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PREDICTING DIFFUSE RADIATION WHERE ONLY DATA ON SUNSHINE DURATION IS AVAILABLE *

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ABSTRACT

In most locations there are no data on either global or diffuse radiation. Yet most of the existing correlations for predicting the latter require measured data on the former. This is because these correlations express the diffuse radiation as a function of the clearness index. To overcome this, one approach has been to develop correlations of diffuse radiation as a function of sunshine hours. This paper considers another approach: that of using predicted values of global radiation when measured values are not available. With this approach one could then use correlations of diffuse radiation as a function of clearness index. In this paper we have carried out a comparative assessment of the two approaches and reached the conclusion that the latter is more accurate.

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1. INTRODUCTION

One of the most important requirements in the design of any solar energy conversion equipment is the intensity of the solar radiation and its components. There are two main components of the radiation reaching the ground- direct radiation and diffuse radiation. In most solar energy applications, the global (or total) solar radiation incident on a horizontal surface is all that is required. However, in other applications, knowledge of diffuse irradiation is also essential. Whereas measurements of global radiation are carried out in several locations all over the world, there are very few data on diffuse radiation. Hence various correlations have been developed to predict the diffuse radiation at different locations.

There are two categories of correlations for predicting diffuse radiation. The first category expresses the diffuse fraction of the global radiation (H_D/H) as a function of the clearness index, K_T, which is defined as

$$K_T = \frac{H}{H_o}$$

where H, H_D and H_o are the monthly average daily global, diffuse and extraterrestral irradiation respectively. Examples of such correlations include the ones by Liu and Jordan [1], Page [2], Iqbal [3], Collares-Pereira and Rabl [4] Erbs et al. [5], Barbaro et al. [6] and Lewis [7]. The correlations are of the general form,

$$\frac{H_D}{H} = \sum_{n=o} a_n K_T^n \qquad (1)$$

and the only measured imput variable is the monthly average horizontal daily global radiation. In some locations where data on global radiation are not available, this can be a disadvantage. Under such a situation correlations of the type in eq. (1) can only be used if a predicted value of H is used in place of the measured value.

Iqbal [8], using physical arguments has suggested a correlation of diffuse radiation as a function of bright sunshine hours. The following correlation was suggested:

$$\frac{H_D}{H_o} = \sum_{n=o} a_n \left(\frac{S}{S_o}\right)^n \qquad (2)$$

where S, is the monthly average daily number of hours of bright sunshine, S_o is monthly average day length in hours and a_n are correlation constants. Several researchers [4], [9] and [10] have determined values of the correlation coefficients for various locations. These coefficients which have been found to be site specific are presented in Table 1. Thus by using eq. (2) one can determine diffuse radiation without the knowledge of the measured value of global radiation at the location.

There are many locations in the world where there is no data on either global radiation or any of its components. In such a situation, in order to predict the diffuse radiation, one is faced with a choice between two routes. One method will be to simply use correlations of the type in eq. (2) which can predict H_D without knowledge of the measured value of H. Another way will be to first predict H using an Angstrom-type [11] correlation and then using this value in eq. (1). The Angstrom-type correlation for predicting H is

$$\frac{H}{H_o} = a + b(\frac{S}{S_o}) \tag{3}$$

where a and b are constants. The possible disadvantage of the latter method is that the cummulative effect of the combined errors of the application of two different correlations will make it less accurate than the use of just one correlation as in the case of the first approach. On the other hand, it is also possible that the errors may interact in such a way as to limit their overall size and hence make the approach more accurate.

This paper compares the two approaches for predicting H_D where only sunshine data is available. It determines H_D using existing correlations of the type in eq. (2) and then compares it with those obtained from correlations of the type in eq. (1) used in sequence with eq. (3). The comparison has been carried out at four locations, two in the South and two in the North.

2. SOLAR RADIATION CORRELATIONS USED IN THIS WORK

2.1 Global radiation correlation:

For predicting the global radiation, the Rietveld [12] modification of the Angstrom correlation is used. This has previously been tested and believed to be universally applicable [13]. The equation is

$$\frac{H}{H_o} = 0.18 + 0.62(\frac{S}{S_o}) \tag{4}$$

2.2 Diffuse radiation correlation as functions of clearness index:

The Page correlation [2] of H_D/H as a function of the clearness index has been tested in ten locations spread between latitude 40^oN and 40^oS. The equation which is given below is given in this model

$$\frac{H_D}{H} = 1.0 - 1.13(\frac{H}{H_o}) \tag{5}$$

2.3 Diffuse radiation correlation as a function of sunshine hour:

Iqbal [9] has developed the following correlation for Montreal (Canada) (Lat. 45^o 30'N)

$$\frac{H_D}{H_o} = 1.63 + 0.478(\frac{S}{S_o}) - 0.655(\frac{S}{S_o})^2 \tag{6}$$

and Barbaro et al. [6] has presented the following for Macerata, Italy (Lat. 43^o 18'N Alt: 338m)

$$\frac{H_D}{H_o} = 0.3627 - 0.4259(\frac{S}{S_o}) + 0.2678(\frac{S}{S_o})^2 \tag{7}$$

3. METHODOLOGIES FOR FINDING H_D FROM SUNSHINE DATA

In a situation where there is no data on global radiation, one of two approaches can be used:

First Approach: This involves the use of correlations such as eqs. (6) and (7) above which express H_D only as a function of sunshine hours.

Second Approach: This involves the sequential application of eqs. (4) and (5) Eq. (4) is used to determine the global radiation H, from the available sunshine data. This predicted value of H is substituted into eq. (5) to obtain H_D. In effect this approach amounts to substituting for H and H/H_o calculated from eq. (4) into eq. (5). This results in the following equation

$$\frac{H_D}{H_o} = 0.143 + 0.368(\frac{S}{S_o}) - 0.434(\frac{S}{S_o})^2 \tag{8}$$

In this work we compare the two approaches for predicting H_D from S/S_o by applying them to four different locations for which data is reported in the literature.

4. RESULTS AND DISCUSSION

The data used in this work are those reported by Lewis [7], Iqbal [14] and Barbaro et al. [6]. In the case of the latter reference, only the data presented for Macerata (Italy) was considered because the period of the sunshine data for this location coincided with that for the diffuse radiation record. This was not true for the other locations reported in their paper. Table 2 gives details on the sources of the data used in this work.

Tables 3 to 6 give data and results of the computation for the four locations. These results are also plotted in Figs. 1 to 4. In each figure the measured data is plotted together with that predicted by eq. (8) and the correlation developed for that location by previous researchers. In Zimbabwe, there is at present no correlation of diffuse radiation as a function of sunshine hours hence the comparison was between the measured value and that predicted by eq. (8) (ie. the second approach). In Fig. 5, an attempt is made to find out whether any of the two approaches for finding H_D is universally applicable.

In Fig. 1, the recorded data for Montreal is compared with those predicted by correlations of Iqbal [9] as well as the eq. (8) that results from the second approach. It is observed visually that the equation resulting from the second approach (eq. 8) gives a better result than Iqbals correlation even though the latter was specifically developed for this location. This picture is further illustrated from Table 3 which compares the errors in the different prediction methods. The average percentage error incurred in predicting H_D using the correlation proposed by Iqbal is -7.95%, with the negative sign indicating that the values predicted were higher than those observed. The average error incurred in applying eq. (8) is only 0.793% which indicates very good agreement. Also, examining the errors for each month, one notices a better agreement between the observed and the predicted values when eq. (8) is applied.

In Table 4 and Fig. 2 the performance of emperical correlations developed by Barbaro et al. for Macerata (Italy) [6] is compared with that of eq. (8). The results show that although the Barbaro et al. correlation gives better values for H_D eq. (8) also gives reliable values. In Tables 5 and 6 and Figs. 3 and 4 the performance of eq. (8) is tested against reported data from two locations in Zimbabwe in the Southern hemisphere.

At both locations the agreemnet between the predicted values and the measured data were found to be very good. It was not possible to make comparison with a local correlation of H as a function of S/S_o because none has been developed for this location.

Since eq. (8) was found to perform very well in both hemispheres, it was decided to examine it further in order to find out whether the approach is universally applicable. In Fig. 5, H_D/H_o is plotted against bright sunshine hours as a fraction of day length. The first thing one observes from this graph is the spread of data points. It is difficult for any single equation to accurately fit all the data points. However eq. (8) which results from the second approach for finding H_D, seams to fit the data better than the other correlations especially at higher values of S/S_o.

5. CONCLUSION

In a location where only recorded data on sunshine duration is available, there are two possible ways of predicting H_D. One way is to use existing correlations that express H_D as a function of S/S_o another way would be to use correlations that express H_D as a function of the clearness index K_T, with the predicted (and not the observed) values of the global radiation used to determine K_T. The latter approach has been found to be more accurate. This is probably due to the fact that the errors involved in the two correlations used in the latter approach, act to eliminate each other.

Thus, it is concluded that in a location where there is no data in global radiation, one can still use the Page [2] equation to predict diffuse radiation.

In such a case value of H used in the Page correlation will be predicted by an Angstrom-type equation. This kind of approach represents in mathematical terms, the application of the following equation

$$\frac{H_D}{H_o} = 0.143 + 0.368\left(\frac{S}{S_o}\right) - 0.434\left(\frac{S}{S_o}\right)^2$$

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REFERENCES

[1] B.Y.H. Liu and R.C. Jordan, "The interrelationship and characteristic distribution of direct, diffuse and total radiation", Solar Energy, 4(3), 1-19 (1960).

[2] J.K. Page, "The estimation of monthly mean values of daily total short wave radiation on vertical and inclined surfaces from sunshine records for latitudes $40^{o}N$ - $40^{o}S$", Proc U.N. Conf. on New Sources of Energy, Paper No. 398, Vol 4, 318-390 (1961).

[3] M. Iqbal, "A study of Canadian diffuse and total solar radiation data - I: Monthly average daily horizontal radiation", Solar Energy, 22(1), 81-86 (1979).

[4] M. Collares-Pereira and A. Rabl, "The average distribution of solar radiation-correlations between diffuse and hemispherical and between daily and hourly insolation values", Solar Energy, 22(2), 155-164 (1979).

[5] D.G. Erbs, S.A. Klein and J.A. Duffie, "Estimation of the diffuse radiation for hourly, daily and monthly-average global radiation", Solar Energy, 28(4), 293-302 (1982).

[6] S. Barbaro, G. Cannata, S. Coppolono, C. Leone and E. Sinagra, "Diffuse Solar radiation statistics for Italy", Solar Energy, Vol 26, 429-435 (1981).

[7] G. Lewis, "Diffuse radiation over Zimbabwe", Solar Energy, 31(1), 125-128 (1983).

[8] M. Iqbal, "Estimation of the monthly average of the diffuse component of total insolation on a horizontal surface", Solar Energy, Vol 20, 101-105 (1978).

[9] M. Iqbal, "Correlation of average diffuse and beam radiation with hours of bright sunshine", Solar Energy, 23(2), 169-173 (1979).

[10] J.E. Hay, "Calculation of monthly mean solar radiation for horizontal and inclined surfaces", Solar Energy, 23(4), 301-307 (1979).

[11] A. Angstrom, "Solar and Terrestrial radiation", Q.J. Roy. Met. Soc. 50, 121-126 (1924).

[12] M.R. Rietveld, "A new method for estimating the regression coefficients in the formula relating solar radiation to sunshine", Agric. Meteorol. 19, 243-252 (1978).

[13] C.C.Y. Ma and M. Iqbal, "Statistical comparison of solar radiation correlations - Monthly average global and diffuse radiation on horizontal surfaces", Solar Energy . 33(2) 143-148 (1984).

[14] M. Iqbal, An introduction to Solar Radiation (Academic Press N.Y. (1983)).

TABLE 1

Reported values of constants for the correlation

$H_D/H_o = a_o + a_1(S/S_o) + a_2(S/S_o)^2$

Location	a_o	a_1	a_1	Reference
Montreal (Canada)	0.163	0.478	-0.655	Iqbal [9]
Palermo (Italy)	0.2205	0.0126	-0.1292	Barbaro et.al. [6]
Macerata (Italy)	0.3627	-0.4259	0.2678	Barbaro et.al. "
Genova (Italy)	0.1717	-0.0461	0.0725	Barbaro et.al. "

TABLE 2

Sources of data used in this work

Location	Latitude	Altitude	Reference
Montreal (Canada)	45°30'N	-	Iqbal [9]
Macerata (Italy)	43°18'N	338m	Barbaro et.al. [6]
Salisbury (Zimbabwe)	17°30'S	1471m	Lewis [7]
Bulawayo (Zimbabwe)	20°09'S	1343m	Lewis [7]

TABLE 3

Comparison between predicted and measured data

for Montreal (Canada)

$$H_D/H_o = 0.143+0.368(S/S_o)-0.434(S/S_o)^2 \quad (8)$$

$$H_D/H_o = 0.163+0.478(S/S_o)-0.655(S/S_o)^2 \quad (6)$$

Measured						H_D Predicted		Percentage Error	
	H_D	S/S_o	H_o	H	H_D/H_o	Equation (8)	Equation (6)	Equation (8)	Equation (6)
JANUARY	2.89	0.35	10.78	5.27	0.268	2.35	2.69	18.68	6.92
FEBRUARY	4.39	0.43	16.52	8.33	0.265	3.65	4.08	16.85	7.06
MARCH	5.88	0.47	25.57	12.5	0.23	5.62	6.2	4.42	-5.44
APRIL	6.61	0.47	32.77	15.81	0.2	7.21	7.96	- 9.07	-20.42
MAY	8.19	0.53	40.47	18.54	0.2	8.74	9.4	- 6.71	-14.77
JUNE	9.19	0.54	41.78	20.70	0.22	9.0	9.6	2.06	- 4.46
JULY	9.26	0.56	42.97	21.19	0.215	9.15	9.68	1.18	- 4.53
AUGUST	8.01	0.54	35.69	17.18	0.22	7.49	8.2	6.49	- 2.37
SEPTEMBER	5.88	0.53	29.04	13.22	0.2	6.27	6.7	- 6.63	-13.94
OCTOBER	3.96	0.45	20.49	8.26	0.19	4.52	5.0	-14.14	-26.26
NOVEMBER	2.56	0.27	12.87	4.47	0.2	2.71	3.1	- 5.86	-21.09
DECEMBER	2.28	0.3	10.44	3.78	0.22	2.23	2.58	2.19	3.94
						AVERAGE	ERROR	0.793	- 7.95

TABLE 4

Comparison between predicted and measured data for Macerata (Italy)

$$H_D/H_o = 0.143+0.368(S/S_o)-0.434(S/S_o)^2 \quad (8)$$

$$H_D/H_o = 0.3627-0.4259(S/S_o)+0.2678(S/S_o)^2 \quad (7)$$

	Measured					H_D Predicted		Percentage Error	
	H_D	S/S_o	H_o	H	H_D/H_o	Equation (8)	Equation (7)	Equation (8)	Equation (7)
JANUARY	3.3	0.34	13.1	6.4	0.25	2.85	3.26	13.63	1.21
FEBRUARY	5.0	0.41	18.2	10.0	0.27	4.02	4.24	19.6	15.2
MARCH	5.6	0.39	25.6	13.9	0.218	5.64	6.07	- 0.71	- 8.39
APRIL	7.1	0.45	33.4	18.8	0.212	7.37	7.52	- 3.8	- 5.91
MAY	8.0	0.57	39	24.8	0.2	8.26	8.07	- 3.25	- 0.875
JUNE	8.6	0.57	41.3	26.9	0.21	8.74	8.54	- 1.63	0.697
JULY	8.3	0.67	40.1	27.0	0.2	7.81	7.92	5.9	4.58
AUGUST	7.3	0.65	35.4	24.2	0.2	7.04	7.04	3.56	3.56
SEPTEMBER	6.1	0.56	28.2	20.4	0.216	6.0	5.87	1.64	3.77
OCTOBER	4.9	0.5	20.4	12.9	0.24	4.45	4.42	9.18	9.8
NOVEMBER	3.6	0.39	14.2	7.7	0.25	3.13	3.37	13.05	6.39
DECEMBER	2.7	0.33	11.6	5.9	0.23	2.52	2.915	6.67	- 7.96
						AVERAGE	ERROR	5.32	1.84

TABLE 5

Comparison between predicted and measured data for Salisbury (Zimbabwe)

$$H_D/H_o = 0.143+0.368(S/S_o)-0.434(S/S_o)^2 \quad (8)$$

	Measured					H_D Predicted	Percentage Error
	H_D	S/S_o	H_o	H	H_D/H_o	Equation (8)	Equation (8)
JANUARY	10.2	0.48	41	22.3	0.248	9.02	11.57
FEBRUARY	9.8	0.5	39.6	21.5	0.247	8.65	11.73
MARCH	8.4	0.61	36.5	21.3	0.23	7.52	10.47
APRIL	6.1	0.69	31.8	20.0	0.192	6.05	0.82
MAY	4.3	0.76	27.3	18.6	0.157	4.69	- 9.07
JUNE	3.8	0.79	25.1	17.2	0.151	4.1	- 7.9
JULY	3.9	0.83	26.0	18.4	0.15	3.9	- 0-
AUGUST	4.1	0.84	29.7	21.1	0.138	4.3	- 4.88
SEPTEMBER	5.6	0.81	34.6	23.9	0.162	5.4	3.57
OCTOBER	7.1	0.73	38.4	24.9	0.185	6.9	2.82
NOVEMBER	8.1	0.527	40.5	23.5	0.2	8.76	- 8.15
DECEMBER	10.2	0.45	41.2	21.8	0.247	9.1	10.78
							2.63

TABLE 6

Comparison between predicted and measured data

for Bulawayo (Zimbabwe)

$$H_D/H_o = 0.143+0.368(S/S_o)-0.434(S/S_o)^2 \qquad (8)$$

Measured						H_D Predicted	Percentage Error
	H_D	S/S_o	H_o	H	H_D/H_o	Equation (8)	Equation (8)
JANUARY	9.7	0.55	41.4	24.2	0.23	8.86	8.66
FEBRUARY	9.4	0.55	39.6	22.9	0.24	8.48	9.78
MARCH	7.6	0.64	36	22.4	0.21	7.23	4.87
APRIL	5.9	0.7	30.9	19.9	0.19	5.8	1.7
MAY	4.0	0.8	26.2	18.6	0.15	4.2	- 5
JUNE	3.8	0.79	23.9	16.9	0.16	3.89	- 2.37
JULY	3.7	0.83	24.9	18.0	0.15	3.72	- 0.54
AUGUST	4.4	0.85	28.8	20.5	0.15	4.1	6.82
SEPTEMBER	5.4	0.8	33.9	23.5	0.16	5.4	0
OCTOBER	7.1	0.7	38.2	24.3	0.18	7.18	-11.26
NOVEMBER	8.6	0.54	40.8	22.9	0.21	8.77	- 1.97
DECEMBER	9.5	0.48	41.7	22.9	0.23	9.16	3.58
							2.03

FIGURE CAPTIONS

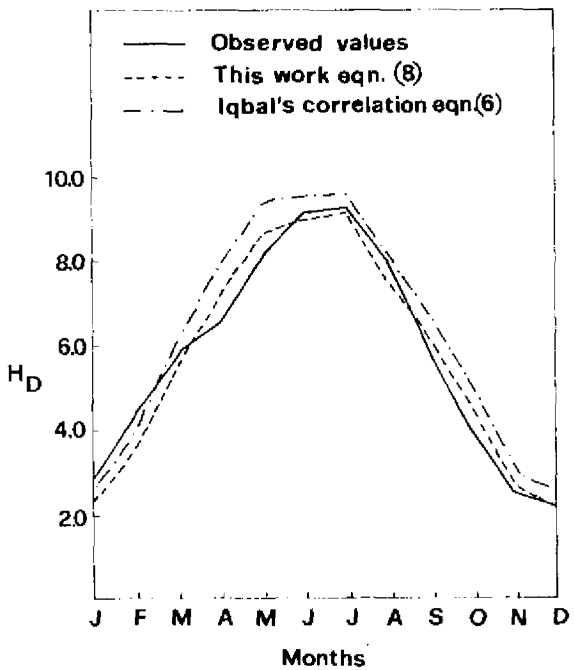
Fig.1 Comparison between predicted and measured values of diffuse radiation over Montreal, Canada.

Fig.2 Comparison between predicted and measured values of diffuse radiation over Macerata, Italy.

Fig.3 Comparison between predicted and measured values of diffuse radiation over Bulawayo, Zimbabwe.

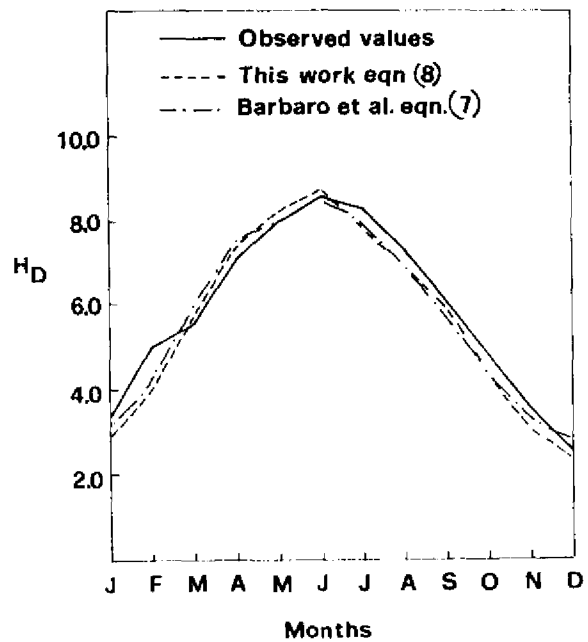
Fig.4 Comparison between predicted and measured values of diffuse radiation over Salisbury, Zimbabwe.

Fig.5 Comparison of the two methods for different locations.



Observed values
This work eqn. (8)
Iqbal's correlation eqn(6)
10.0
8.0
6.0
4.0
2.0
H_D
J F M A M J J A S O N D
Months

Fig. [illegible]



Observed values
This work eqn (8)
Barbaro et al. eqn.(7)
10.0
8.0
6.0
4.0
2.0
H_D
J F M A M J J A S O N D
Months

Fig. [illegible]

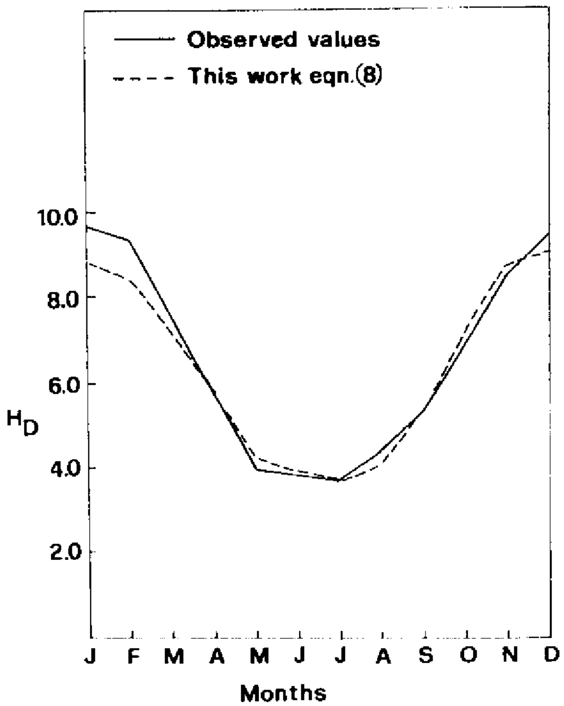

Observed values
This work eqn.(8)
10.0
8.0
6.0
4.0
2.0
H_D
J F M A M J J A S O N D
Months

Fig. 3

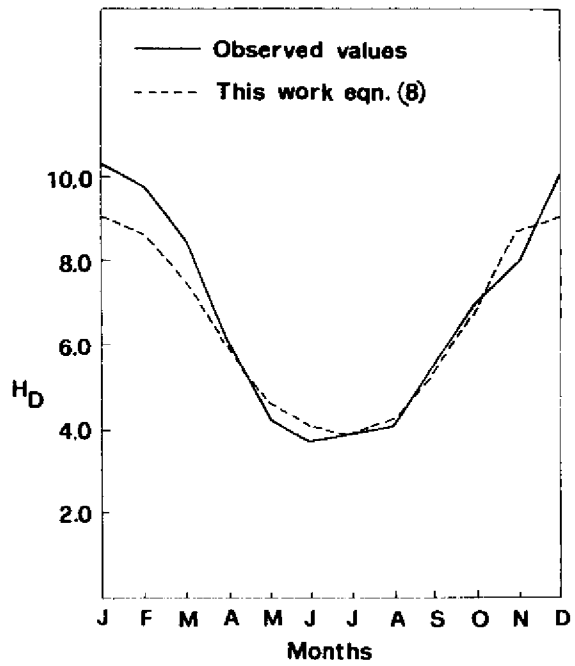

Observed values
This work eqn. (8)
10.0
8.0
6.0
4.0
2.0
H_D
J F M A M J J A S O N D
Months

Fig. 4

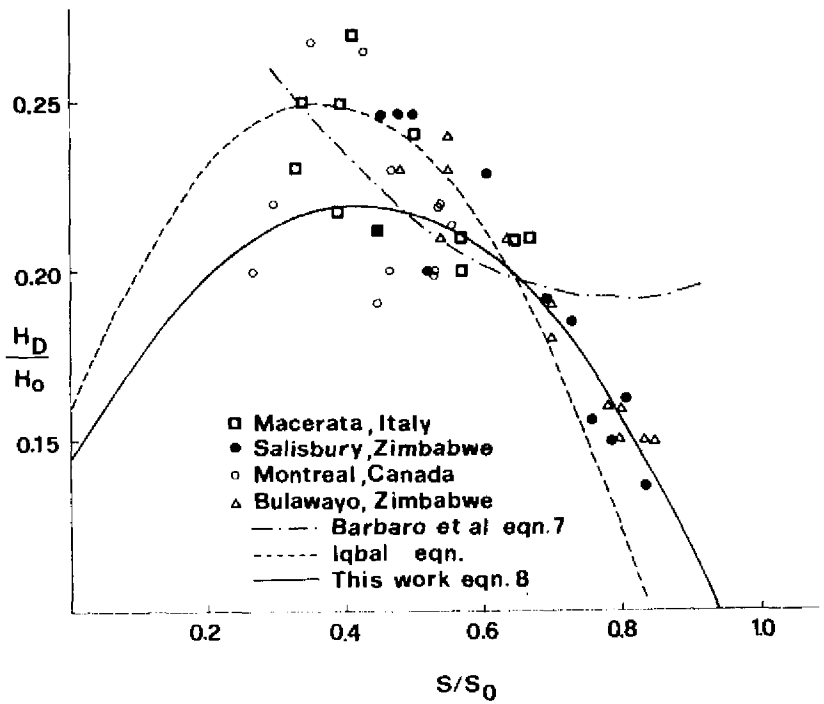

0.25
0.20
0.15
$\frac{H_D}{H_o}$
0.2
0.4
0.6
0.8
1.0
S/S_0
Macerata, Italy
Salisbury, Zimbabwe
Montreal, Canada
Bulawayo, Zimbabwe
Barbaro et al eqn. 7
Iqbal eqn.
This work eqn. 8

Fig. [illegible]