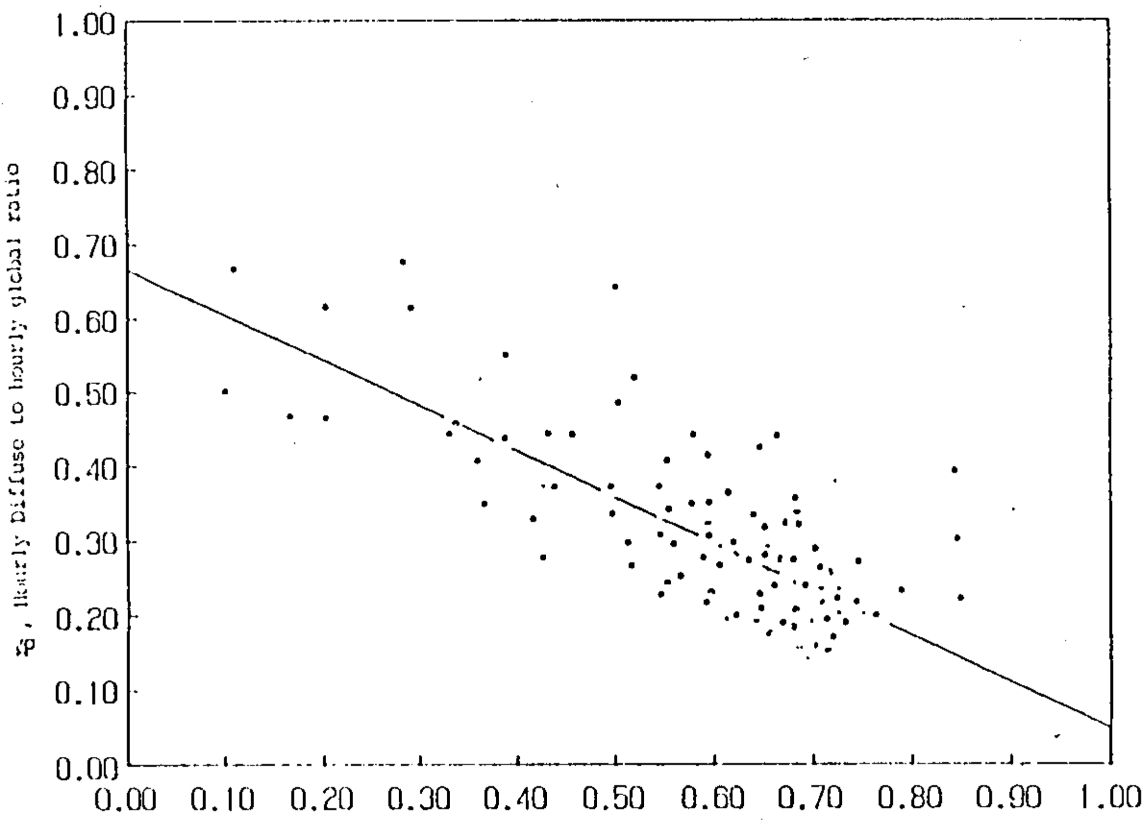

Figure.5.40 Hourly diffuse to hourly global ratio versus clearness index based on obtained Linear Equation-Aqaba. Eqn. (4.20)

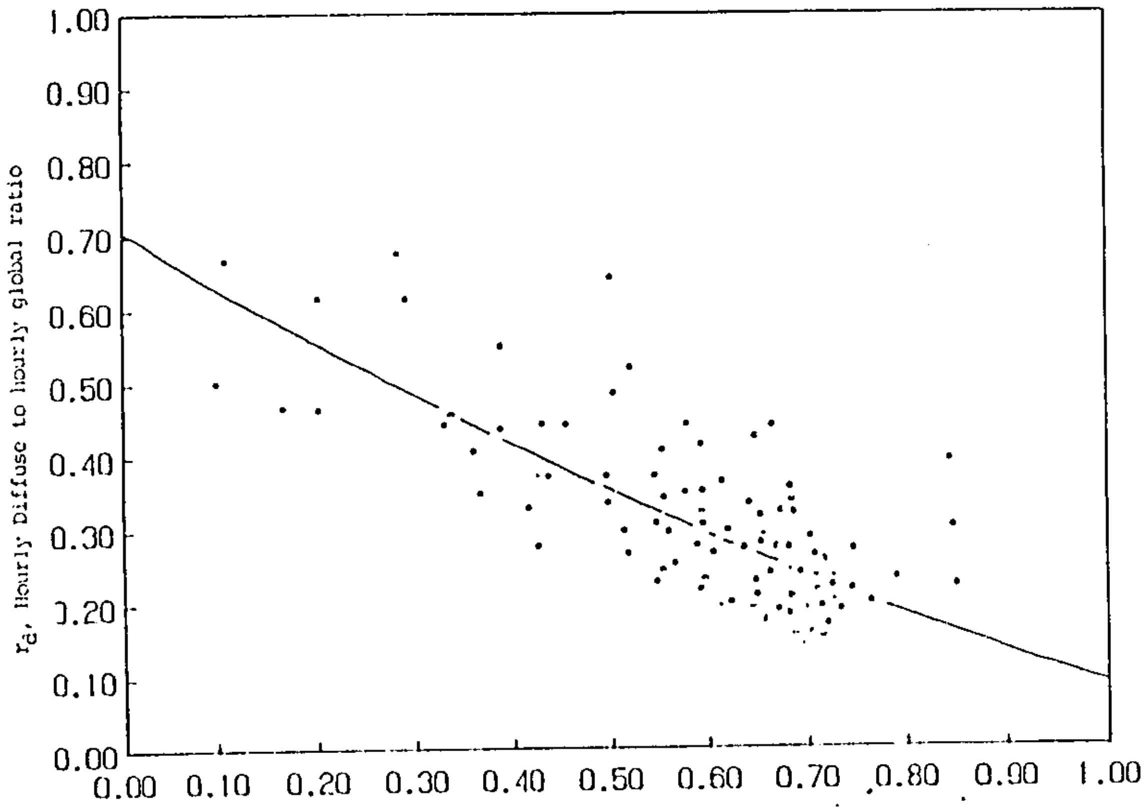

Figure. 5.41 Hourly diffuse to hourly global ratio versus clearness index based on obtained Second Degree Equation.Aqaba. Eqn (4.21)

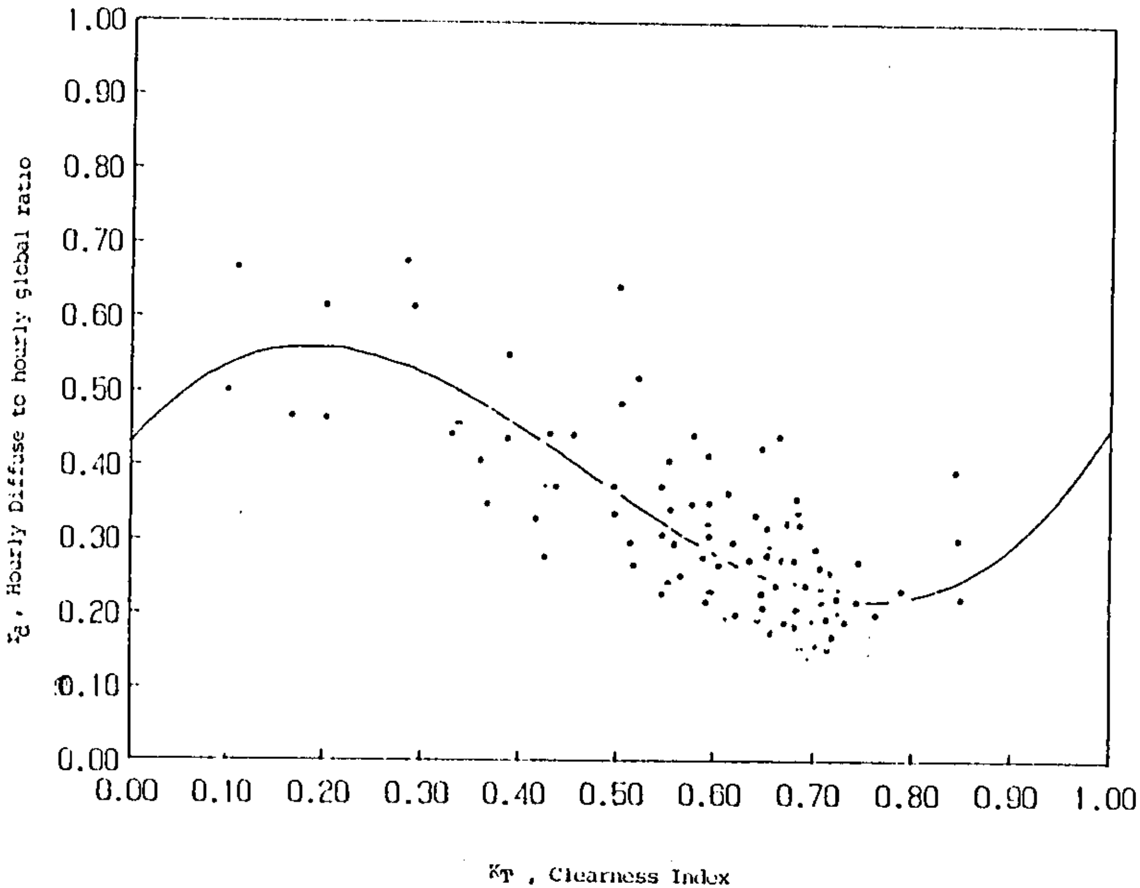

Figure 5.42 Hourly diffuse to hourly global ratio versus clearness index based on obtained third degree equation. Aqaba. Eqn (4.22)

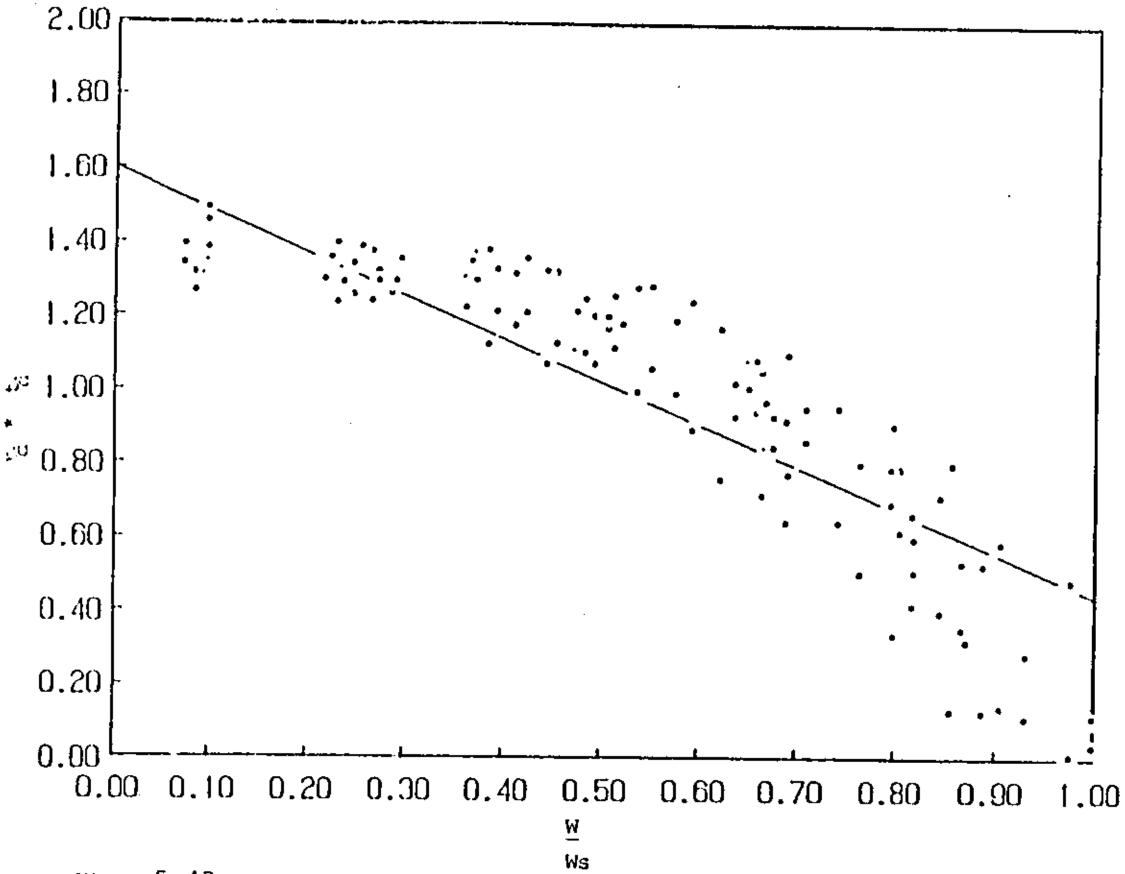

Figure 5.43 , Hourly Diffuse to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on obtained linear Equation - Aqaba Eqn. (4.41)

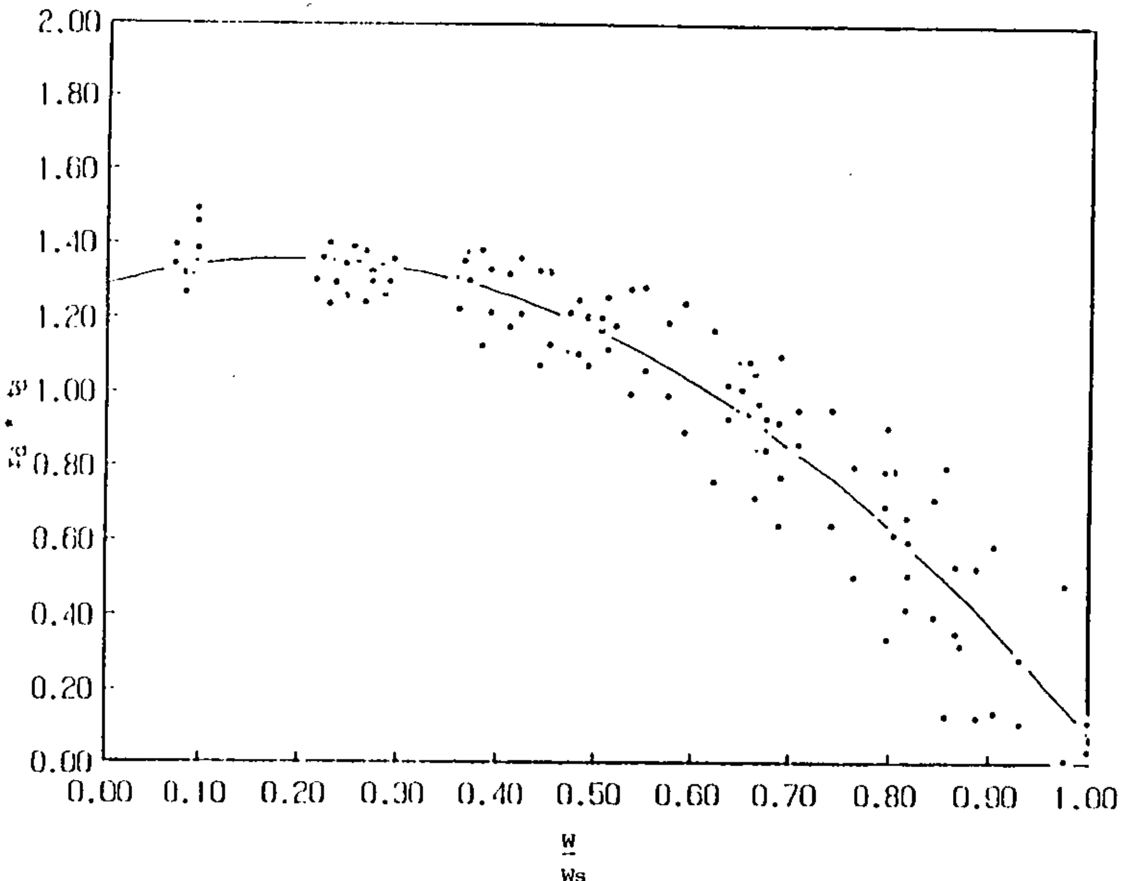

Figure 5.44 Hourly Diffuse to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on Second Degree Equation - Aqaba. Eqn. (4.42)

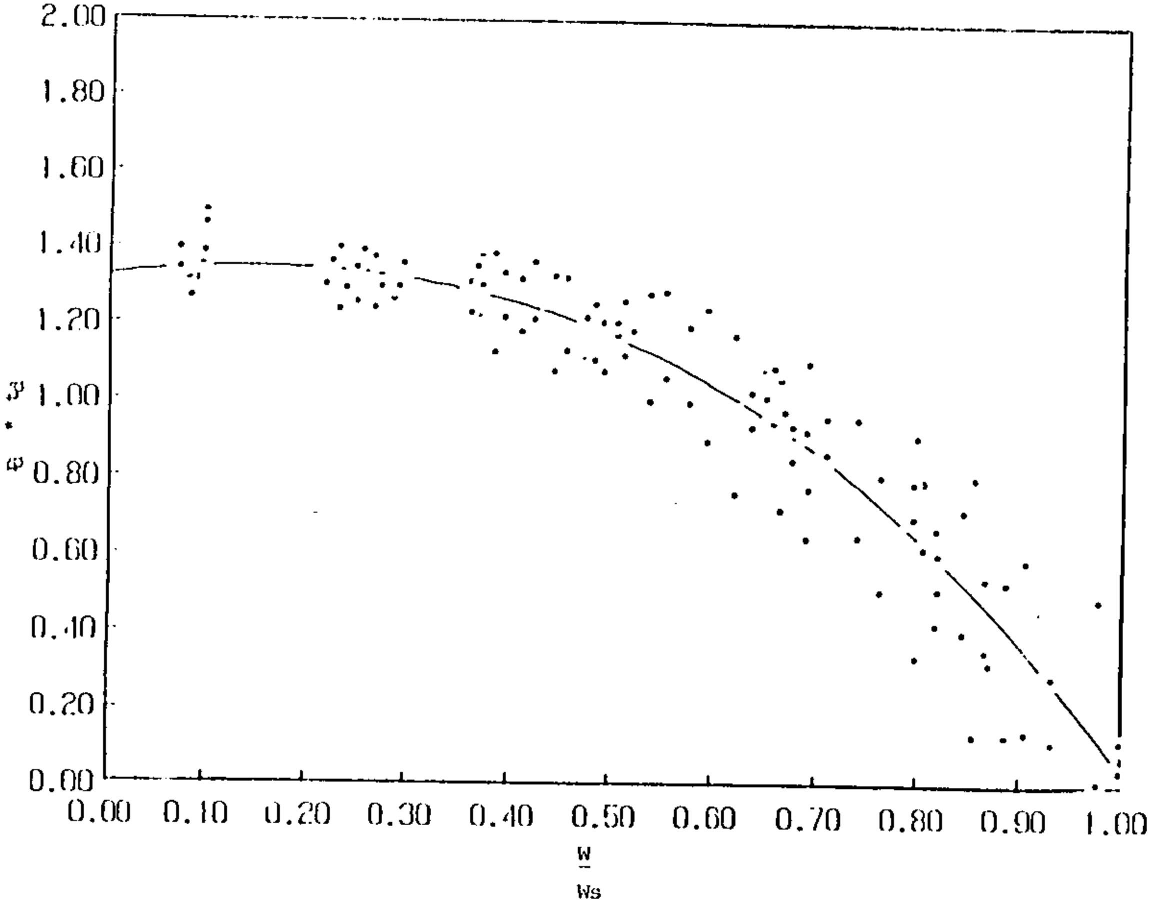

Figure 5.45 Hourly Diffuse to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on obtained Third Degree Equation - Aqaba. Eqn. (4.43)

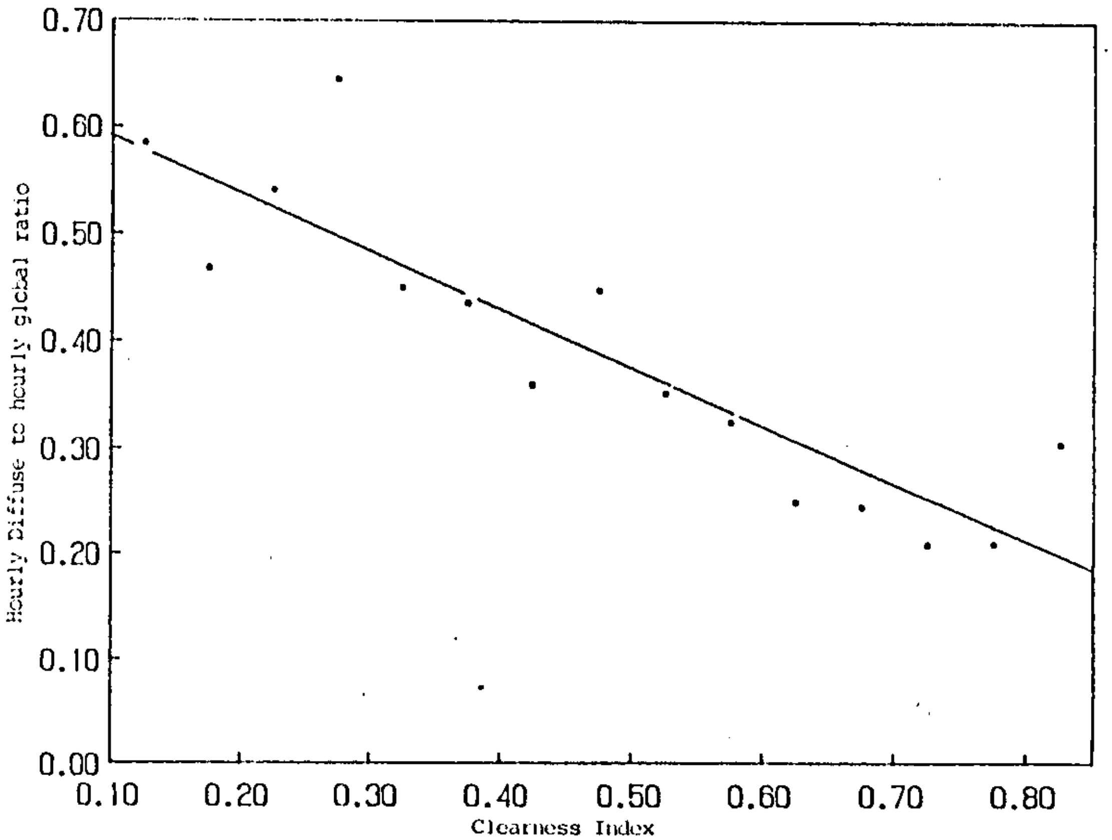

Fig. 5.46 Hourly diffuse to hourly global ratio versus clearness index based on obtained linear equation (using orgill and hollands method) - Aqaba. Eqn.(4.31)

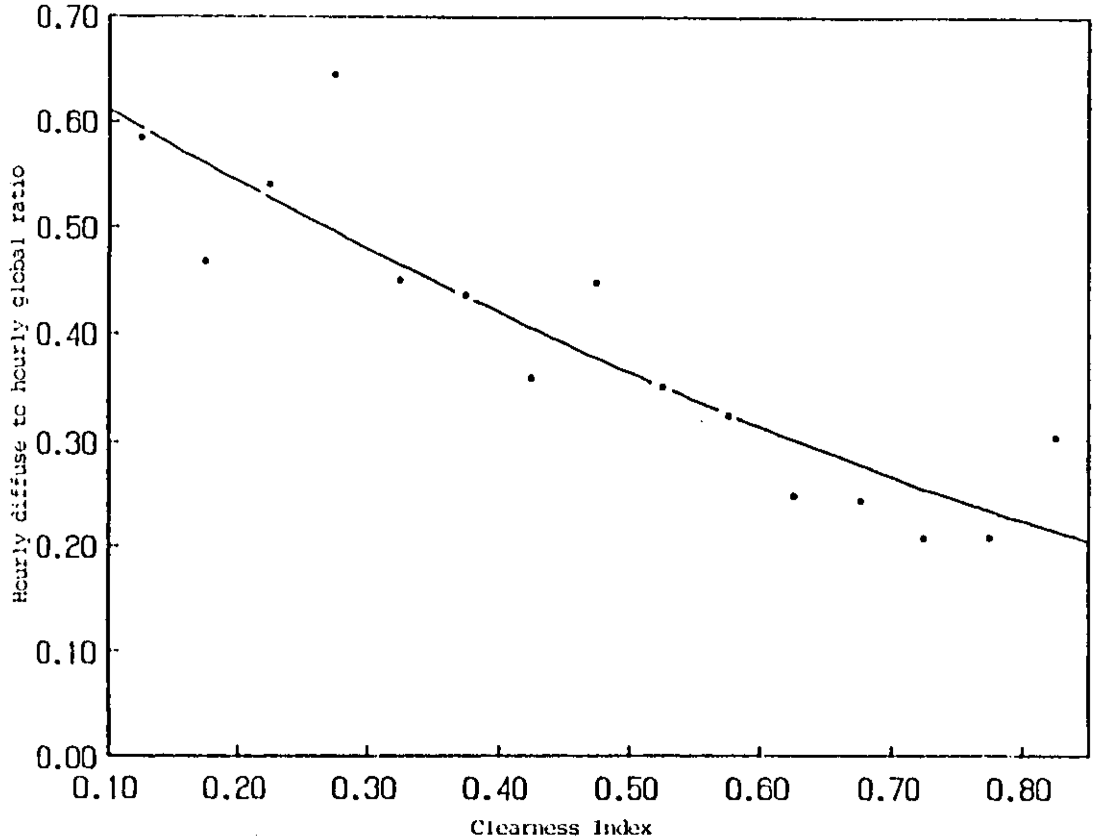

Fig.5.47 Hourly diffuse to hourly global ratio versus clearness index based on obtained second degree equation (using orgill and Hollands method)-Aqaba. Eqn.(4.32)

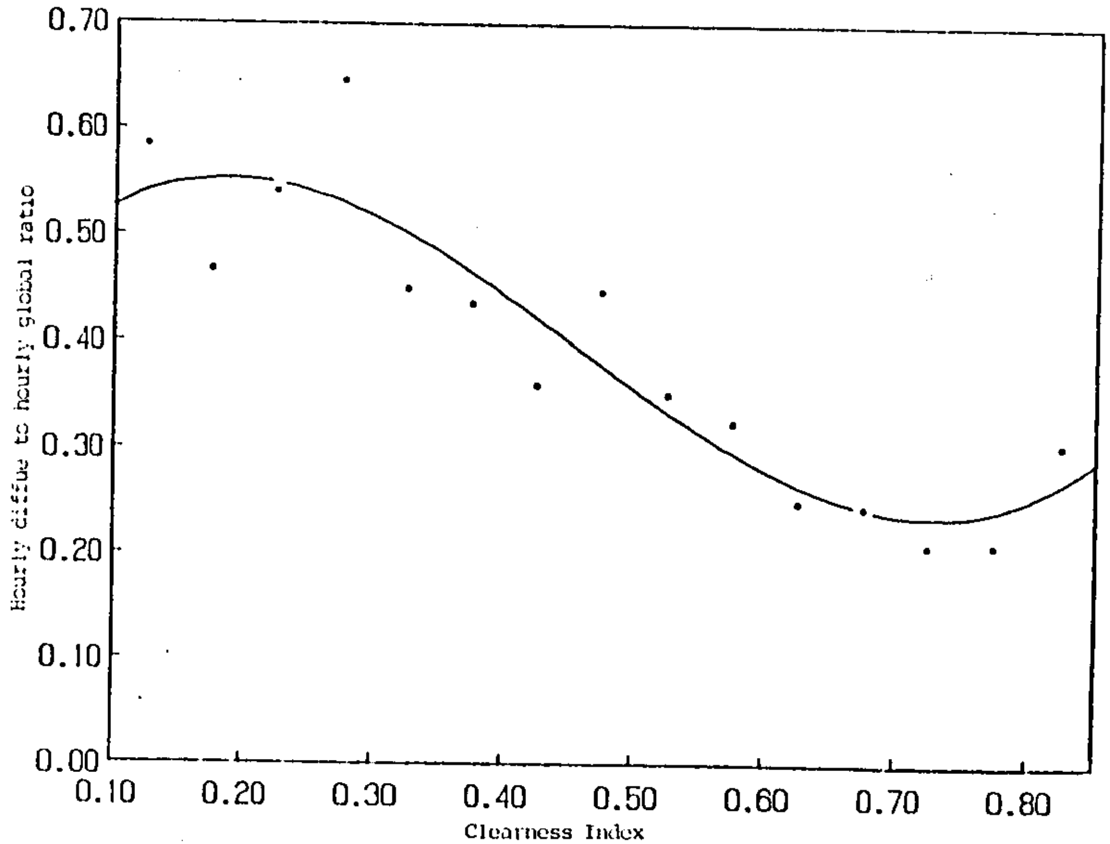

Fig 5.48 Hourly diffuse to hourly global ratio versus clearness index based on obtained third degree equation (using orgil and Hollands method)-Aqaba. Eqn.(4.33)

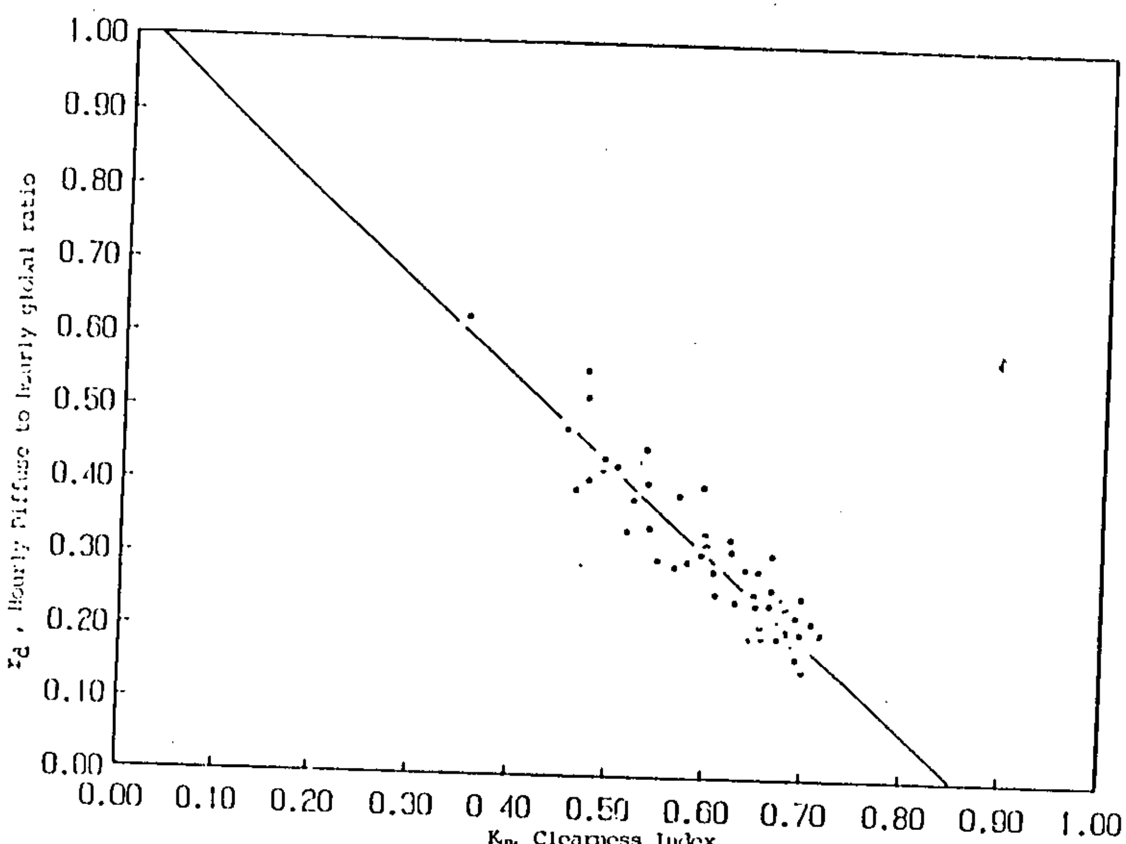

Figure 5.49 Hourly diffuse to hourly global ratio versus clearness index based on obtained Linear Equation • Ajloun. The average data around solar-noon is taken. Eqn.(4.24)

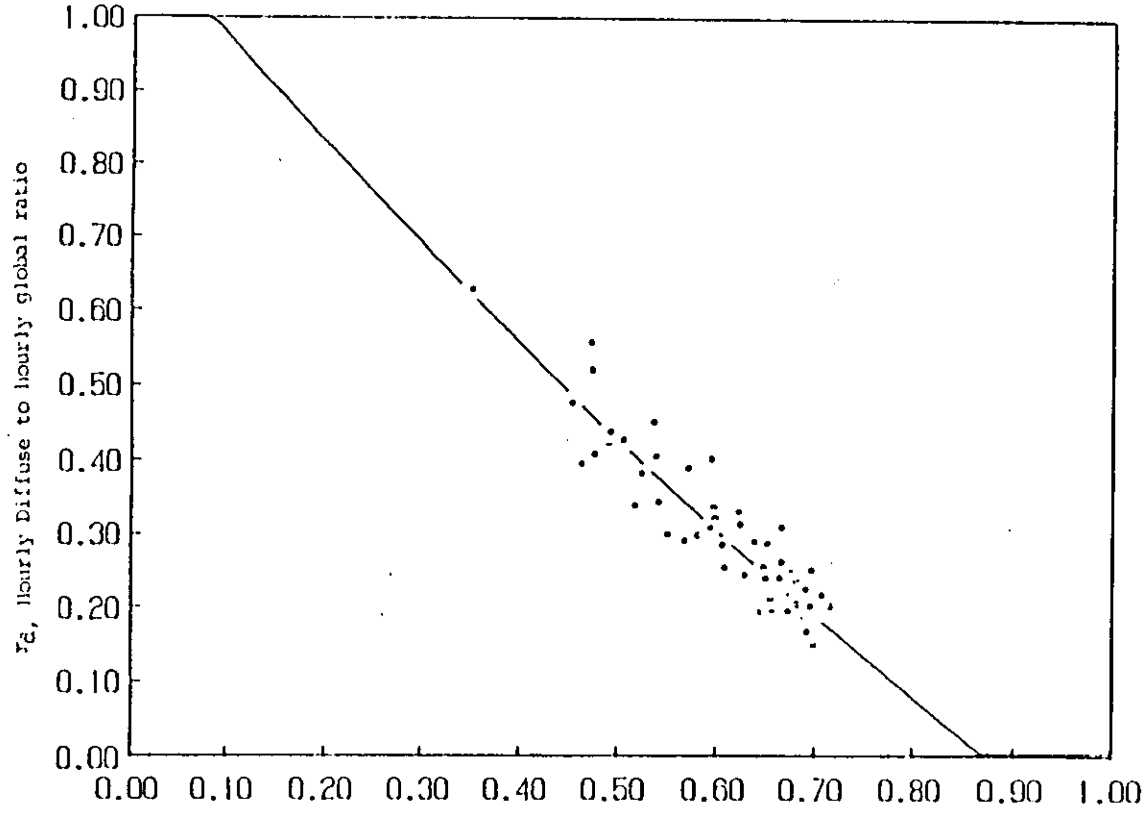

Figure 5.50 Hourly diffuse to hourly global ratio versus clearness index based on obtained second degree equation Aqaba. The average data around solar-noon is taken. Eqn.(4.25)

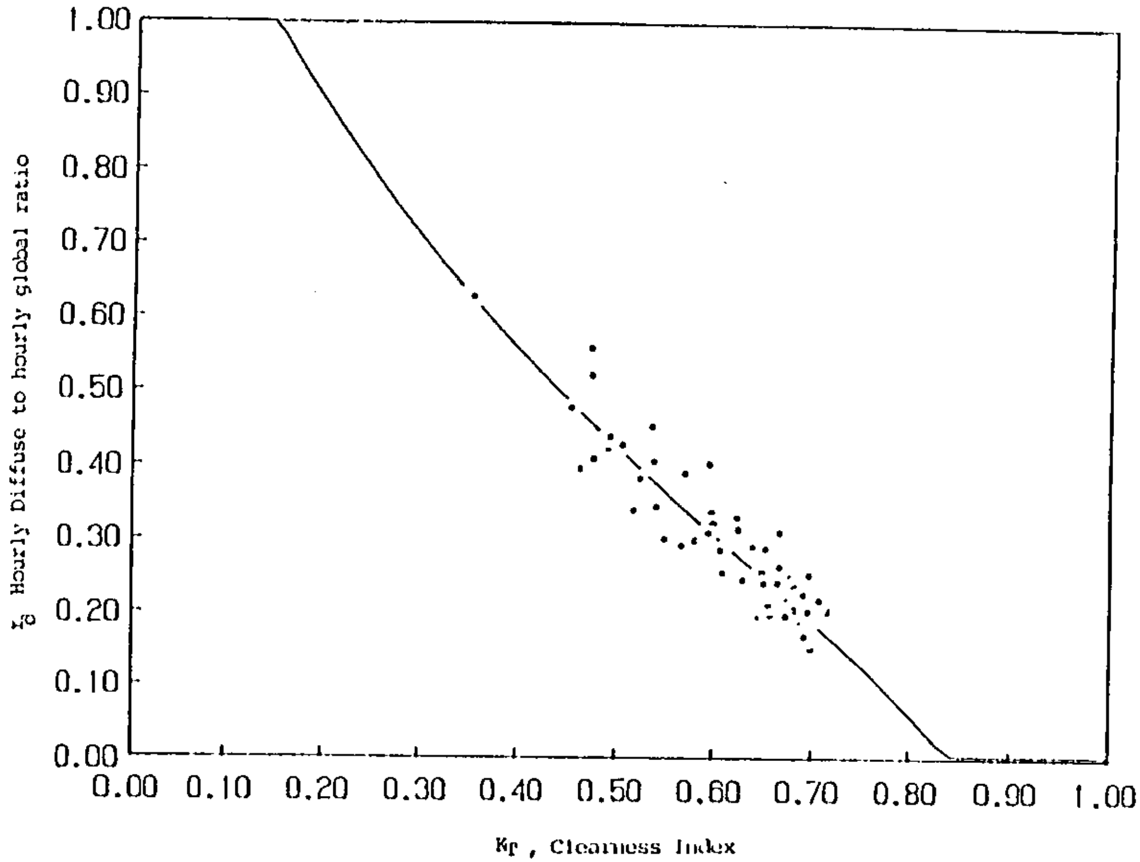

Figure 5.51 Hourly diffuse to hourly global ratio versus clearness index based on obtained third degree equation-Aqaba , The average data around Solar-noon is taken ·Eqn(4.26)

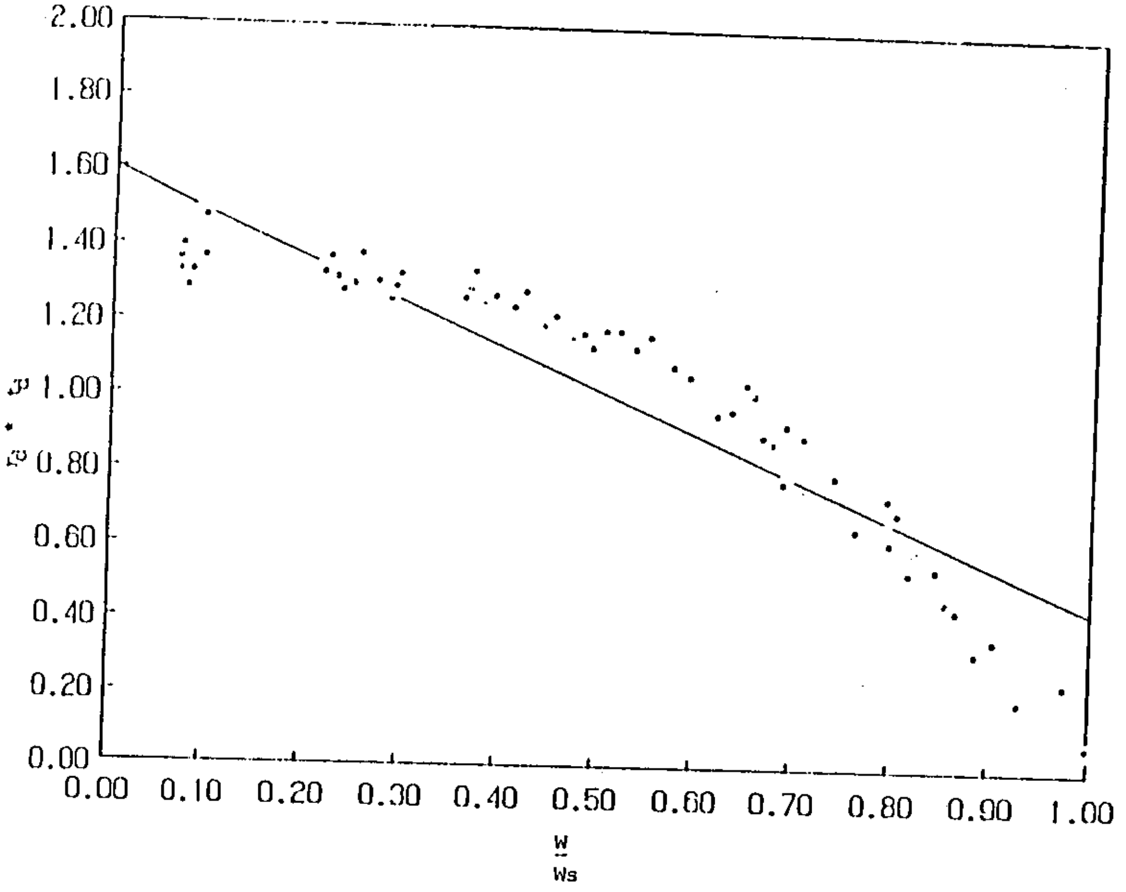

Figure 5.52, Hourly Diffuse to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on obtained Linear Equation – Aqaba. Eqn.(4.44)

The average data around solar noon is taken .

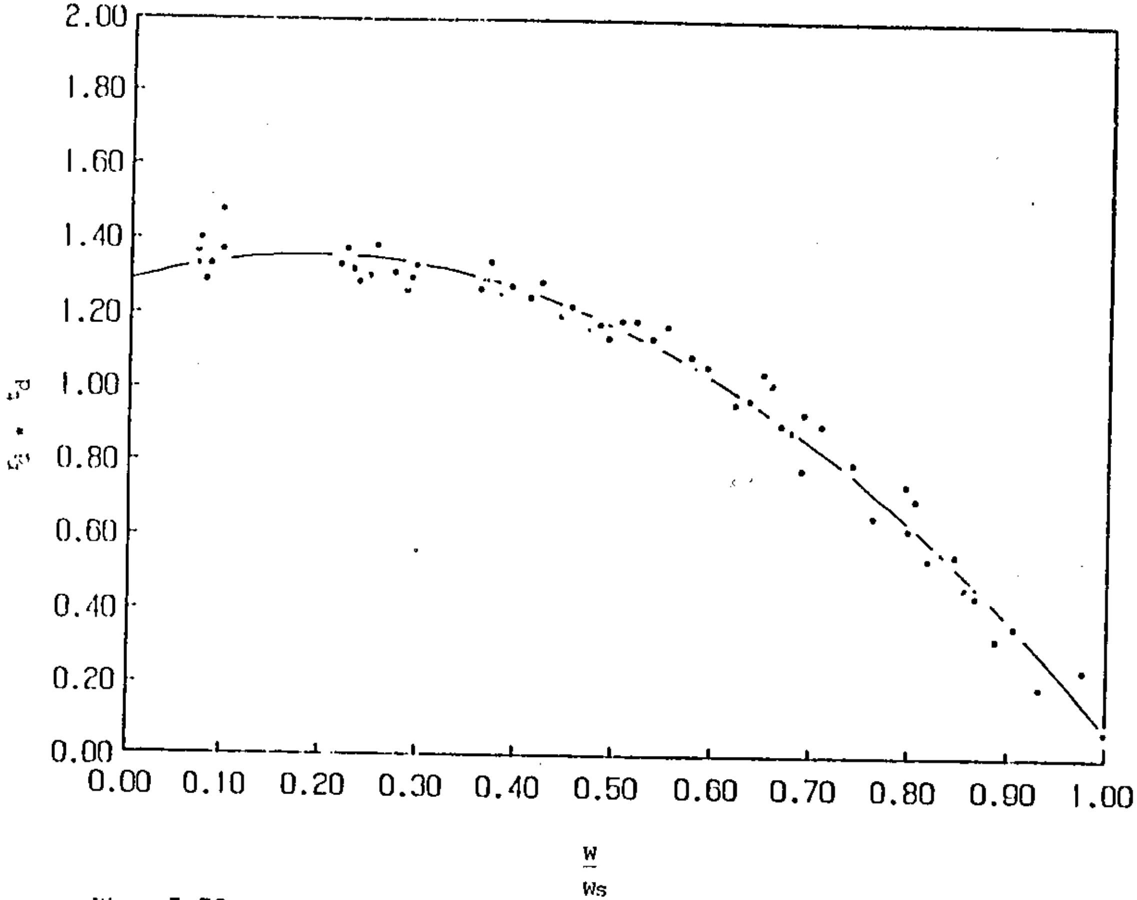

Figure 5.53, Hourly Diffuse to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on obtained second degree equation - Aqaba. Eqn(4.45)
The average data around solar noon is taken .

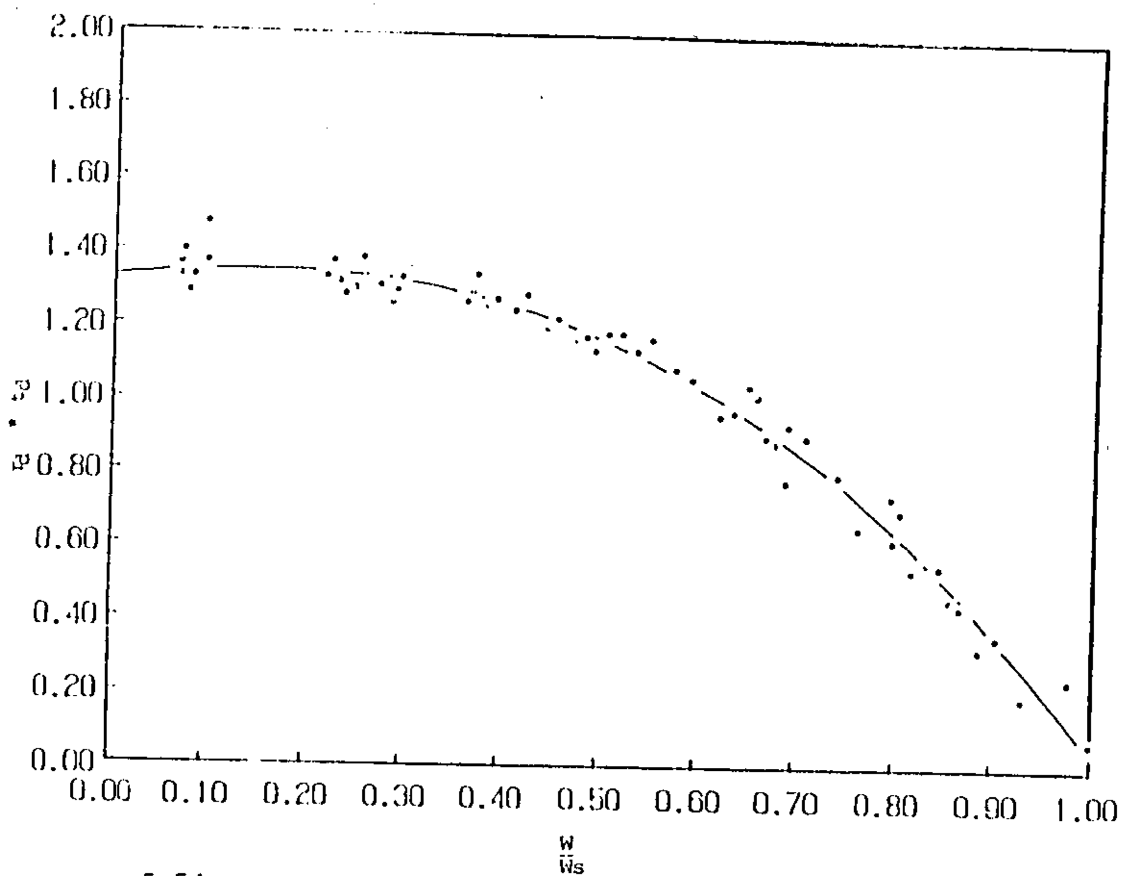

Figure 5.54 Hourly Diffuse to monthly average daily ratio versus ratio of hours from Solar Noon to Sun Set Angle based on obtained third degree equation - Aqaba. Eqn.(4.46)

The average data around solar noon is taken .

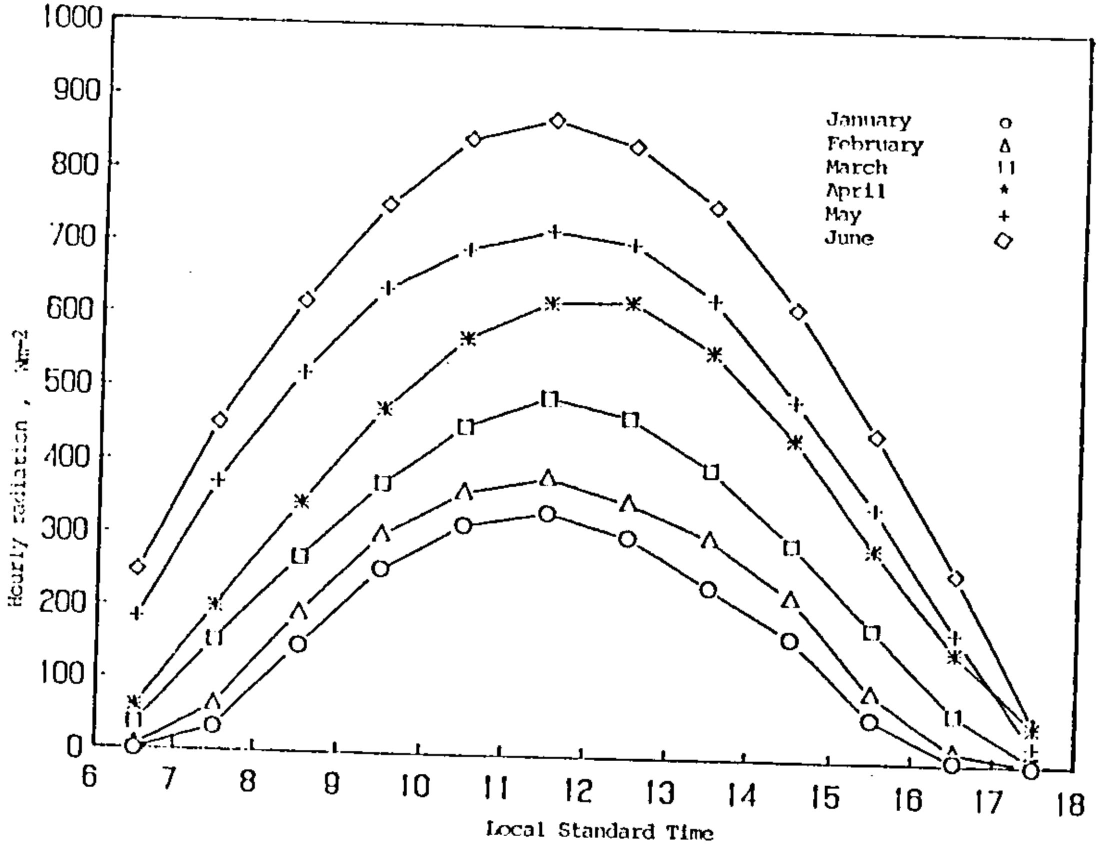

Fig 5.55 variation of hourly beam radiation for the months of Jan.- June for Amman .

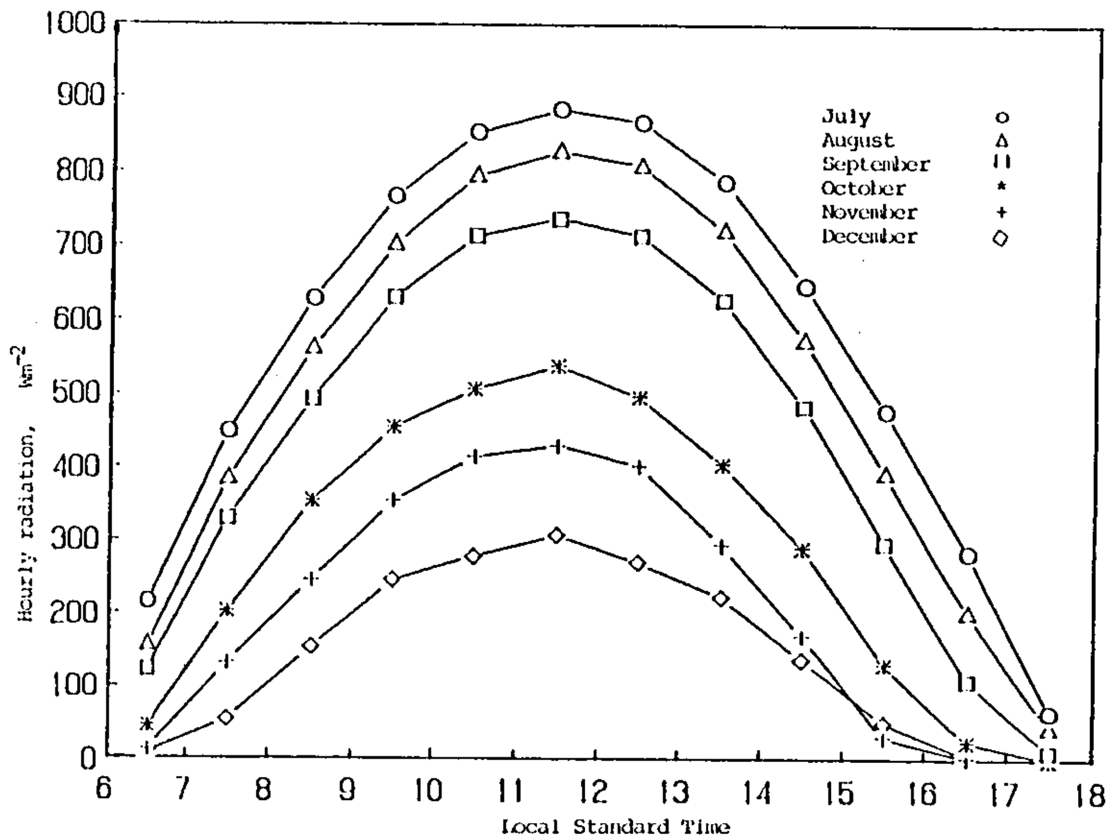

Fig 5.56 variation of hourly beam radiation for the months of July - December for Amman.

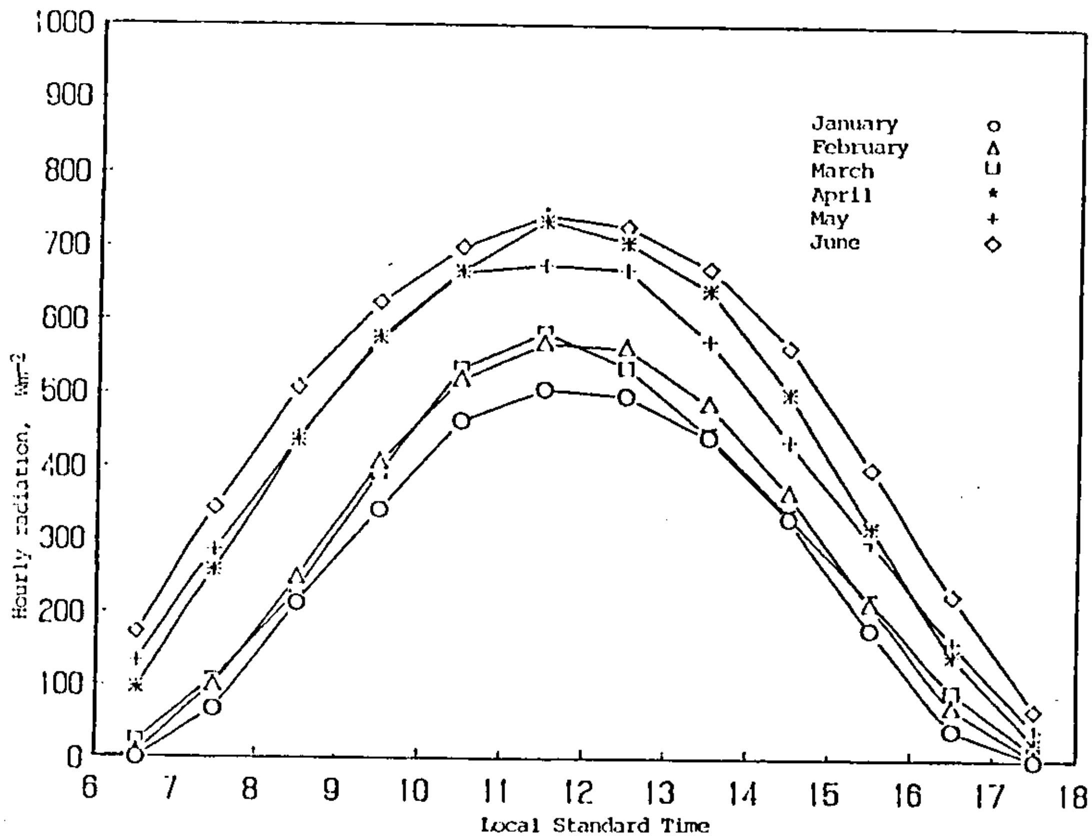

Fig5.57, variation of hourly beam radiation for the months of Jan - June for Aqaba.

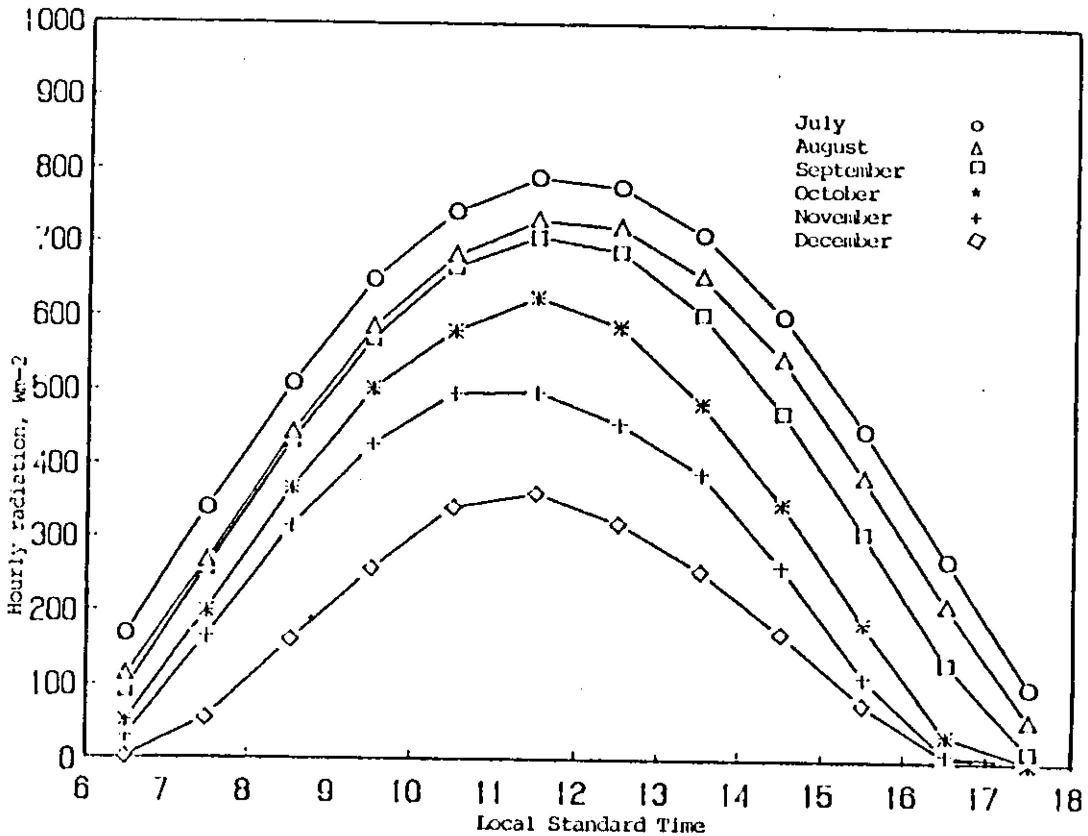

Fig5.58 , variation of hourly beam radiation for the months of July-December for Aqaba.

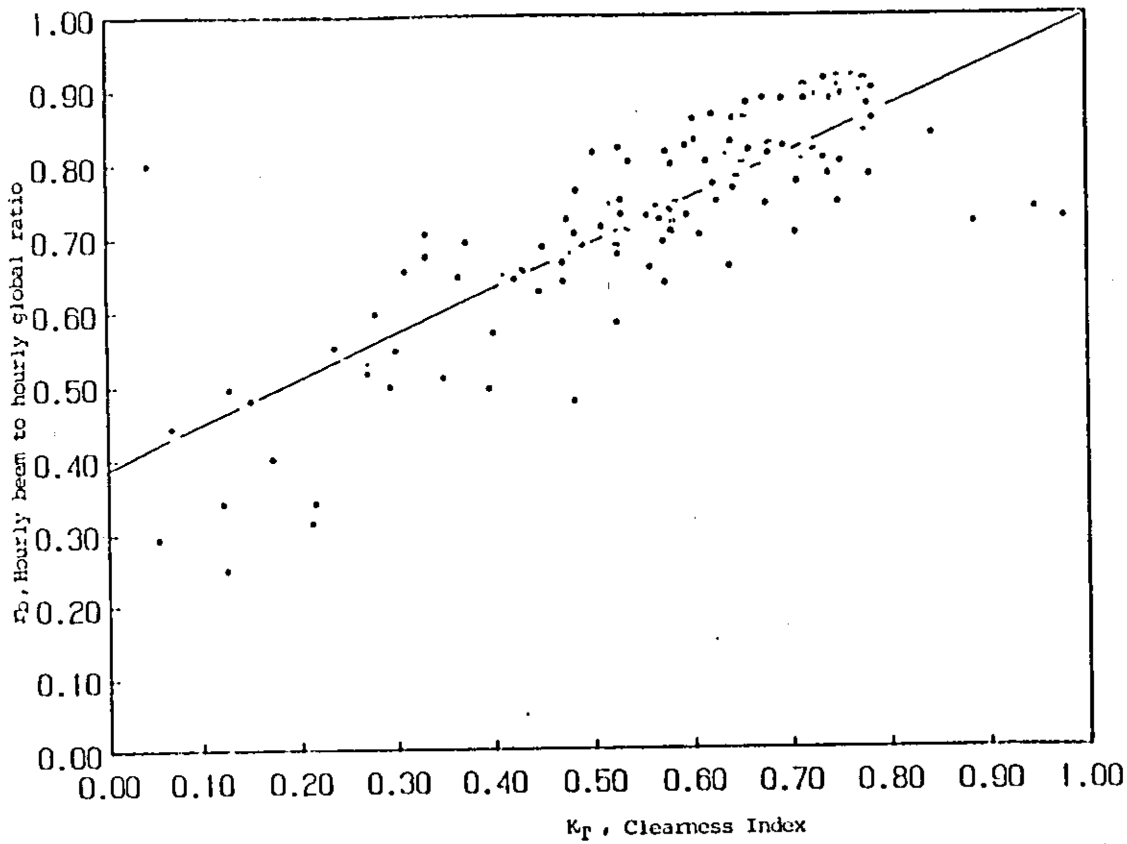

Figure 5.59, Hourly beam to hourly global ratio versus clearness index based on obtained Linear Equation-Amman ·Eqn(4.47)

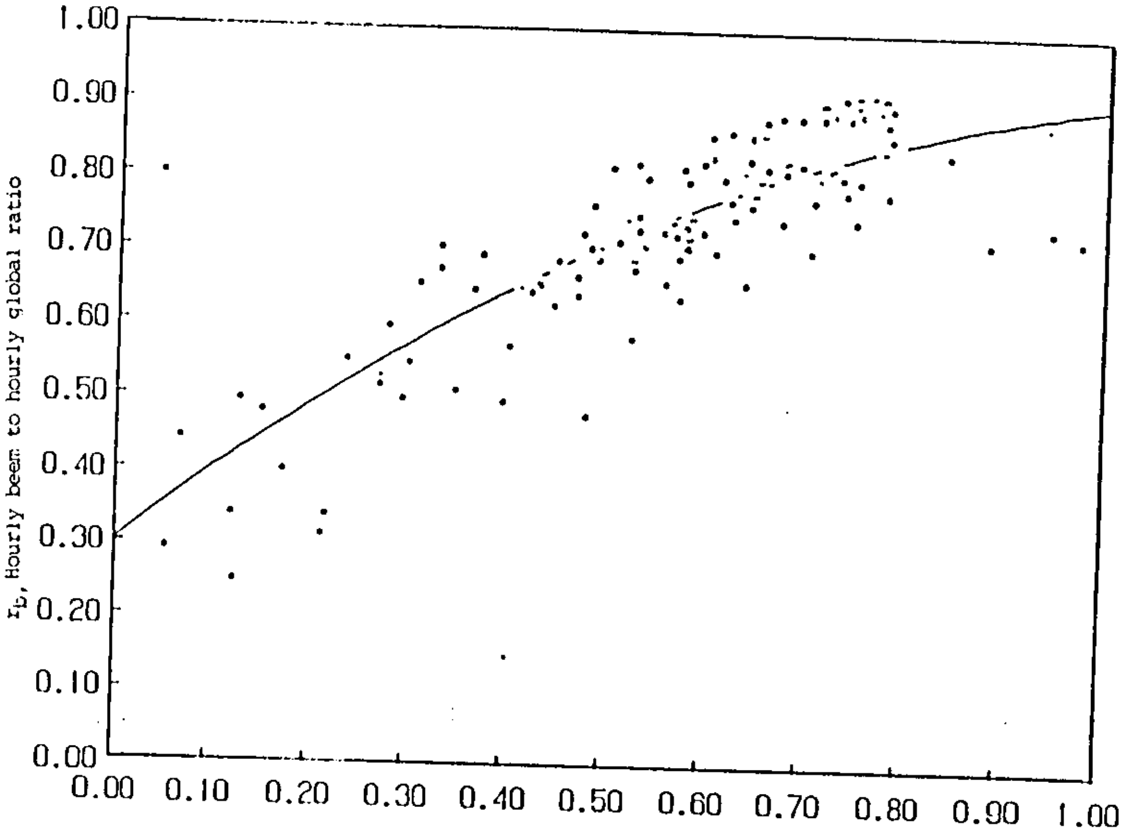

Figure 5.60, Hourly beem to hourly global ratio versus clearness index based on obtained second degree equation-Amman . Eqn.(4.48)

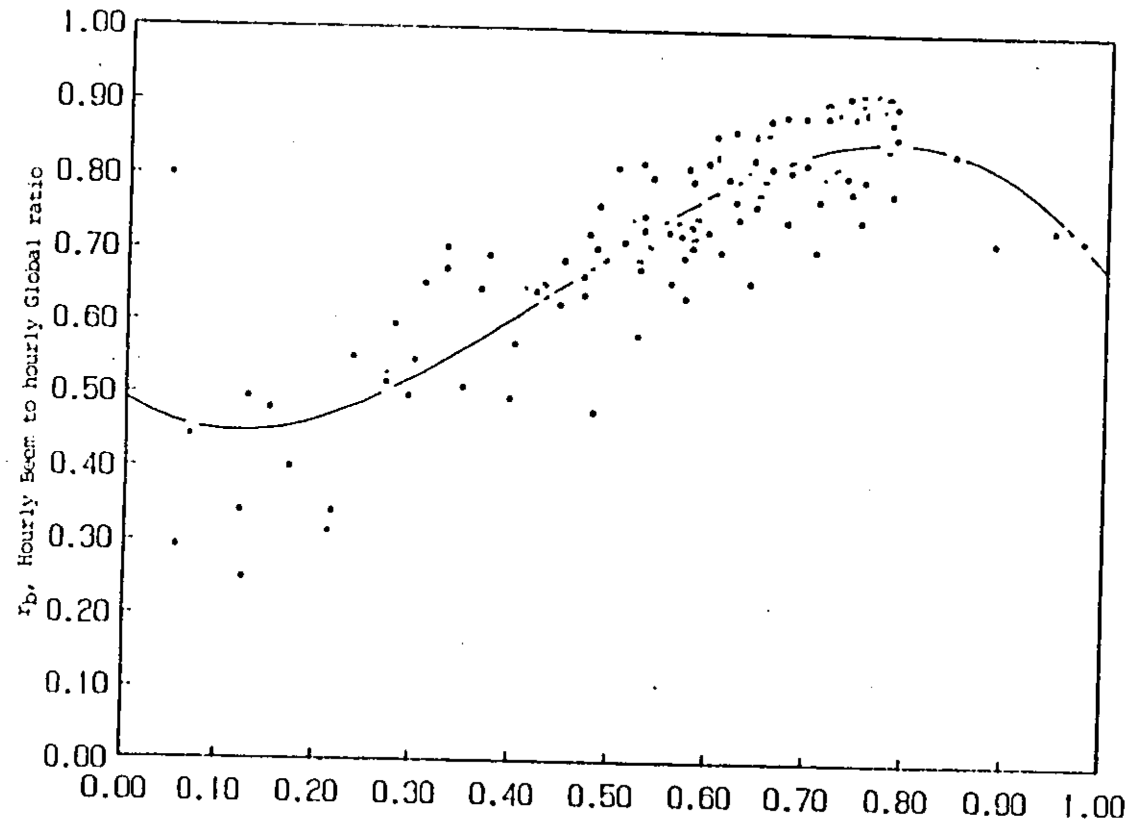

Figure 5.61 , Hourly beam to hourly global ratio versus clearness index based on obtained Third Degree Equation-Amman . Eqn(4.49)

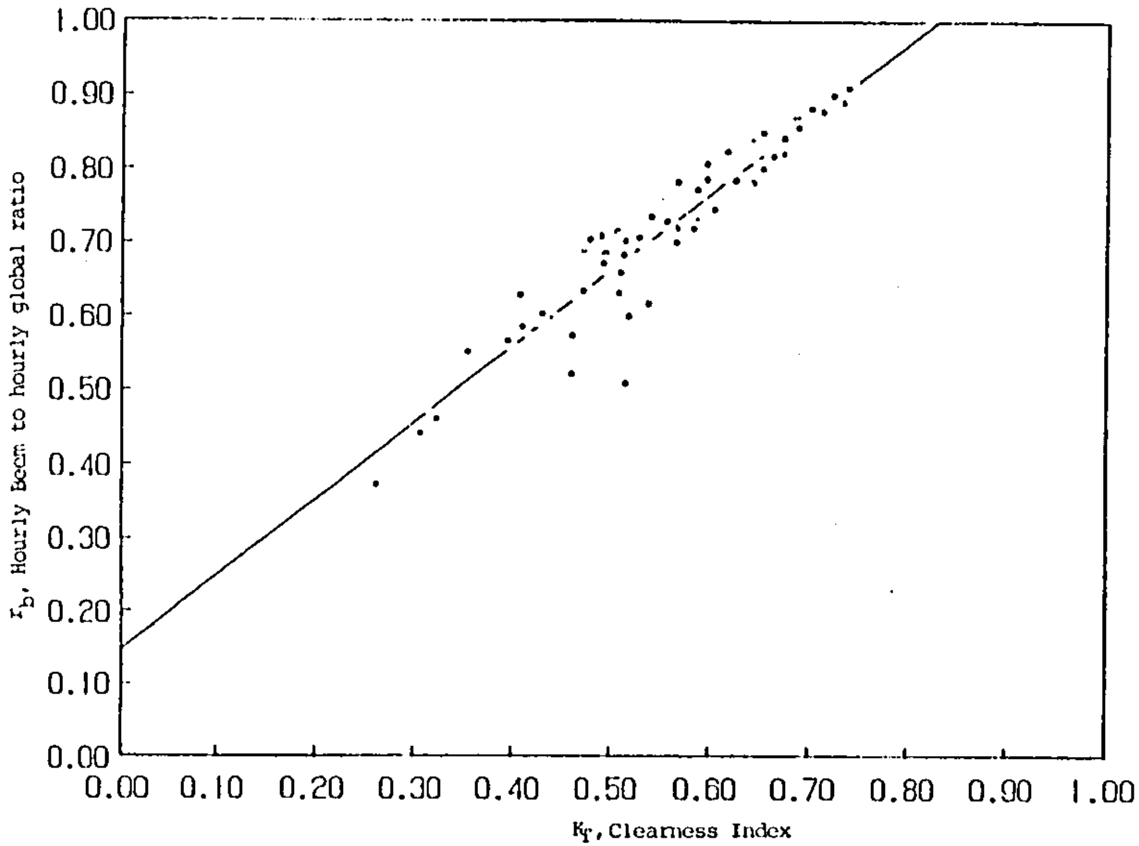

Figure 5.62 Hourly beem to hourly global ratio versus clearness index based on obtained Linear Equation-Amman , The average data around solar-noon is taken . Eqn(4.50)

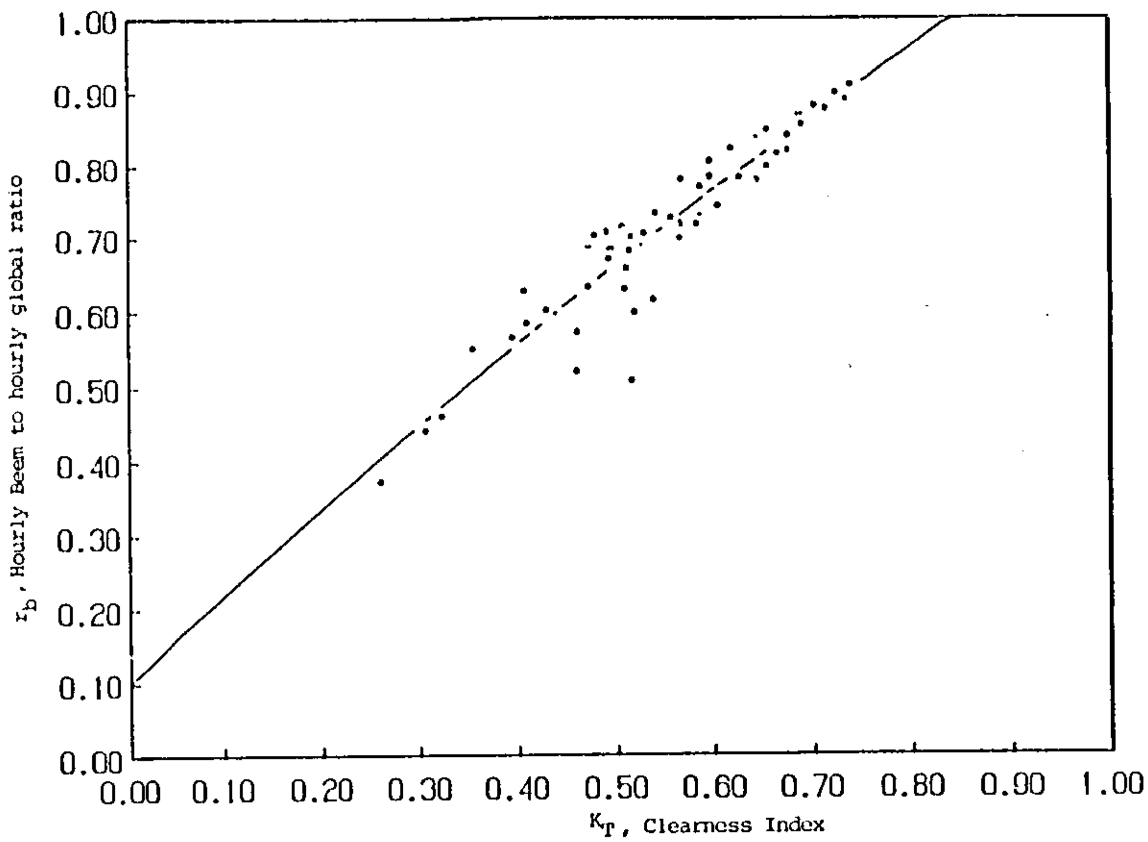

Figure 5.63 , Hourly Beem to hourly global ratio versus clearness index based on obtained Second Degree Equation-Amman. The average data around solar noon is taken . Eqn(4.51)

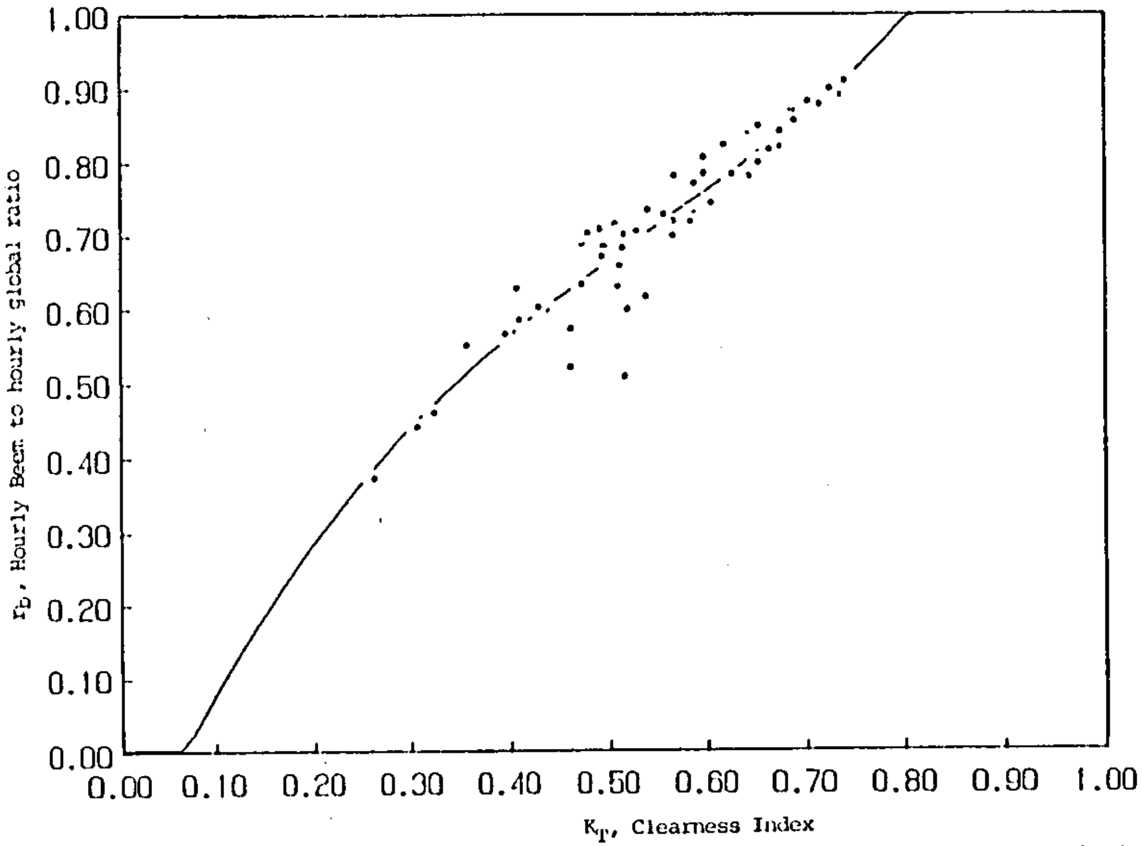

Figure 5.64, Hourly beem to hourly global ratio versus clearness index based on obtained Third Degree Equation-Amman. The average data around Solar Noon is taken. Eqn (4.52)

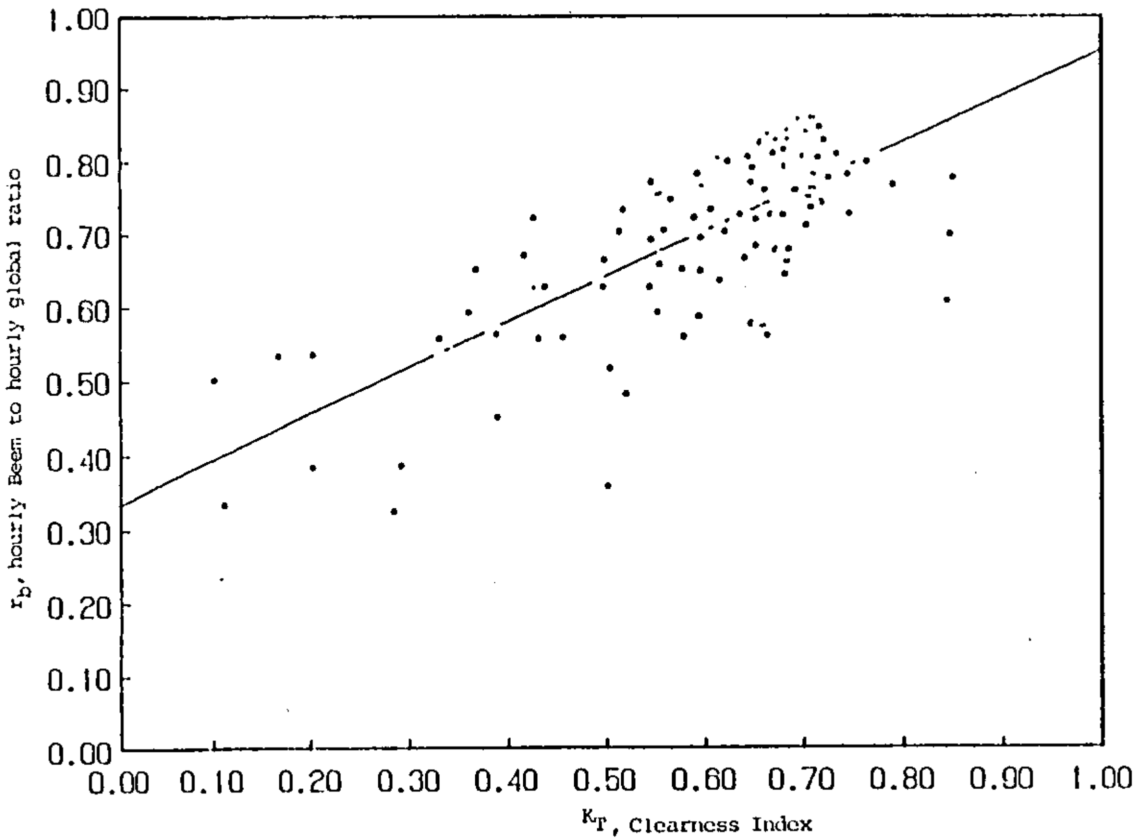

Figure 5.65 , Hourly beem to hourly global ratio versus clearness index based on obtained Linear Equation - Aqaba Eqn(4.53)

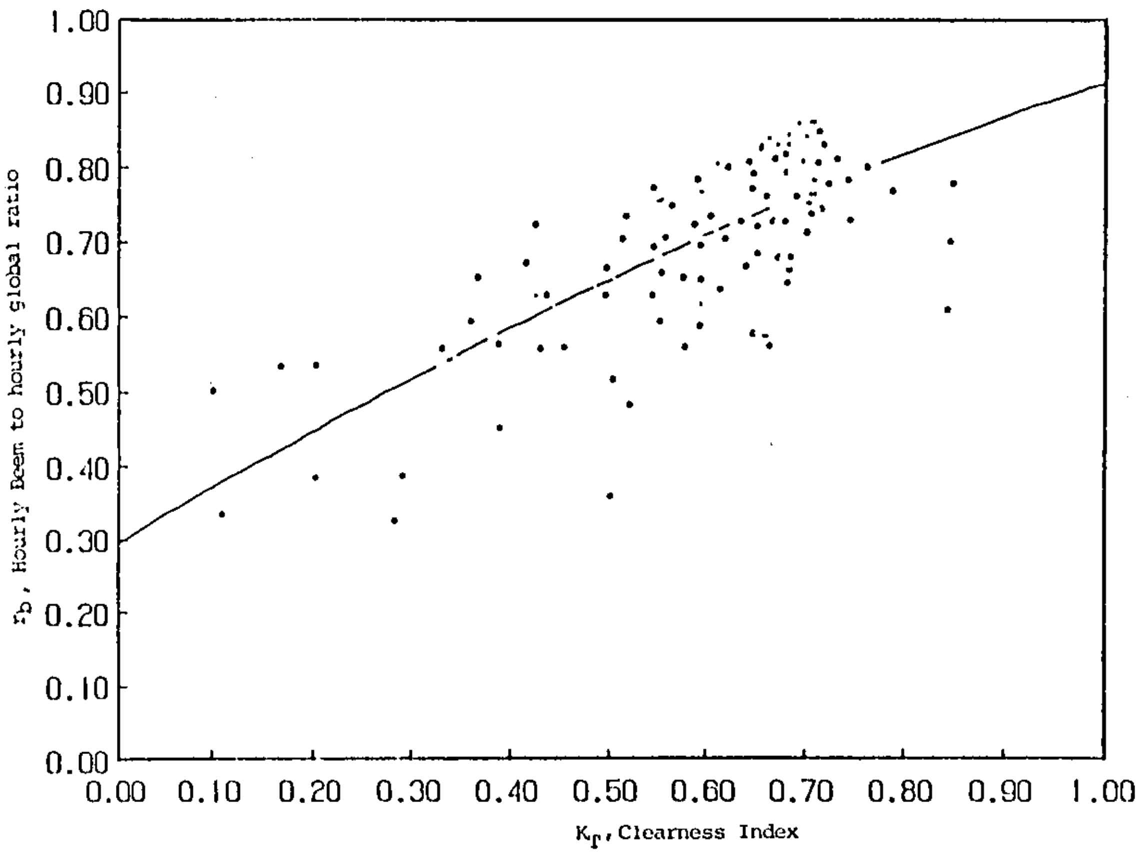

Figure 5.66 , Hourly beem to hourly global ratio versus clearness index based on obtained Second Degree Equation-Aqaba. Eqn.(4.54)

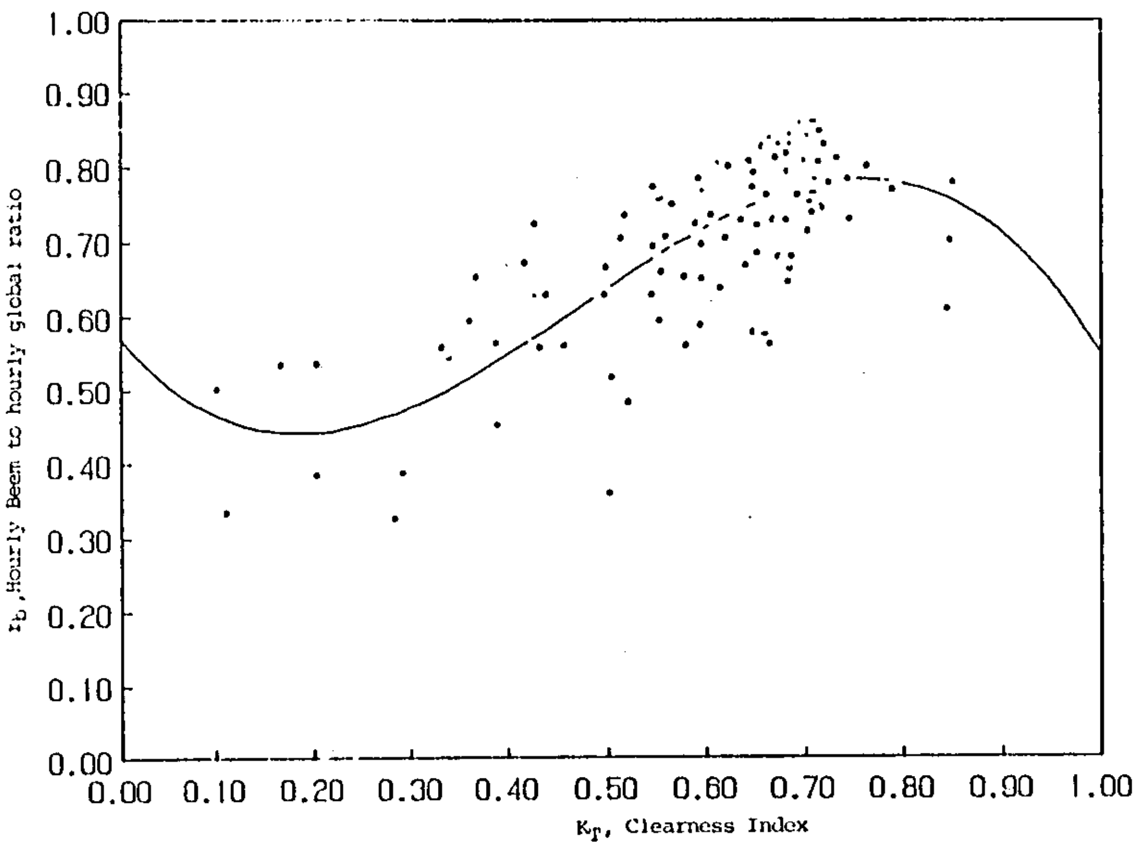

Figure 5.67 Hourly beem to hourly global ratio versus clearness index based on obtained Third Degree Equation-Aqaba. Eqn (4.55)

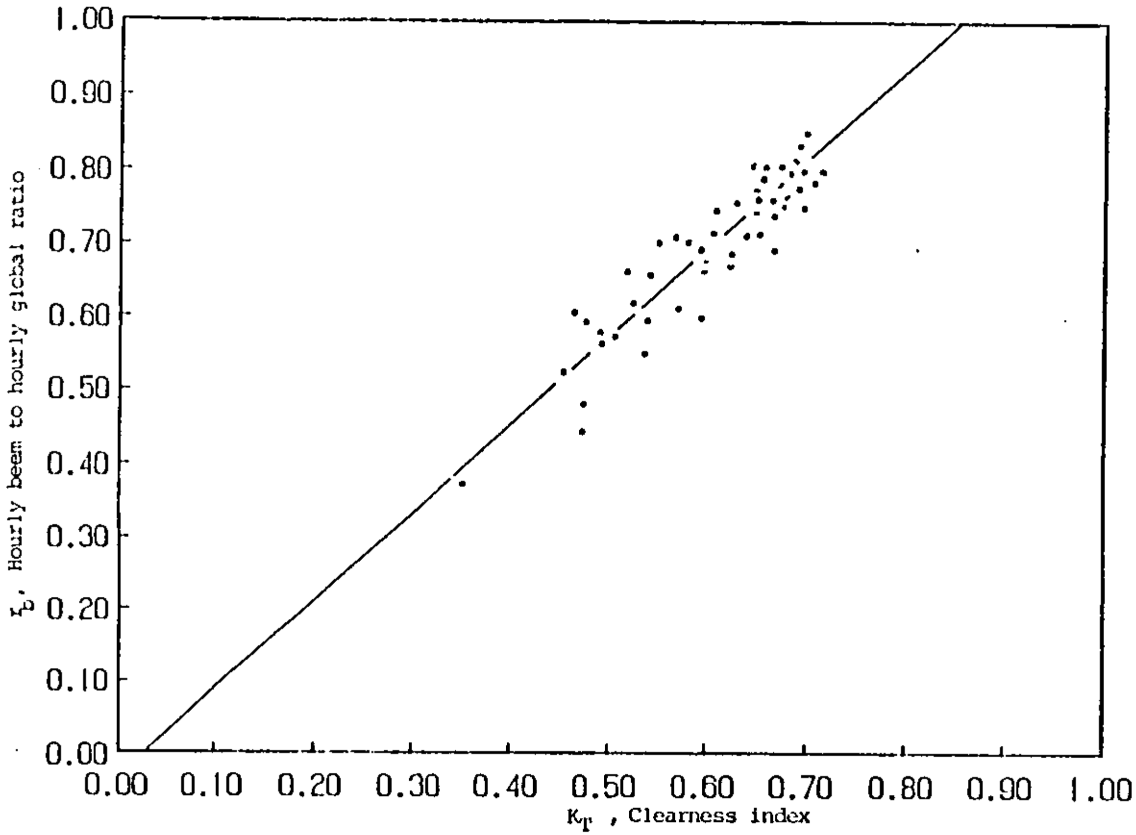

Figure 5.68 , Hourly beem to hourly global ratio versus clearness index based on obtained Linear Equation – Aqaba, The average data around solar noon is taken · Eqn(4.56)

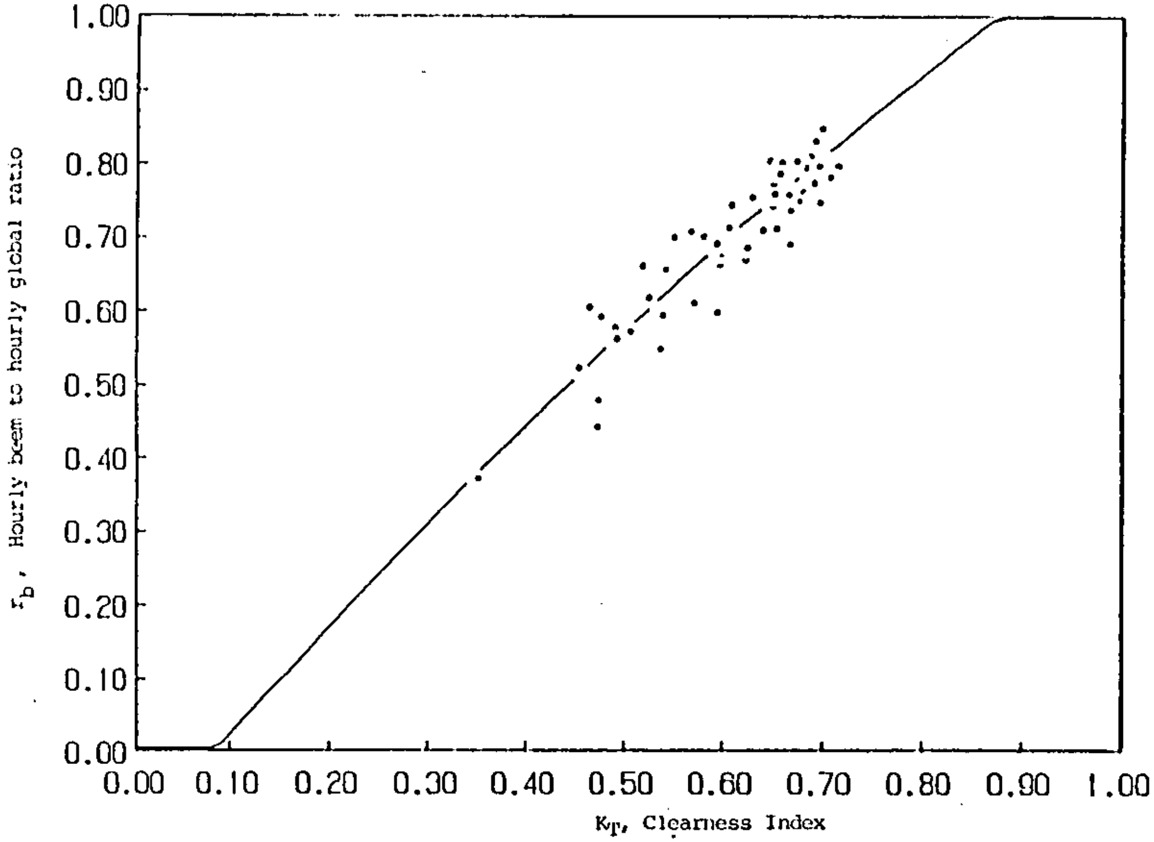

Figure 5.69 , Hourly beem to hourly global ratio versus clearness index based on obtained Second Degree Equation - Aqaba. The average data around solar noon is taken . Eqn.(4.57)

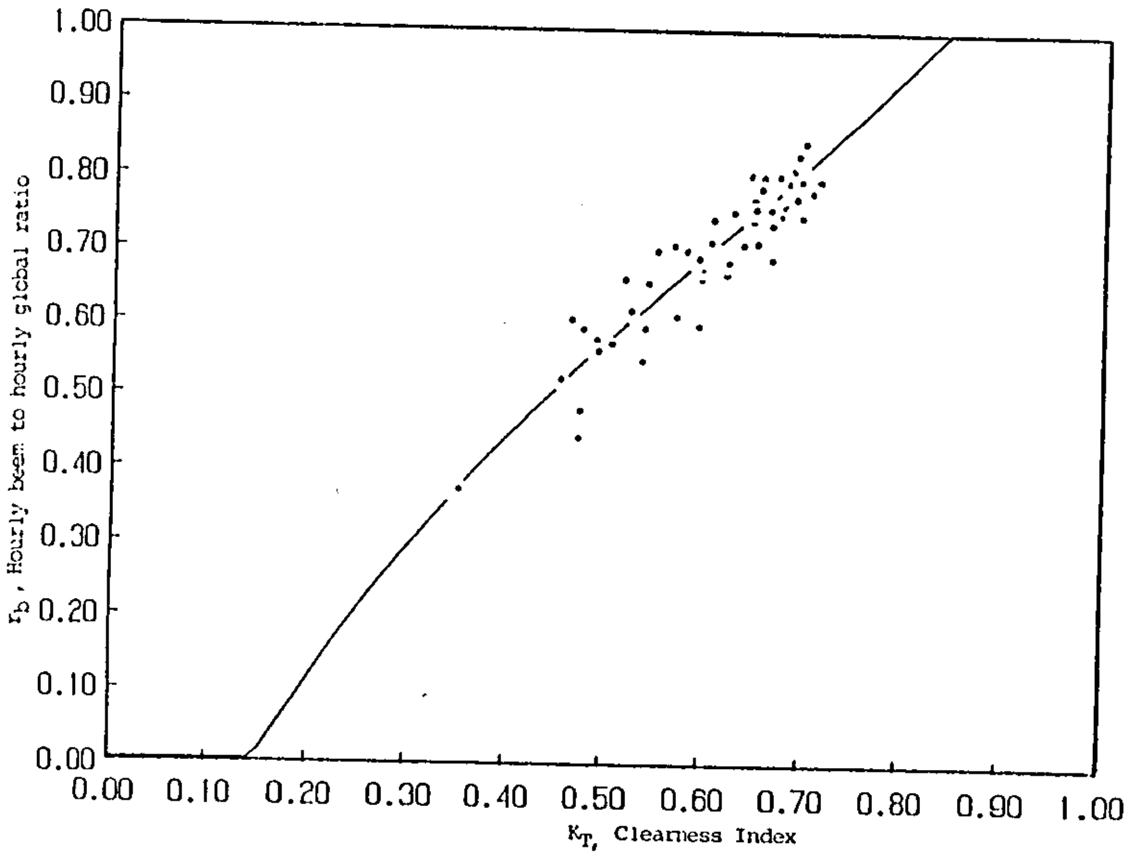

Figure 5.70 , Hourly beem to hourly global ratio versus clearness index based on obtained Third Degree Equation - Aqaba. The average data around solar noon is taken . Eqn(4.58)

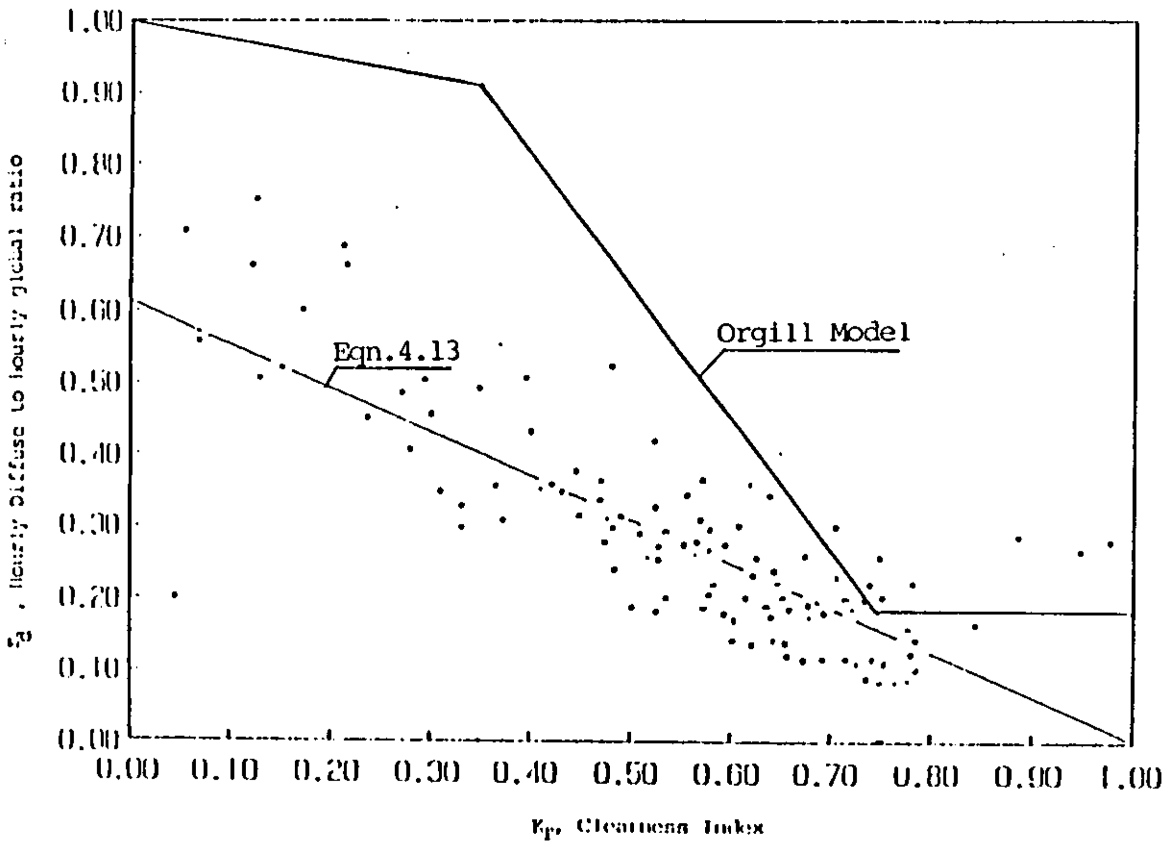

Figure 5.71 Hourly diffuse to hourly global ratio versus clearness index.

Comparison of diffuse radiation calculated by using Orgill and Hollands, model and the developed model Eqn. 4.13 - Amman.

CHAPTER SIX

APPLICATION OF DEVELOPED MODELS TO HEATING SYSTEMS

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APPLICATION OF DEVELOPED MODELS TO HEATING SYSTEMS

The heating load for a typical residential house is estimated by using a computer program and equations (4.6), (4.40), (4.12), and (4.46). The selected house consists of four bed rooms sitting room, guest room, kitchen and three baths totaling 240 m^2 as shown in figure 6.1.

Data needed for calculating the heating loads are taken from the standard data adopted by the Ministry of public works and the Royal Scientific society [22] and reference [23].

Conductivities and thicknesses of building materials are shown in table 6.1.

Table 6.1 : Conductivities [W/m.C^0] and Thicknesses (m) of each building material element

MATER./THICK.	WALL	CEIL 1	CEIL 2	FLOOR	CONDUCT
STONE	0.07	—	—	—	1.70
CONCRETE	0.20	0.05	0.05	—	1.75
INSULATION	0.03	0.03	0.03	0.03	0.04
PLASTERY	0.03	0.02	0.02	—	1.20
TILES	—	—	—	0.02	1.10
ASPHALT	—	0.02	0.02	—	0.70
BRICK	—	—	0.14	—	0.95
REINF. CONCR.	—	0.20	0.06	0.06	1.75
SILICA SAND	—	—	—	0.05	1.75

The inside and outside air resistances [m^2.c^0/W] are taken 0.12 and 0.06 for external walls, 0.1 and 0.04 for the roof, and 0.1 and 0.02 for the floor respectively.

Outside design temperature is taken as 5^0C for Amman and 10^0C for Aqaba. The interior design temperature is taken as 20^0C. The ground temperature needed to estimate the heating load for the basement floor is taken as 10^0C and 15^0C for Amman and Aqaba respectively. Basement heating load can be estimated by assumeing an arbitrary temperature difference between the inside air and the ground.

Infiltration rates per unit crack length are taken as 6.875 m^3/hr/m for windows and 10.219 m^3/hr/m for doors, as recommended in Ref [23].

Windows frame is considered of Aluminum type, while transparent double glazed glass is assumed to cover all faces. Doors are constructed of iron and wood.

The overall heat transfer coefficient, U, for metal doors is taken as 5.8 $W/m^2.c^0$, for wooden doors 3.5 $W/m^2.c^0$, and that for windows, 5.6 $W/m^2.c^0$.

In calculating heat losses for the ceiling, equation 2.7 is used to evaluate the overall heat transfer coefficient as 20% of the ceiling does not include brick material.
Table 6.2 represents the obtained heating loads for each individual building element. It is noticed that total heating

load needed for the assumed residential house in Amman and Aqaba are 13739 [W] and 8851 [W] respectively. This heating load will be supplied by using a flat plate solar heating system.

To estimate the useful heat extracted from a flat plate collectors, one needs to know values of diffuse, beam and global radiation. In addition, the geometric factor, R_b, tilt angle, β, reflectivity, ρ_{ref}, flat plate collector efficiency, η, and the transmissivity absorptivity product, $(\tau\alpha)$, should be known. Hourly global and hourly diffuse radiation data are estimated by using the developed models of equation (4.6) and (4.40) for Amman, and equation (4.12) and equation (4.46) for Aqaba. Beam radiation values are taken as the difference between global and diffuse radiation.

The geometric factor is calculated using equation (2.3). The flat plate collector tilt angle is taken as 45^0. Calculated R_b, values are represented in table 6.3.

The total solar radiation on tilted surface, I_t is calculated using equation (2.4) by assuming ρ_{ref} as 0.20. The useful heat extracted from a given collector is equal to the absorbed energy,S, multiplied by the collector efficiency, η, where S values are obtained using the relation:

$$S = (\tau\alpha)_{av} * I_t$$

Transmissivity absorbtivity product and the collector efficiency are taken as 0.8 from [24],and 0.281 from [25] respectively. The obtained usefull heat are presented in table 6.4. The useful heat are determined but using measured data instead of calculated one and presented in table 6.5.

The required flat plate collectors area needed to meet the heating load can be found by dividing the heating load needed for the residential house by the useful heat extracted from the flat plate collectors. Results are shown in tables 6.6 and 6.7. As seen from these tables the collecting area needed ranges from 102 m^2 and 141 m^2 for Amman and between 58 m^2 and 80 m^2 for Aqaba.

Errors between areas obtained using measured and calculated data were computed and presented in table 6.8 for both Amman and Aqaba.

It is observed that mean errors range between -0.001 and 0.032 for Amman and between -0.001 and 0.01 for Aqaba. This reflects an excellent agreement between areas obtained using actual measured and calculated data.

Furthermore, graphs of useful solar energy developed by using the minimum flat plate collectors area needed against local solar time are plotted for each month, as shown in figures 6.2 to 6.13. It can be observed that auxiliary heating is needed to meet the required heating load in both Amman and Aqaba.

It is also noticed that during computation the collecting area needed for the hour 7-8 is larger than ceiling area so calculations related to this hour are discarded.

TABLE 6.2 CALCULATED HOURLY HEAT LOAD FOR A RESIDINTIAL HOUSE IN JORDAN (W)

a) FOR AMMAN

ROOM NO./ITEM	1	2	3	4	5	6	7	8	9	10	11	12	ITEM. H.LOAD	HEAT PERC.
WALLS	265.570	59.030	126.970	19.180	253.950	47.400	346.210	99.960	126.970	250.030	59.030	0.000	1654.300	0.120
GLASS	336.000	40.320	168.000	0.000	168.000	40.320	504.000	168.000	168.000	336.000	40.320	0.000	1968.960	0.143
DOORS	0.000	0.000	0.000	174.000	174.000	0.000	105.000	105.000	0.000	174.000	0.000	0.000	732.000	0.053
FLOOR	184.740	54.780	171.853	51.553	171.853	42.107	297.733	279.260	206.220	197.627	73.040	118.687	1849.453	0.135
CEILING	228.050	67.620	212.140	63.640	212.140	51.970	367.530	344.730	254.570	243.960	90.160	146.510	2283.020	0.166
INFILTR.	501.270	121.740	250.640	425.760	676.400	121.740	1177.670	676.400	250.640	927.030	121.740	0.000	5251.030	0.382
ROOM H. L.	1515.630	343.490	929.603	734.133	1656.343	303.537	2798.143	1673.350	1006.400	2128.647	384.290	265.197	13738.763	1.000

b) FOR AQABA

ROOM NO./ITEM	1	2	3	4	5	6	7	8	9	10	11	12	ITEM. H.LOAD	HEAT PERC.
WALLS	177.047	39.353	84.647	12.787	169.300	31.600	230.807	66.640	84.647	166.687	39.353	0.000	1102.867	0.125
GLASS	224.000	26.880	112.000	0.000	112.000	26.880	336.000	112.000	112.000	224.000	26.880	0.000	1312.640	0.148
DOORS	0.000	0.000	0.000	116.000	116.000	0.000	70.000	70.000	0.000	116.000	0.000	0.000	488.000	0.055
FLOOR	92.370	27.370	85.927	25.777	85.927	21.053	148.867	139.630	103.110	98.814	36.520	59.343	924.727	0.104
CEILING	152.033	45.080	141.427	42.427	141.427	34.647	245.020	229.820	169.713	162.640	60.107	97.673	1522.013	0.172
INFILTR.	334.180	81.160	167.093	283.840	450.933	81.160	785.113	450.933	167.093	618.020	81.160	0.000	3500.687	0.396
ROOM H. L.	979.630	219.843	591.093	480.830	1075.587	195.340	1815.807	1069.023	636.563	1386.160	244.020	157.016	8850.933	1.000

TABLE 6.3 GEOMETRIC FACTOR (R)

a)FOR AMMAN

HOURS/MONS	JAN	FEB	MAR	APR	NOV	DEC
8 - 9	2.260	1.630	1.220	0.920	2.090	2.060
9 - 10	1.320	1.500	1.200	0.970	1.730	1.340
10 - 11	1.700	1.440	1.200	0.990	1.620	1.720
11 - 12	1.650	1.420	1.190	1.000	1.550	1.720

b)FOR AQABA

HOURS/MONS	JAN	FEB	MAR	APR	NOV	DEC
8 - 9	2.010	1.550	1.170	0.880	1.370	2.170
9 - 10	1.720	1.430	1.160	0.930	1.630	1.320
10 - 11	1.610	1.370	1.150	0.950	1.540	1.620
11 - 12	1.560	1.350	1.140	0.960	1.500	1.530

TABLE 6.4 CALCULATED HOURLY USEFUL HEAT BASED ON PREDICTED MODELS

a)FOR AMMAN

HOURS/MONS	JAN	FEB	MAR	APR	NOV	DEC
8 - 9	63.573	71.111	84.973	95.732	79.930	60.631
9 - 10	102.063	108.352	122.541	134.752	122.350	97.354
10 - 11	132.532	137.175	152.103	163.468	155.727	127.340
11 - 12	146.573	150.416	164.113	176.055	172.348	141.677

b) FOR AQABA

HOURS/MONS	JAN	FEB	MAR	APR	NOV	DEC
8 - 9	100.663	103.360	94.595	107.312	99.553	73.259
9 - 10	151.346	152.122	135.724	150.691	147.523	111.122
10 - 11	190.315	183.416	166.237	131.499	135.642	142.379
11 - 12	237.763	204.314	173.353	194.553	201.335	157.545

TABLE 6.5 CALCULATED HOURLY USEFUL HEAT BASED ON MEASURED DATA

a) FOR AMMAN

HOURS/MONS	JAN	FEB	MAR	APR	NOV	DEC
8 - 9	63.632	71.215	84.329	95.120	75.730	64.625
9 - 10	106.551	114.173	119.223	133.750	120.417	100.553
10 - 11	130.755	126.477	150.279	163.395	149.322	122.129
11 - 12	145.672	148.172	167.213	178.376	170.222	125.634

b) FOR AQABA

HOURS/MONS	JAN	FEB	MAR	APR	NOV	DEC
8 - 9	104.375	103.239	90.686	110.223	106.731	72.521
9 - 10	153.264	153.313	134.590	151.951	148.250	110.215
10 - 11	183.325	137.143	169.331	179.376	177.715	139.825
11 - 12	202.910	205.497	135.143	196.344	185.929	155.031

TABLE 6.6 REQUIRED FLAT PLATE COLLECTOR AREA TO MEET THE HEATING LOAD BASED ON PREDICTED MODELS

a) FOR AMMAN

HOURS/MONS	JAN	FEB	MAR	APR	NOV	DEC
8 - 9	216.393	193.223	161.634	143.513	171.385	226.598
9 - 10	124.610	126.736	112.115	101.955	111.743	140.243
10 - 11	103.625	100.155	90.304	84.046	87.561	107.468
11 - 12	93.730	91.323	83.715	78.037	79.715	95.373
AV. AREA	137.314	127.371	111.355	101.338	112.751	142.320

b) FOR AQABA

HOURS/MONS	JAN	FEB	MAR	APR	NOV	DEC
8 - 9	37.322	35.622	93.566	32.020	38.307	125.253
9 - 10	53.598	58.133	65.223	53.725	59.254	79.653
10 - 11	46.225	46.375	53.224	48.756	47.677	51.347
11 - 12	42.601	43.225	49.541	45.437	43.222	55.130
AV. AREA	53.375	52.521	55.225	59.755	50.232	90.335

TABLE 5.2 REQUIRED FLAT PLATE COLLECTOR AREA TO MEET THE HEATING LOAD BASED ON MEASURED DATA a) FOR AMMAN

HOURS/MONS	JAN	FEB	MAR	APR	NOV	DEC
8 - 9	225.737	192.543	161.359	146.420	131.298	212.555
9 - 10	128.940	120.223	114.654	102.720	114.073	126.632
10 - 11	105.372	100.667	91.361	84.023	91.539	112.376
11 - 12	94.013	92.722	82.114	76.763	80.559	101.233
AVER. AREA	136.008	126.592	112.522	101.397	116.322	140.744

b) FOR AQABA

HOURS/MONS	JAN	FEB	MAR	APR	NOV	DEC
8 - 9	84.395	85.691	97.600	80.308	82.388	120.337
9 - 10	57.325	57.542	65.306	58.249	59.703	79.371
10 - 11	46.374	47.225	52.270	49.206	49.304	63.209
11 - 12	43.520	43.371	47.306	45.079	47.354	57.373
AVER. AREA	58.178	58.400	65.371	58.210	59.937	80.160

TABLE 5.3 ERROR DIFFERENCE BETWEEN FLAT PLATE COLLECTOR AREAS USING MEASURED AND CALCULATED DATA a) FOR AMMAN

HOURS/MONS	JAN	FEB	MAR	APR	NOV	DEC
8 - 9	-0.002	-0.003	0.002	0.006	0.052	-0.066
9 - 10	-0.044	-0.054	0.022	0.007	0.021	-0.026
10 - 11	0.014	0.005	0.012	0.000	0.043	0.045
11 - 12	0.006	0.015	-0.019	-0.017	0.012	0.043
MEAN ERROR	-0.006	-0.009	0.004	-0.001	0.002	-0.001

b) FOR AQABA

HOURS/MONS	JAN	FEB	MAR	APR	NOV	DEC
8 - 9	-0.042	0.001	0.041	-0.021	-0.073	-0.046
9 - 10	-0.013	-0.011	0.009	-0.008	-0.004	0.003
10 - 11	0.010	0.007	-0.013	0.009	0.043	0.022
11 - 12	0.023	-0.003	-0.025	-0.009	0.074	0.016
MEAN ERROR	-0.005	-0.002	-0.001	-0.008	0.013	-0.002

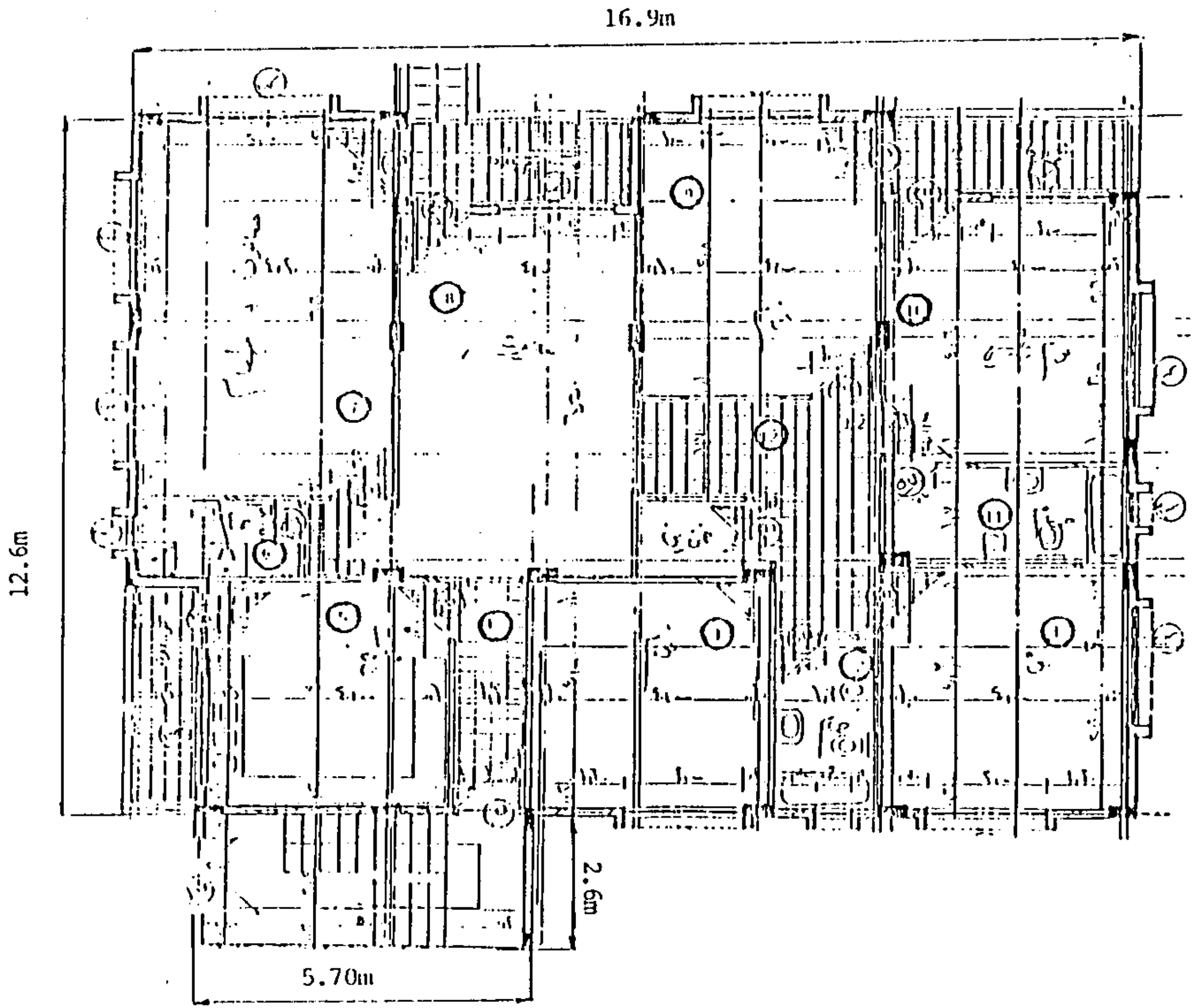

Figure 6.1 Layout of the residential house

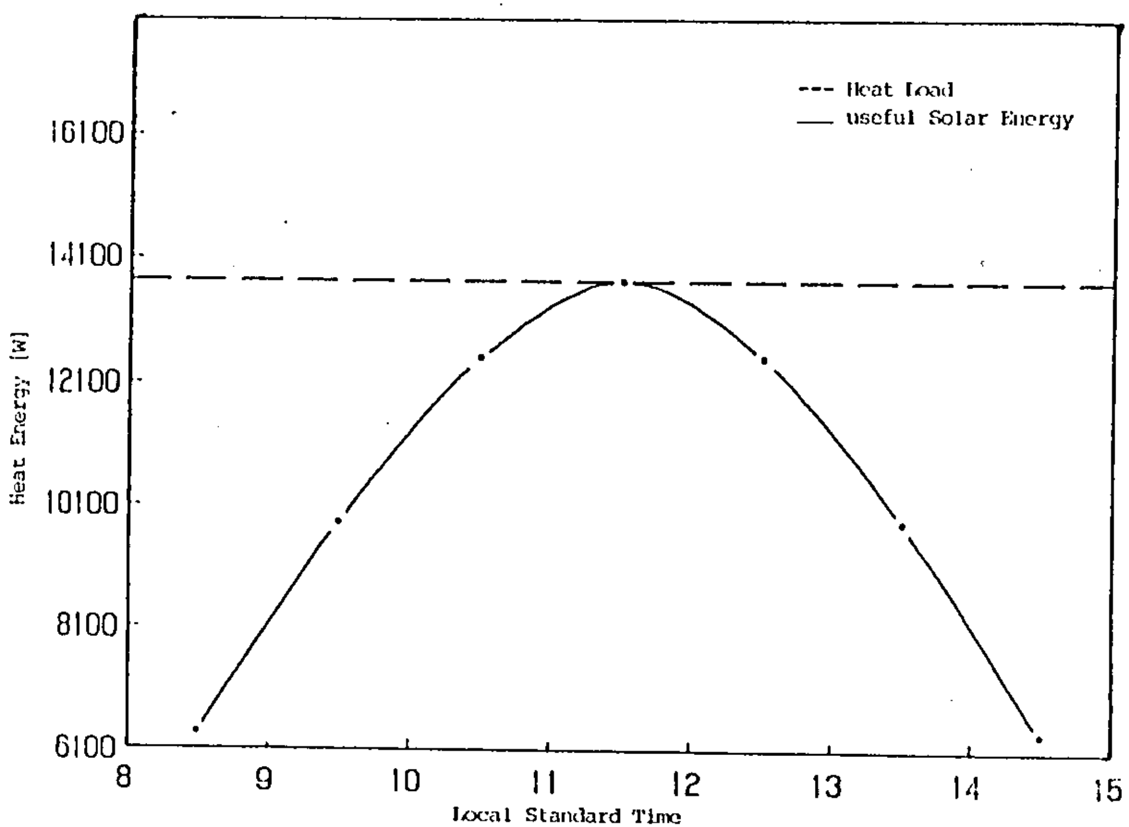

Fig.6.2 Hourly variation of useful Solar Energy developed by using the minimum flat plate collectors are calculated for the month of November - Amman .

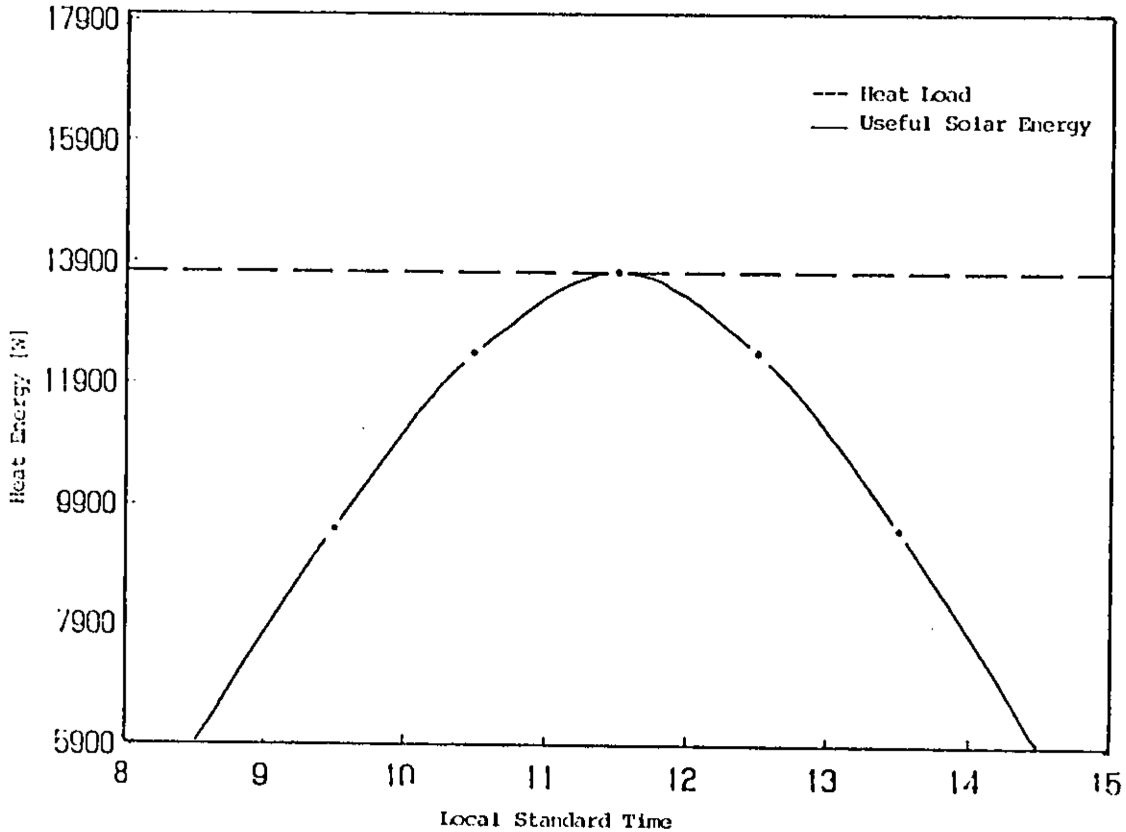

Fig. 6.3 Hourly variation of useful Solar Energy developed by using the minimum flat plate collectors area calculated for the month of December - Amman .

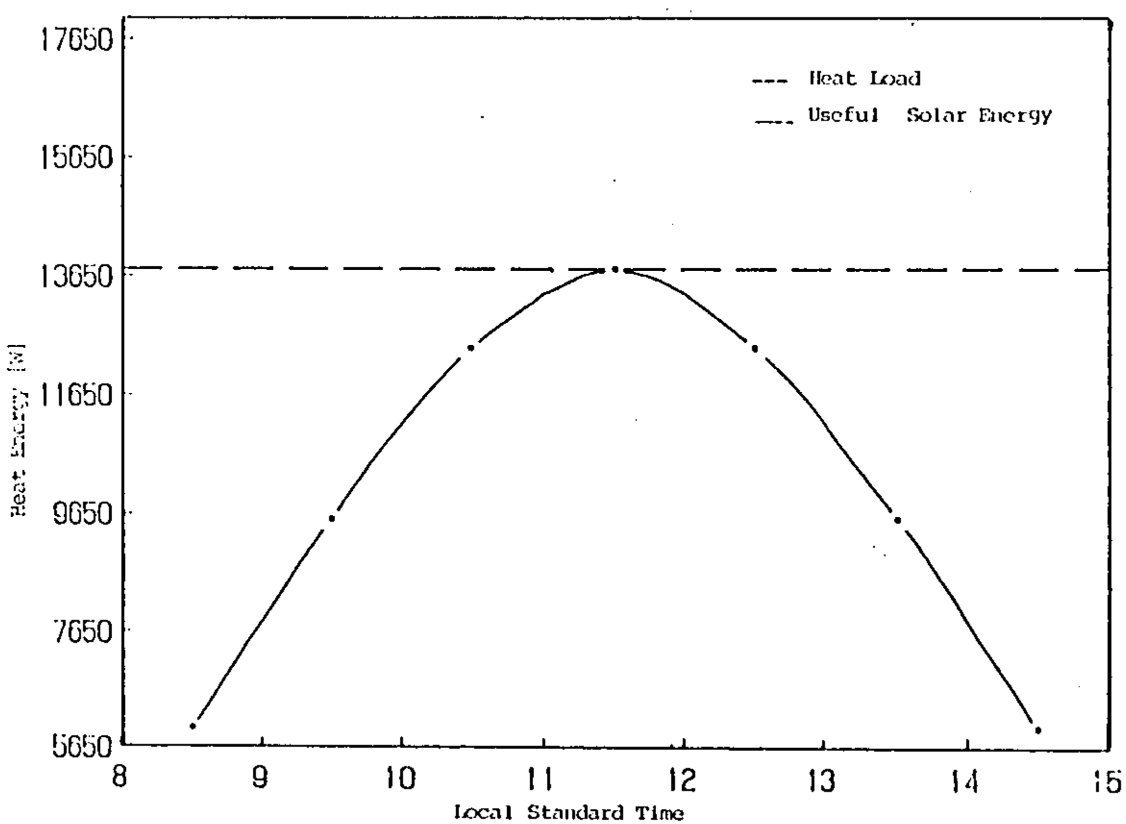

Fig.6.4 Hourly variation of useful Solar Energy developed by using the minimum flat plate collectors area calculated for the month of January - Amman .

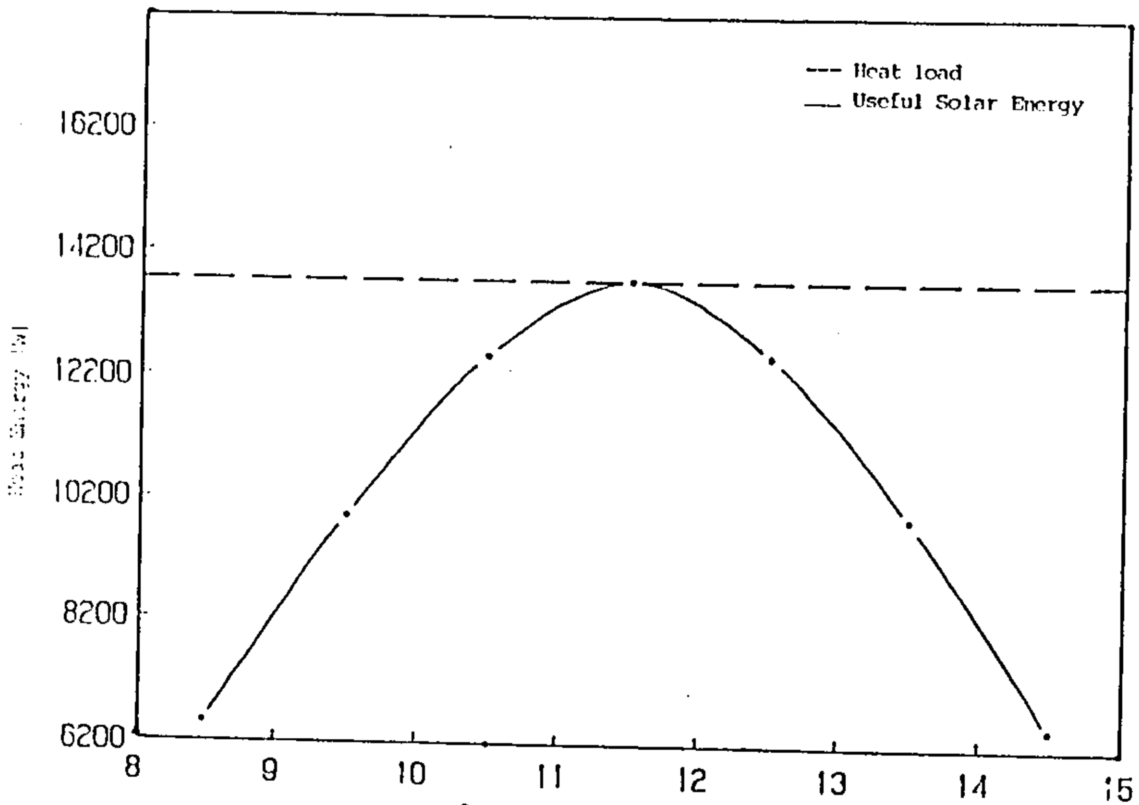

Fig6.5 Hourly variation of useful Solar Engergy developed by using the minimum flat plate collectors area calculated for the month of February - Amman .

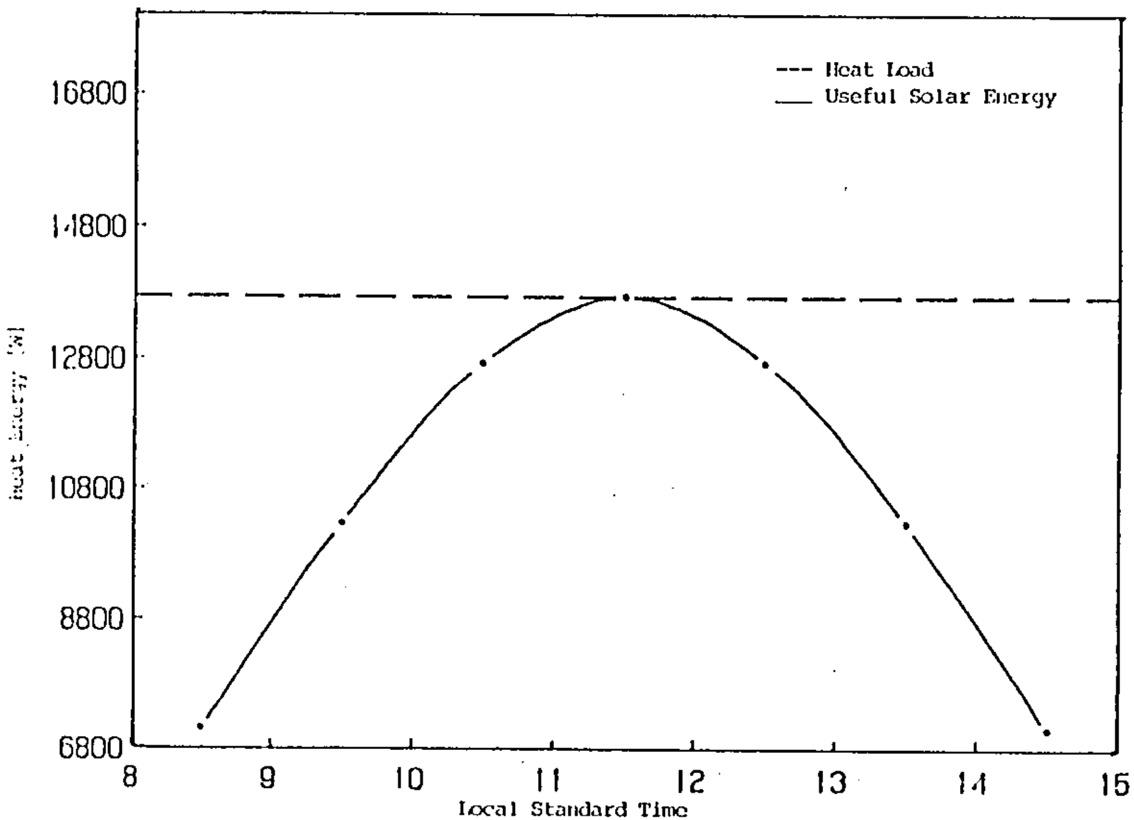

Fig6.6 Hourly variation of useful Solar Energy developed by using the minimum flat plate collectors area calculated for the month of March - Amman .

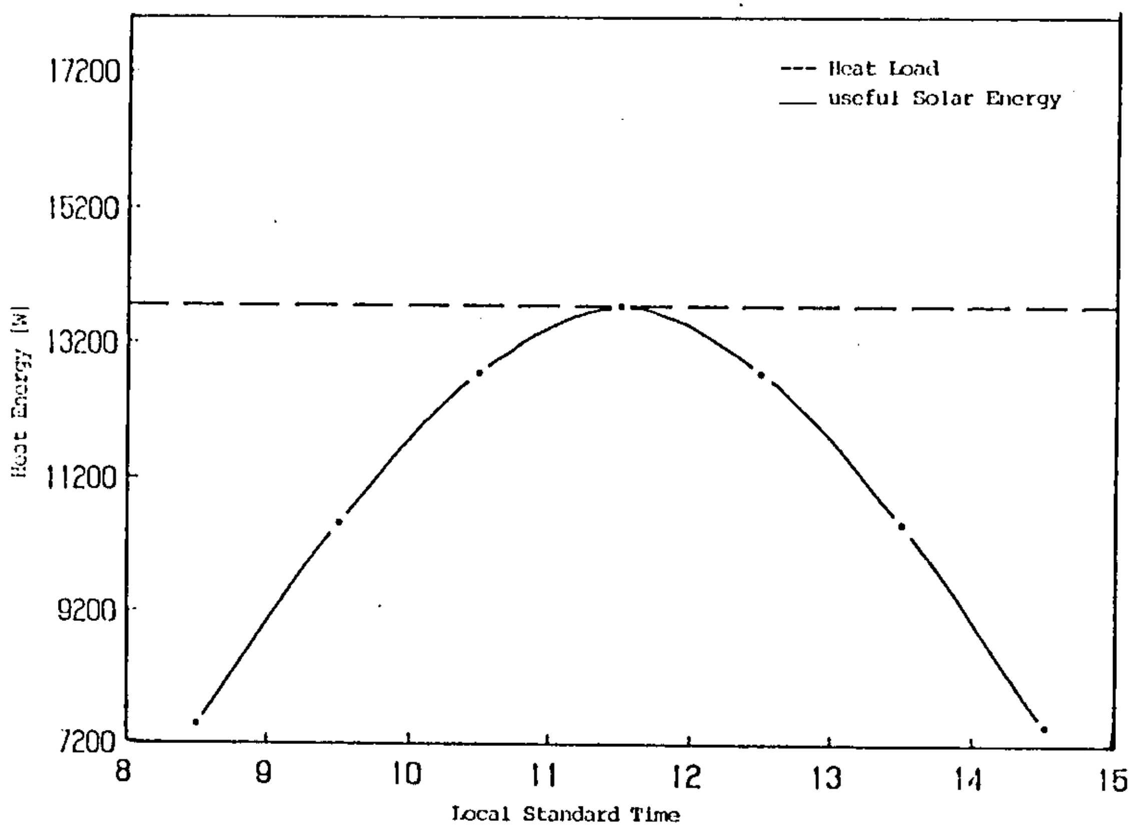

Fig6.7 Hourly variation of useful Solar Energy developed by using the minimum flat plate collectors area calculated for the month of April - Amman .

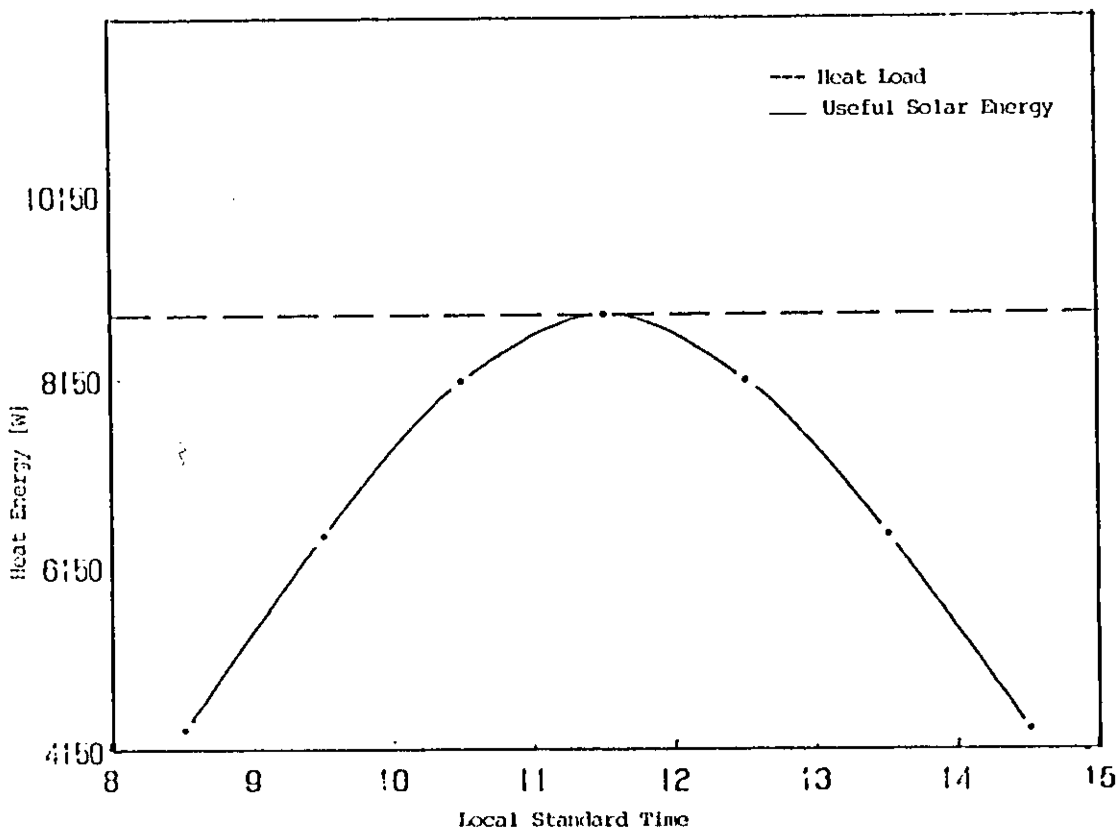

Fig .6.8 Hourly variation of useful Solar Energy developed by using the minimum flat plate colectors area calculated for the month of November - Aqaba.

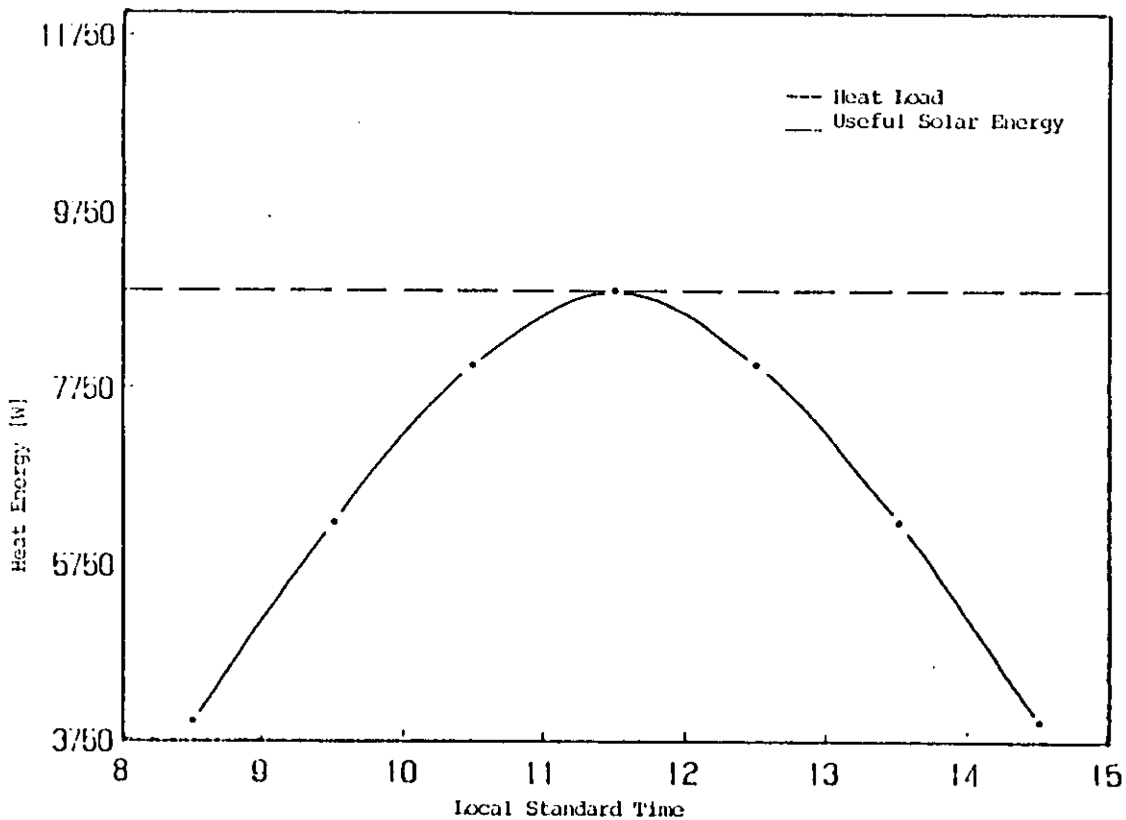

Fig.6.9 Hourly variation of useful solar energy developed by using the minimum flat plate colectors area calculated for the month of December - Aqaba.

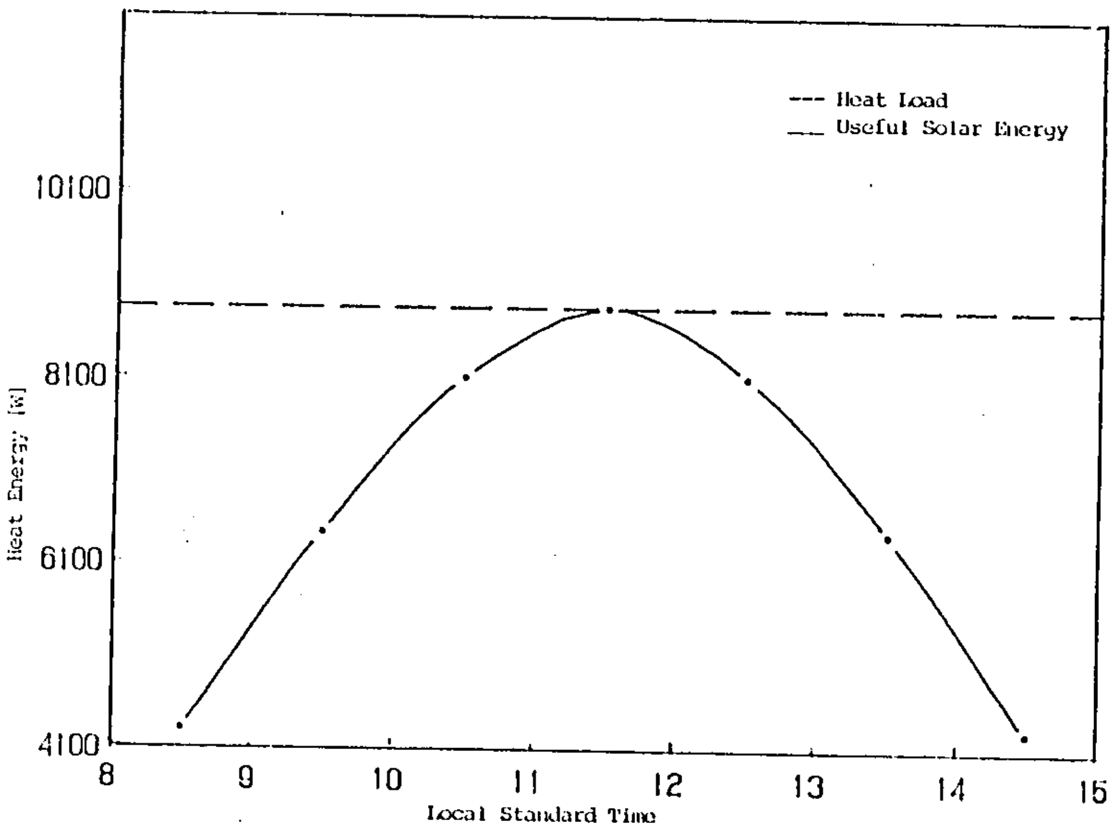

Fig .6.10 Hourly variation of useful Solar Energy developed by using the minimum flat plate collectors area calculated for the month of January - Aqaba .

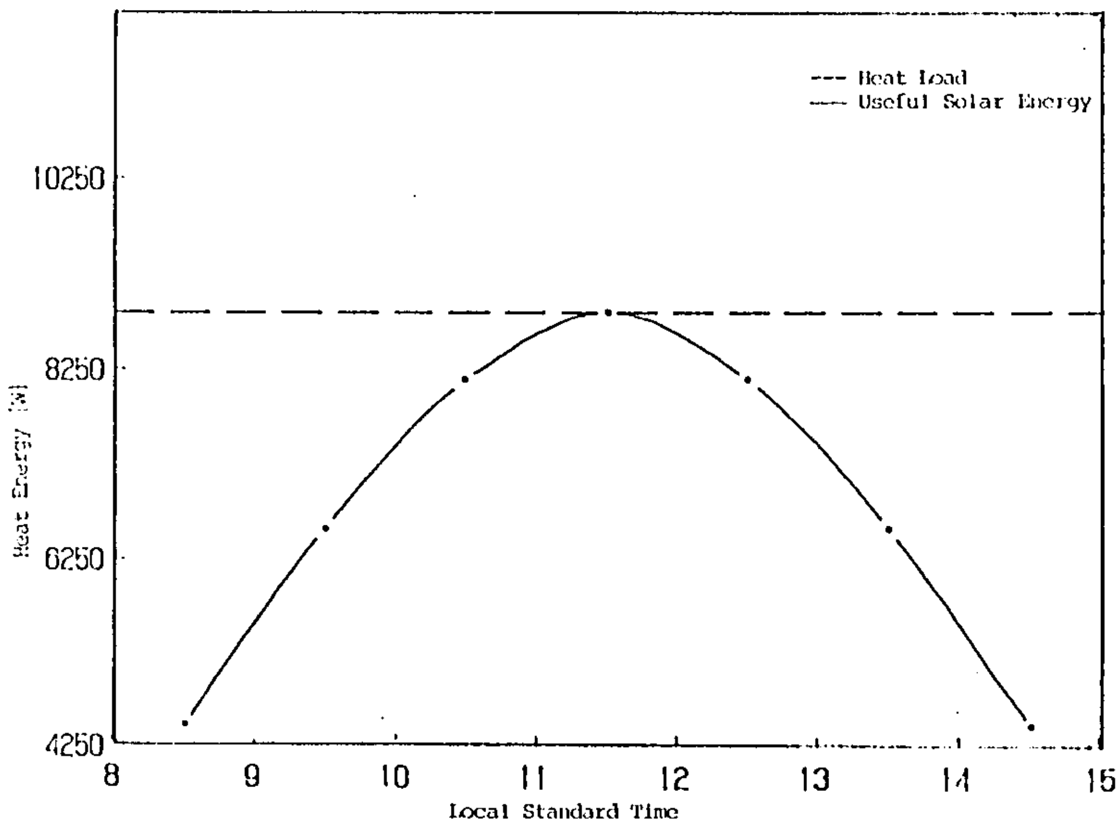

Fig.6.11 Hourly variation of useful Solar Energy developed by using the minimum flat plate collectors area calculated for the month of February - Aqaba.

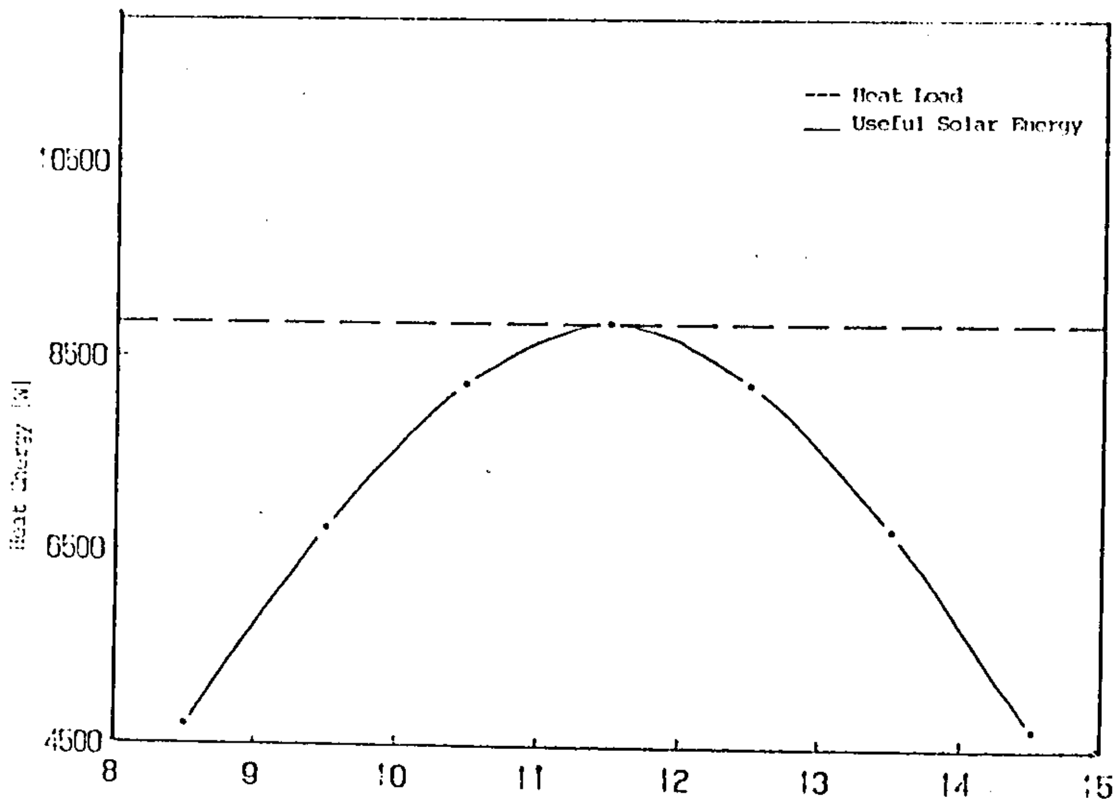

Fig. 6.12 Hourly variation of useful Solar Energy developed by using the minimim flat plate collectors area calculated for the month of March - Aqaba .

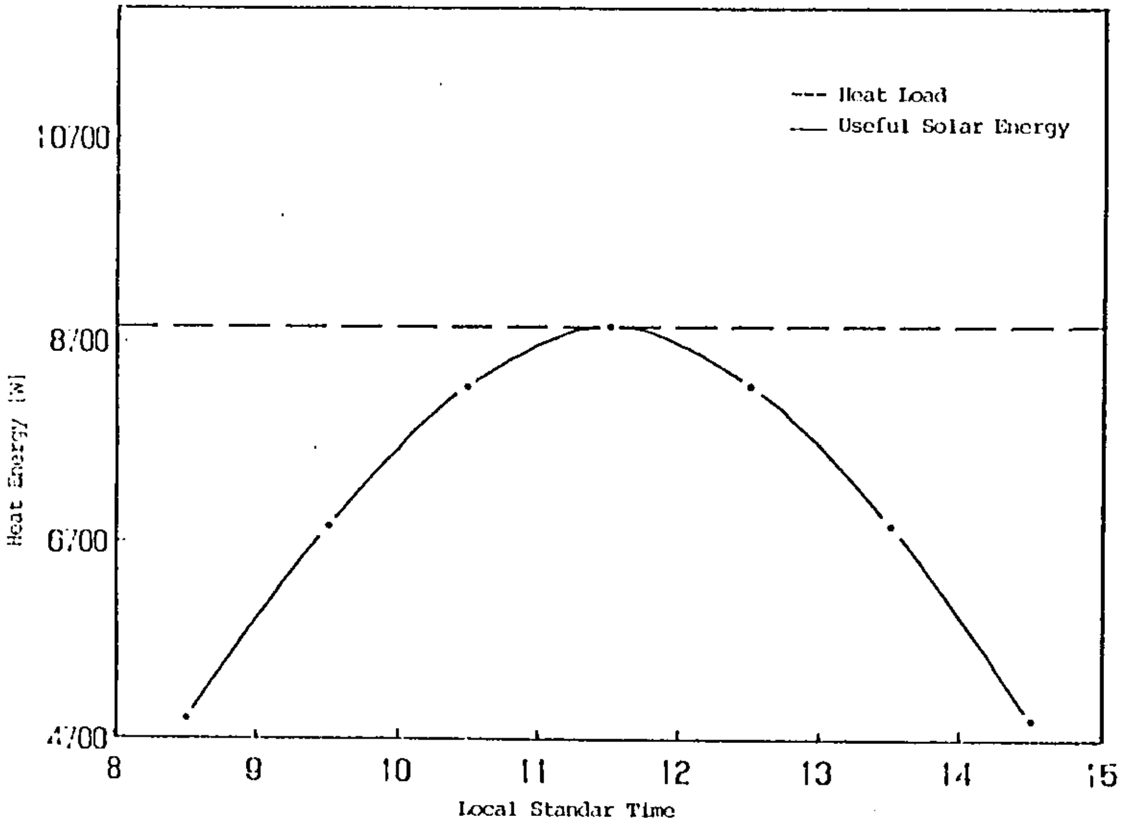

Fig6.13 Hourly variation of useful Solar Energy developed by using the minimum flat plate colectors area calculated for the month of April - Aqaba

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

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7.1 Conclusions

In this work, hourly global, diffuse and beam radiation models are investigated. Various available models have been tested against measured data. New models have been developed for Amman and Aqaba and tested against measured data too. An application of developed models to heating systems is performed. The following conclusions are made:

a. Available models.

1. Collars pereira equation (1.2) and Garg and Garg correlation (1.3) are found to be the most suitable among other global radiation models when all and averaged data are tested for both Amman and Aqaba.

2. Liu and Jordan theoretical model, equation (1.1) gives the best estimates for diffuse radiation when all data are tested, while Garg and Garg equation (1.15) gives the best estimates, when the averaged data are tested for both Amman and Aqaba. Orgill and Hollands model, equation (1.16), failed to fit measured data for both Amman and Aqaba.
3. Turner and Mujahed equation (1.24) hourly beam radiation model found to be not suitable for Jordan.

b. Developed models

1. The second degree polynomial equation (4.2) and equation (4.8) are the most suitable hourly global radiation models among other developed global models when all data are tested, while third degree polynomials equation (4.6) and equation (4.12) are the most suitable when the averaged data are tested for both Amman and Aqaba.
2. To determine hourly diffuse from the hourly global radiation, linear regressions, equation (4.13) and equation (4.20) are found to be the most suitable fits when all data are tested, while second degree polynomials equation (4.18) and equation (4.25) are the most suitable when averaged data are tested for both Amman and Aqaba. To estimate hourly diffuse from monthly averaged daily radiation, third degree polynomials, equations (4.37), (4.40), (4.43) and (4.46) are found to be suitable when all and averaged data are tested for both Amman and Aqaba respectively. Also it is noticed that among all developed diffuse models these latter models give the best results.
3. All developed beam models for Amman are suitable to estimate hourly beam radiation, mainly linear regressions equation (4.47) and equation (4.50). For Aqaba linear and second degree regressions; equation (4.53) and equation (43.57) give the best results, when all averaged data are tested.
4. All developed global, diffuse and beam radiation models are of simple forms, easy to use for hourly radiation estimation and give improved and reasonable results compared with the available models.

c. Application to heating systems

1. Collecting area for the solar heating system based on developed radiation models approved to be acceptable and reliable.
2. Flat plate Solar heating systems cannot be used to supply all the required heating load alone. If used auxiliary heating or large storage is needed.

7.2 Recommendations

The following suggestions are recommended for further investigations.

1. Different climatalogical parameters, such as humidity, turbidity, and correction factors should be taken into consideration in developing new models whenever available.
2. In this work the selected hourly global and diffuse radiation data range is between 6.a.m and 18 p.m. It is recommended to decrease this range to be only from 7 a.m up to 17 p.m to avoid unreliable readings of measured data.
3. It is recommended to investigate more locations in Jordan, Whenever measured data are available. Due to the lack of available measured data in most locations in Jordan, developed models for Amman can be applied to the higher latitude regions, while developed models for Aqaba can be applied to the Jordan valley and desert areas.
4. The present results can be improved if more measured data are available, therefore it is recommended to collect more of measured data.

5. On application to heating systems, it is recommended to use concentrators instead of flat plate collectors in order to generate more useful solar energy and lessen area needed.

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الخلاصة

ايجاد نماذج رياضية لحساب الاشعاع الشمسي في الأردن واستخدامها في أمثلة انظمة التدفئة

لدراسة الاشعاع الشمسي الساقط في الساعة في كل من عمان والعقبة، تم الحصول على القياسات المتوفرة لدى الجمعية العلمية الملكية حيث تم ترتيبها واحتساب نسبة الاشعاع الكلي (Global) والاشعاع المتشتت (Diffuse) الى قيمة الاشعاع الكلي والمتشتت للشهر الواحد ممثلة باليوم الذي يمثل ذلك الشهر في السنة. هذه القيم قورنت بالنتائج المماثلة التي تم الحصول عليها باستخدام النماذج المتوفرة في الدول الأخرى وذلك باستخدام المعادلة ٢/٢ . أظهرت النتائج ان نموذج Garg ونموذج Collares لاحتساب الاشعاع الكلي هما الأفضل، بينما نموذج Liu ونموذج Garg لاحتساب الاشعاع المتشتت هما الأفضل لكل من عمان والعقبة على التوالي بينما نموذج (Turner) الذي تم دراسته لاحتساب الاشعاع المباشر (Beam) غير ملائم للأردن.

أيضا تم ايجاد نماذج جديدة لتقدير الاشعاع الساقط باستخدام برنامج Ener Graphics حيث تم الحصول على معادلات من الدرجة الاولى والثانية والثالثة على شكل $r_t * t_d = f(\frac{W}{W_s})$ لاحتساب الاشعاع الكلي وعلى شكل $r_d * t_d = f(\frac{W}{W_s})$ و $\frac{I_d}{I} = f(k_T)$ لاحتساب الاشعاع المتشتت وعلى شكل $\frac{I_b}{I} = f(k_T)$ لاحتساب الاشعاع المباشر. كذلك تم مقارنة قيم الاشعاع الساقط المحتسبة باستعمال النماذج الجديدة بالقياسات الفعلية باستخدام المعادلة ٢/٢ ايضا.

أظهرت النتائج ان المعادلات ٢/٤ ، ٨/٤ ، ٦/٤ ، ١٢/٤ هما الأفضل لاحتساب الاشعاع الكلي والمعادلات ٣٧/٤ ، ٤٠/٤ ، ٤٣/٤ ، ٤٦/٤ هما الأفضل لاحتساب الاشعاع المتشتت بينما المعادلات ٤٧/٤ ، ٥٠/٤ ، ٥٣/٤ ، ٥٧/٤ هي الأنسب لاحتساب الاشعاع الساقط مباشرة في كل من عمان والعقبة.

لمعرفة مدى صلاحية النماذج الجديدة فقد تم استخدامها لاحتساب كمية الحرارة والمساحة اللازمة من السخانات الشمسية (Flat Plate Collectors) لتدفئة منزل مساحته ٢٤٠م٢ ومقارنتها بالنتائج الممكن الحصول عليها عند استخدام القياسات الفعلية حيث وجد ان معدل الخطأ يتراوح بين (-٠,٠٠١ و ٠,٠٣٢) لمنطقة عمان و (-٠,٠٠١ و ٠,٠١) لمنطقة العقبة مما يؤكد فعالية استعمال مثل هذه النماذج لغايات التصميم.