Journal of Engineering Science and Technology
Vol. 13, No. 7 (2018) 2181 - 2194

PREDICTING DAYLIGHT ILLUMINANCE IN URBAN CITY USING STATISTICAL REGRESSION TECHNIQUES

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Abstract

Prediction of daylight illuminance has become the prime concern for building designers. This paper presents the daylight illuminance frequency distribution, correlation coefficients amongst climate variables and linear regression models developed for moderate climate zone. The emphasis of the present study is to predict daylight illuminance intensities and to investigate its relationship amongst the important climatic variables such as temperature, percentage sky clearance and percentage relative humidity at specific timings of the day, observed during different climatic conditions and seasons. The daylight illuminance data is collected with the help of digital 'Lux' meter across the Pune city (India). The daylight illuminance frequency distribution, correlation coefficients and the linear regression models derived for four climate specific months are presented and explained. The minimum illuminance level of 6260 Lux is observed at 8.00 am whereas the maximum is 147300 Lux at 12.00 noon in the month of July and the highest frequency of illuminance intensities falls in the range 140000-145000 Lux. A better association (positive) of illuminance intensities has been observed with percentage sky clearance variable; the correlation coefficients in the month of July are 0.678, 0.656 and 0.453. The percentage error between predicted and measured values of daylight illuminance levels derived from the developed regression models varies from 4.47% to 12.33%.

Keywords: Correlation coefficients, Daylight illuminance, Frequency, Regression models, Relative humidity, Temperature.

1. Introduction

Daylighting is an interesting topic in building designer community, researchers, engineers and policy-makers; directly associated with productivity, occupant health and reduction of electrical energy in buildings and also a prime component of passive building design [1, 2]. Daylighting is used as an important component for constructing energy efficient buildings; also enhances greener building development [3]. Building designers have to consider the daylighting potential of the location. Environmental changes, occupant expectations, and technological changes have created opportunities and challenges for developing smart townships and cities [4]. All citizens desire good natural lighting in their living environment [5]. Daylight illuminance intensities are neither uniform nor constant and vary from location to location; quantity and quality of daylight changes due to variation in sky conditions. India is a tropical country, extreme climatic conditions occur in many places. Variation in the intensities of climate variables occurs throughout the country [6]. Daylight is available in abandon quantity at some of the geographical areas of the country; an average 3000 to 3200 hours of bright illumination is observed in a year over western part of India [7]. Lam and Li [8] developed a correlation model to predict diffuse components from solar radiation derived for the three different sky conditions. This model performs better with the mean bias error (MBE) ranging -0.45 to 0.82% and root mean square error from 7.76 to 14.86%. Cucumo et al. [9] compared correlations of global and diffuse luminous efficacy with different models and experimental data to predict efficacy for all sky types. They observed that a local variation of the atmosphere characteristics is the main reason for the difference between global and diffuse efficacy values.

Joshi et al. [10] estimated hourly exterior daylight illuminance levels using daylight models of solar radiation and calculated the average values of luminous efficacies on horizontal and sloping surfaces. The average values of luminous efficacy were observed to be 115.0 lm/W (diffuse) and 101.0 lm/W (global); indicates that the diffuse component in daylighting design is more important. Singh and Garg [11] used Perez models to estimate illuminance; ADELINE 3.0 software was adopted for the computation of savings from lighting energy. They observed that the energy saving due to daylighting increases when the window (reflective) visible transmittance value is low (0.07) and it remains constant with a high transmittance value (0.78).

Researchers have developed various sky luminance distribution models which require data of global and diffuse illumination. Sokol and Ardeshir [12] presented a simple luminous efficacy model to obtain values of external horizontal illuminance. They considered clearness factor, humidity ratio and solar altitude for developing the model. Others recommended CIE (International Commission on Illumination) model, Perez et al. and Igawa models to find daylight levels. An all-weather model (based on the CIE standard clear sky formula) was developed and evaluated by Perez et al. for deriving luminance values also evaluated six other models [13].

Li et al. [14] presented luminous efficacies studies for the various standard skies, an approach has been suggested to estimate luminous efficacy and daylight illuminance on the inclined surface; developed a luminous efficacy model of measured illuminance and irradiance data. Patil et al. [15] carried out an outdoor daylight assessment for six Indian cities, presented an experimental validation of the empirical model. The model derived global illuminance values are very close to measured illuminance. The MBE was -8.65%, 0.3%, 3.87% and 7.89% for the north, south, east and west surface respectively. Li [16] presented a review of illuminance levels measurements, development of daylight prediction model for different sky conditions and the daylight-linked lighting energy reductions. Li et al. [17] present a review of different approaches to determine daylight factor and daylight metrics; proposed techniques to simplify the mathematical procedures to estimate interior daylight for unobstructed and obstructed skies.

In India, daylight illuminance data are not available for most of the locations; therefore, in this work, measured daylight illuminance data is used. The main object of this work is to predict daylight illuminance intensities for different climatic seasons and specific time periods.

1.1. Description of case study

The work presents the case study of Pune city; recently converted as the metropolitan city of India and included in the list of smart cities by Government of India. As per the ESR (2016) of Pune Municipal Corporation, the geographical area is 250.56 km^2, located between 18° 32' North latitude and 72° 51' East longitudes, having an altitude of 560 m above mean sea level, receiving 770 mm of rainfall (refer to Fig.1). Pune city limits are expanding rapidly due to migration and other reasons; many new multistoried residential buildings (townships) are being constructed in and suburban area. Increased population demands number of housing units to accommodate the people.

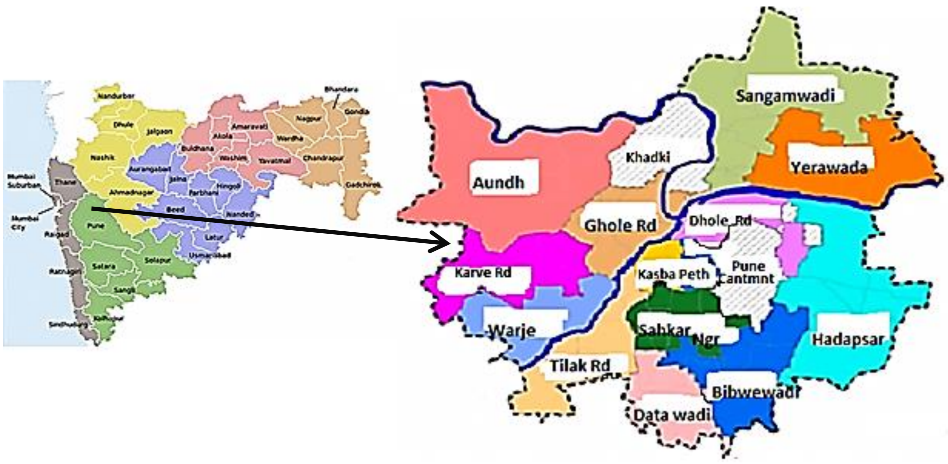


Fig. 1. Location and map of Pune city [18].

In the present work, daylight illuminance frequencies are worked out for the climate-specific months and discussed in subsequent sections. Frequency studies will be helpful to understand the range, occurrence, and potential of daylight illuminance intensities. The work also highlights the correlation and regression analysis of the climatic variables for Pune city; regression models have been developed to predict daylight illuminance intensities at specific time periods and climatic months.

1.2. Climate of Pune city

Pune falls under the moderate climate zone as per IMD. In general, the climate is healthier. The period from November to February is considered as winter followed by the summer ending up to early June. Monsoon starts from early June to the beginning of October and extends up to November is post monsoon. From March, temperature increases rapidly until April or May (hottest months). The days are usually hottest in April (36º C or 39º C) but nights are warmer during May or June than in April (23º C or 24º C). The day temperature in early June (start of monsoon) drops rapidly but nights are warm with increased humidity of monsoon air. The day temperatures increase slightly after the monsoon (September and October) period but the nights are cooler. Generally, the sky conditions are overcast or heavily clouded in monsoon and mostly clear or lightly clouded in the rest part of the year [19].

2. Database and Methodology

The data of daylight illuminance are measured from field survey across Pune city; daylight illuminance intensities are measured with the help of digital 'Lux meter' and other hourly climatic data such as 'Temperature, percentage relative humidity and total amount of clouds (*TC*) data' are obtained from India Meteorological Department, Pune. The methodology is presented in Fig. 2. The total amount of clouds consists of an amount of low cloud, medium cloud and high cloud. Percentage sky clearance is worked out from the total amount of clouds.

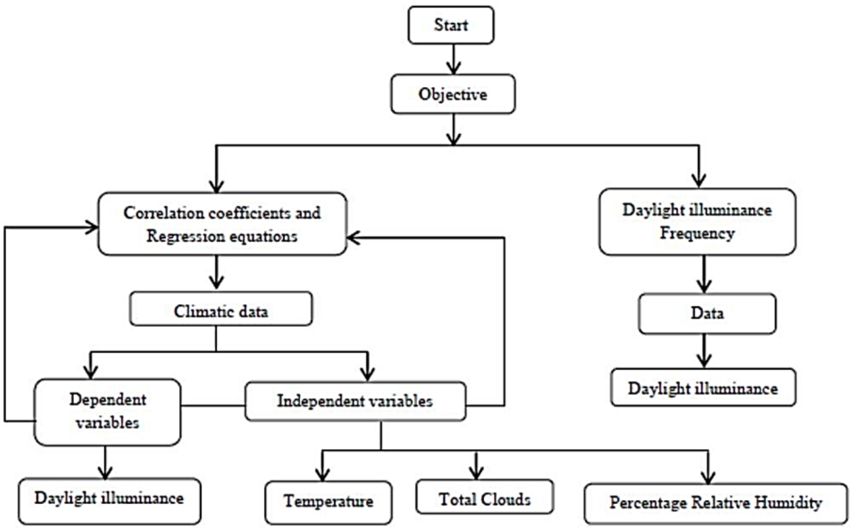


Fig. 2. Flow chart.

For example, if the total amount of cloud is 3 Oktas,

then, percentage sky clearance $=100-\left[\left(\frac{3}{8}\right)\times 100\right]=100-37.5=62.5\%$

The daylight illuminance intensities in Pune city (moderate climate zone) are observed by the first author during February 2015 to February 2016 daily at specific time periods, that is at 8.00 a.m., 12.00 noon and 4.00 p.m. In the present work, an analysis of February, May, July and December months are presented and discussed. There is total about 1308 datasets have been used in this work. The data for illuminance, temperature and sky clearance factor is arranged according to days and timings of the corresponding months. In the correlation and regression analysis work, temperature, percentage sky clearance factor and percentage relative humidity are considered as independent variables while daylight illuminance level is considered as the dependent variable. Separate correlation coefficients are worked out between daylight illuminance levels and temperature, between illuminance and percentage sky clearance factor. These coefficients are presented in Tables 1 and 2. The relation between dependent and independent variables have been analysed and established using Karl Pearson's (Eq. 1) technique of correlation of coefficient (r).

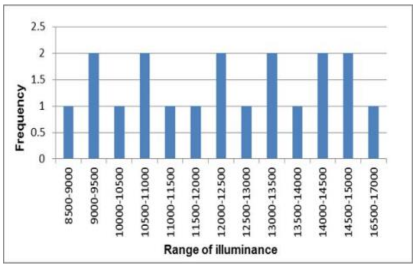
$$r = \frac{\Sigma xy - \frac{\Sigma x \Sigma y}{N}}{\sqrt{\left(\Sigma x^2 - \frac{(\Sigma x)^2}{N}\right)\left(\Sigma y^2 - \frac{(\Sigma y)^2}{N}\right)}} \quad (1)$$

where, 'r' refers to the coefficient of correlation between 'x' and 'y' variables (independent and dependent), and 'N'denotes the number of observations.

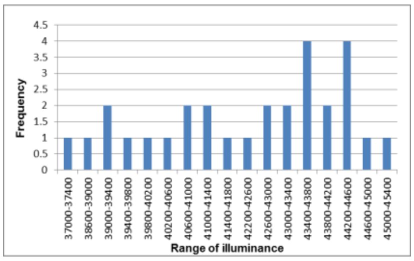
Frequency distribution of daylight illuminance

Following Fig. 3 presents the frequency distribution of daylight illuminance intensities of different climatic months and time periods. The intention is to know the potential, range and frequency of occurrence of these illuminance intensities. The measured daylight illuminance (diffuse) data is used in this work. The horizontal scale of the diagram represents the range of illuminance and the vertical scale is frequency.

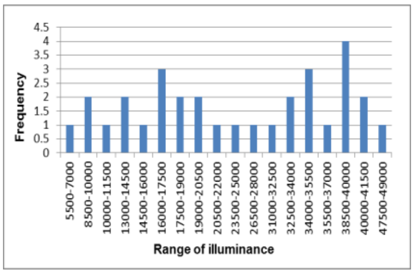
Figures 3(a) to (d), indicates the variation of frequencies of illuminance intensities in different months at 8.00 am. In the beginning of summer season (February), the skies are mostly cleared; the range is 8000-17500 Lux; 46 percentage frequencies of illumination intensities within corresponding range occur twice and 54 percentage occur one time. In May (peak summer), the temperatures are high up to 40 degrees Celsius with bright sunlight along with heat, the illuminance intensities at all time periods are more as compared to other months, it ranges from 36600-45400 Lux, the illuminance levels are nearly four times more as compared to February. In May, illuminance intensities having single frequency occurs 9 times (53 percentage), frequency 2 occurs 6 times (35 percentage) and the frequency 4 (maximum) with illumination range, that is 43400-43800 Lux and 44200-44600 Lux occurs two times (12 percentage). In the month of July, combinations of sunny, cloudy and rainy days are observed. The range of illumination is comparatively good; it ranges from 5500-49000 Lux, illuminance intensities decreases due to the presence of clouds. Fifty percentage of illumination range frequencies occur nine times, 34 percentage (frequency 2) occurs six times, frequency three appears two times (11 percentage) and highest frequency of range 38500-40000 Lux occurs one time (5 percentage) in the corresponding month. In winter (December) season the days are mostly sunny, the illuminance intensities vary from 9500-13750 Lux, which is similar to February to some extent. In this month, the illumination ranges having frequency one appears seven times (47 percentage), frequency 2 and 3 appears three times (40 percentage); frequency 4 and 5 appears once (13 percentage).



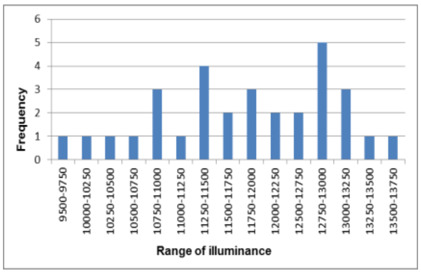
(a) February.



(b) May.



(c) July.

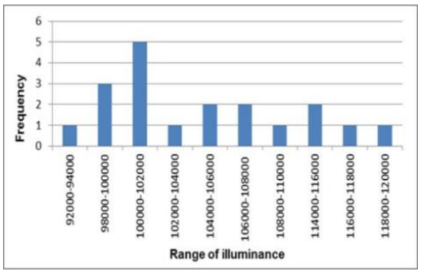


(b) December.

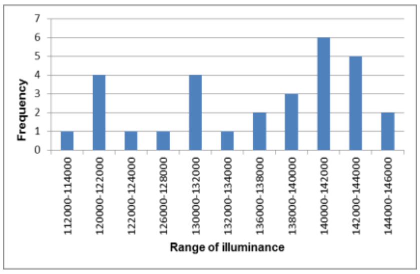
Fig. 3. Frequency curves at 8.00 a.m.

Figures 4(a) to (d) indicates the illuminance levels at 12.00 noon, the intensities vary from 92000-120000 Lux, 112000-146000 Lux, 250001-50000 Lux and 76000-116000 Lux in February, May, July and December months respectively. Amongst these values, the illuminance intensities are maximum in the month of May followed by February, which is the illuminance intensities increases from February month. In April and May months, the heat component is more predominant along with illumination in solar radiation; most of the days in these months are sunny. In these months, the illuminance intensities are maximum at this period as the solar radiations are perpendicular to earth; daylight illuminance decreases rapidly after 4.00 pm.

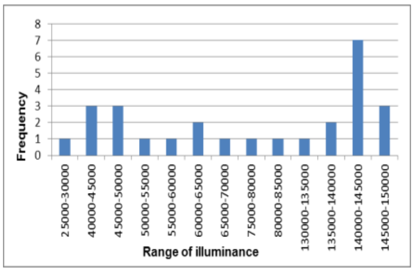
In February, ten percentages of the illuminations between the ranges of 100000-102000 Lux (maximum) occurs five times similarly ten percentages of illuminations between 98000-100000 Lux occurs three times in a month. Thirty percentage illumination intensities occur two times and fifty percentages of illuminance intensities in the corresponding range occur once in a month; the highest illuminance intensity occurs once.



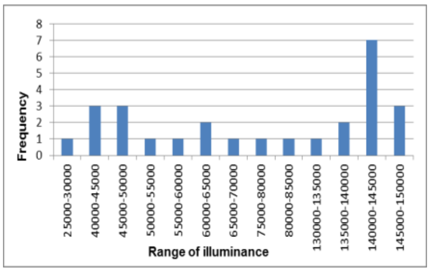
(a) February.



(b) May.



(c) July.



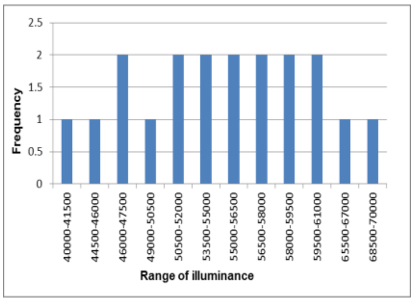
(d) December.

Fig. 4. Frequency curves at 12.00 noon.

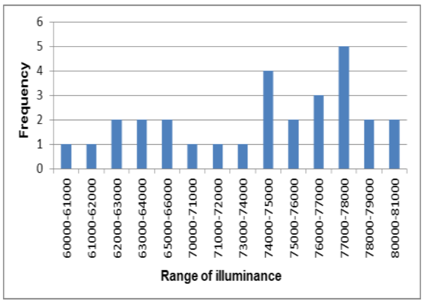
In May, nine percentages of illuminance values between 140000-142000 Lux and nine percentages intensities between 142000-144000 Lux appears six and five times respectively in a month. Eighteen percentages of illumination intensities occur four times. Illuminations (nine percentages) between the ranges of 138000-140000 Lux occurs three times. Similarly, the maximum illuminance intensities occur two times between 144000-146000 Lux and two times between 136000-138000 Lux (eighteen percentages each). Thirty- six percentages of illuminance values occur once in a month; high illuminance values of daylight levels are available for the maximum duration of a month. In July month, mostly the sky conditions are cloudy; intensities are reduced due to the presence of clouds.

Though there are high illuminance intensities are observed up to range of 145000-150000 Lux; the highest illuminance level observed is 147300 Lux. Eight percentage illuminance values occur seven times in between 140000-145000 Lux whereas fifty-four percentage daylight levels occur once in a month and twenty-three percentage intensities occur three times. The minimum illuminance range is as low as 25000-30000 lux; a minimum intensity of daylight illuminance of 27900 Lux is observed under clear sky condition. In rest part, illuminance intensities are fairly good as Pune belongs to moderate climate zone. December month is considered as the typical month of the winter season, the illuminance intensities are fairly good in this month at 12.00 noon. The highest frequency (four) occurs between ranges 92000-94000 Lux, 96000-98000 Lux and 100000-102000 Lux, contributing twenty-three percentage levels. Fifteen percentage values between 86000-90000 Lux occur three times in a month. The maximum percentage (thirty- nine) of illuminance intensities occurs once only. Twenty- three percentage of illuminance intensities between 90000-92000 Lux, 94000-96000 Lux, and 98000-100000 Lux occur twice.

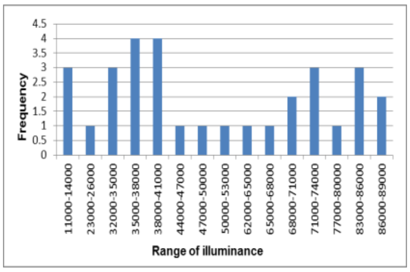
It is observed from the above Figs. 5(a) to (d) that in February, the frequency is constant in the initial period (40000-46000 Lux), then it increases to two between the range 46000-47500 Lux and further decreases to one. The frequency remains constant from 50500 Lux up to 61000 Lux; maximum values of illuminance levels appear in this range. Fifty percentage daylight illuminance intensities occur two times, forty-two percentage intensities occur one time and eight percentages (minimum) occurs two times. The highest value of illuminance in this month is observed as 68800 Lux whereas in May it was 80700 Lux, it means the intensity in May is increased by 11900 Lux. The lowest value in February is 40200 Lux and in May, it is 60700 Lux, which is the intensity is more at 20500 Lux in May. Seven percentages of illuminance intensities between the ranges 77000-78000 Lux occurs five times, seven percentages between 74000-75000 Lux occurs four times, thirty-six percentages occur once and forty- three percentages of illuminance intensities occurs two times in May. In the month of July, the lowest illuminance level is 11280 Lux under the cloudy conditions and the maximum value under clear sky conditions is 87800 Lux, which is more than May month's value.



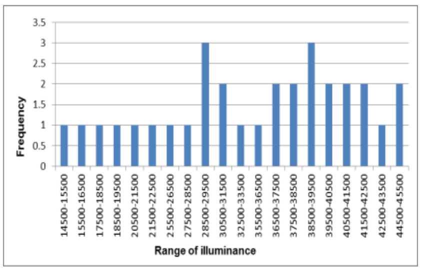
(a) February.



(b) May.



(c) July.



(d) December.

Fig. 5. Frequency curves at 4.00 p.m.

The maximum frequency of illuminance falls between 35000-41000 Lux contributing thirteen percentages, twenty- seven percentages of illuminance intensities occurs three times and forty- seven percentages occur once. The highest intensity between 86000-89000 Lux occurs twice in this month. In December, the frequencies are constant from 14500 Lux up to 28500 Lux, highest percentages (fifty-five) occurs once. The percentage contributions of frequency two and three illuminance intensities are thirty-five and ten respectively; high illuminance intensity occurs in this range. The minimum illuminance intensity of 14520 Lux under the cloudy conditions and maximum 45400 Lux under clear sky conditions have been observed during the month.

3. Correlation Analysis

Tables 1 to 3 presents the correlation coefficients between temperature (*T*), the total amount of clouds (*TC*), percentage relative humidity (*RH*) and daylight illuminance intensities during three periods of the day. Four climate specific months, that is Feb, May, July and December of the year 2015 are considered and analysis is presented. The climatic data has been procured from IMD; daylight illuminance intensities are observed by the author at 8.00 a.m., 12.00 noon and 4.00 p.m.

Table 1 indicates the correlation between temperature and daylight illuminance intensities. In February, the correlation between variables at morning (r_1) and evening is positive but poorly correlated at morning period as compared to the evening period (4.00 p.m.). In the afternoon period (r_2) the association is poorly correlated in a negative sense that is the variables are inversely proportional to each other. It indicates that the rise in temperature does not increase illuminance intensities. The correlation in May (peak summer) month is also poorly correlated though illuminance and temperature intensities are higher; it indicates that the rise in temperature does not increase daylight illuminance levels. July month presents a very good and strong positive association between variables, as the values are more than 0.7 at all time periods. It clearly shows that the rise in temperature will lead to an increase in illuminance levels. In December month (peak winter), the illuminance levels are low in morning and evening period because of the presence of fog. The temperatures are also low in December month. The association between variables is negative at morning (r_1) and evening period (r_3); it means variables are inversely proportional to each other. In the afternoon period, the illuminance level is better due to the absence of fog; in the afternoon period (r_2) the correlation is positive and poor. After observing all the correlation coefficients, the relation between variables (temperature and daylight illuminance) is positive and negative but not strongly correlated except July month.

Table 1. Correlation coefficients (*r*) between temperature and daylight illuminance.

Month	r_1	r_2	r_3
February	0.312	-0.241	0.447
May	0.257	0.205	-0.30
July	0.734	0.828	0.728
December	-0.411	0.221	-0.126

Cloud cover is recorded and measurements are carried out by skilful observers; expressed in Oktas. In Table 2, the total amount of clouds is used; the presence of the cloud decides the amount of solar radiation received by the earth. Above table presents the association between daylight illuminance intensities and percentage sky clearance. It is observed that the correlation coefficients are positive in all the climactic months and time periods. The correlation is very strong in February during afternoon and evening period except for the morning period. July month coefficients are also good at morning and afternoon periods. The association in May month is better at morning (0.492) compared to afternoon and evening periods.

Table 2. Correlation coefficients (*r*) between percentage sky clearance and daylight illuminance.

Month	r_1	r_2	r_3
February	0.294	0.852	0.651
May	0.492	0.396	0.413
July	0.678	0.656	0.453
December	0.211	0.114	-0.206

It is observed from Table 3, that most of the correlation coefficients are negative except for May and December during the afternoon time period. Since the coefficients are very poor (0.036 and 0.051) it indicates that there is no relation at these timings. In May, at mid-day (12.00 noon), the relative humidity is minimum as compared to morning and evening periods. In December, the negative relation shows that the variables are inversely proportional to each other; it means the rise in the percentage relative humidity decreases corresponding daylight levels. The correlation is strong in the month of July and in February during the evening time period (-0.618).

Table 3. Correlation coefficients (*r*) between percentage relative humidity and daylight illuminance.

Month	r_1	r_2	r_3
February	-0.181	-0.346	-0.618
May	-0.310	0.036	0.465
July	-0.643	-0.836	-0.677
December	-0.325	0.051	-0.153

4. Regression Equations

Regression equations to predict daylight illuminance intensities at various time periods and months are developed and presented in Tables 4 to 6 respectively. The variables used are temperature, percentage sky clearance and percentage relative humidity etc. in the respective tables. Daylight illuminance values can be estimated from the appropriate model for the corresponding time. Different models represent different climate seasons that are February, May, July and December.

Table 4. Regression equations between temperature and daylight illuminance [Model 1].

	8.00 a.m.	12.00 noon	4.00 p.m.
Feb	$y=284.75x+6550$	$y=-1486x+145987$	$y=1706.73x+1332$
May	$y=1271.85x+4528$	$y=1818x+68147$	$y=-780.76x+101052$
July	$y=8197x-183250$	$y=21735x-517809$	$y=8123.47x-174082$
Dec	$y=-160.55x+15068$	$y=-50.61x+95746$	$y=-542.26x+48523$

Table 5. Regression equations between percentage sky clearance and daylight illuminance [Model 2].

	8.00 a.m.	12.00 noon	4.00 p.m.
Feb	$y=93.45x+2896.67$	$y=660.35x+39191$	$y=351.13x+22165$
May	$y=135.44x+31355$	$y=278.08x+108893$	$y=105.52x+65071$
July	$y=470.26x+14557$	$y=2227x+43309$	$y=836.80x+35895$
Dec	$y=9.08x+11258.56$	$y=32.37x+860.53$	$y=-73.48x+37867$

Table 6. Regression equations between percentage relative humidity and daylight illuminance [Model 3].

	8.00 a.m.	12.00 noon	4.00 p.m.
Feb	$y=-47.75x+15706$	$y=-377x+117835$	$y=-1255x+81562$
May	$y=-131.08x+48534$	$y=54.78x+130036$	$y=263x+64793$
July	$y=-1000x+107383$	$y=-3563x+343779$	$y=-1278x+143693$
Dec	$y=-54.25x+17287$	$y=197.54x+80969$	$y=-438x+47556$

4.1. Sample of calculations to predict daylight illuminance levels

Sample calculations for the different climatic variables considered in the present work are worked out separately. For different climatic months and periods, the corresponding equation can be used.

4.1.1. For temperature

Sample calculation of 25 May 2015 date is presented. May is considered as a peak month of summer. The actual temperature intensity (at noon) in Pune was 32.2 deg. C (as per IMD data) on this date. The value of daylight illuminance obtained from the developed regression equation of May month is 126686 Lux whereas the observed intensity of illuminance is 144500 Lux. It means that the result is 87.67% correct; the percentage error is 12.33%.

4.1.2. For percentage sky clearance

The sky clearance of 6 July 2015 is considered. On this date, the *TC* was 4 Oktas (IMD) at noon as per IST. Hence, percentage sky clearance=100-[(4/8)×100]=100-50=50.00%. Therefore, using the second equation of July (monsoon) month, the value of daylight illuminance obtained is 154659 Lux whereas the observed value of illuminance is 139900 Lux. It indicates that the result is 89.45% correct; the percentage error is about 10.55%.

4.1.3. For percentage relative humidity

Calculating daylight illuminance on 23 May, 2015, the percentage relative humidity is 70% as per IMD. Therefore, using the first equation of May $y=-131.08x+48534$, the daylight illuminance intensity is 39358 Lux whereas the observed was 41200 Lux. The result shows an error of 4.47%.

Above calculations indicate that these equations can be used for predicting daylight illuminance intensities for moderate climate zone.

5. Conclusions

It is difficult to predict daylight illuminance intensity due to weather change; the fluctuations become more significant under partly cloudy conditions. Frequency distribution of daylight illuminations indicates the range and occurrence of respective illuminance levels in different months and time periods. Attempts have been made to correlate daylight with different climatic (*T, TC, RH*) variables.

In the month of July (monsoon season), a good amount of illuminance intensity is observed under clear sky condition. The results obtained in Table 2 are showing better association as compared to Table 1, that is the daylight illuminance intensities are much dependent on sky clearance factor (cloud coverage). Correlation between daylight illuminance and temperature variables is positive and strong in the month of July; the coefficients are 0.734, 0.828 and 0.728 (Table 1) at morning, afternoon and evening periods respectively. In other months, the association is not strong; it is negative in certain months. Solar radiation is significantly affected due to the presence of clouds; all the correlation coefficients are positive. In July, most of the days are cloudy, the coefficients are 0.678, 0.656 and 0.453. It means, the correlation is good in morning and afternoon periods as compared to evening. Similarly, a strong positive correlation is observed in the month of February (0.852 and 0.651) at afternoon and evening periods whereas correlation in December (0.211, 0.114 and -0.206) is very poor. It is observed that relative humidity and daylight illuminance intensities (Table 3) are inversely proportional to each other. Most of the correlation coefficients are negative; the strong coefficients (negative) are observed in July, that is -0.643, -0.836, and -0.677 whereas it is very poor in other months.

Such data (daylight illuminance) is not available for the Pune city; these studies are essential. Proposed regression models provide a viable alternative to actual field measurements. Regression equations derived in this work are based on the measured daylight illuminance data in Pune, it is expected that these equations can be used to predict daylight illuminance intensity for similar climatic locations. The results obtained through regression equations are showing 90.00% accuracy. With rapid building development in Pune, these models would be of use to building designers and architects in the daylighting design of buildings.

Nomenclatures

N	Number of observations
RH	Relative Humidity
r	Karl Pearson’s coefficient of correlation
r_1	Correlation coefficients at 8.00 am
r_2	Correlation coefficients at 12.00 noon
r_3	Correlation coefficients at 4.00 p.m.
SC	Sky clearance
T	Temperature in deg. C
TC	Total amount of clouds in Oktas
x	Independent variables
y	Dependent variables
%	Percentage

Abbreviations

ESR	Environmental Status Report
IMD	India Meteorological Department
IS	Indian Standard Code
IST	Indian Standard Time

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