Review of Methods for Estimating Urban Surface Roughness

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ABSTRACT

Growing urban population is rapidly changing the roughness of today's cities and greatly influencing the urban climate. Two methods of roughness estimation, micrometeorological and morphometric methods are used by researchers. Micrometeorological methods require extensive setup of filed instruments which is costly and quite unfeasible in urban areas. However, morphometric based method uses geometry of urban roughness elements, which can be easily determined with the use of high resolution remote sensing data sets. The computation of roughness parameters is easier than before due to increasing computation capabilities in GIS domain. Hence, morphometric methods holds a promising future for understanding urban climate.

Keywords: *Urban climate; Urban Roughness; Morphometric; GIS; Remote Sensing*

1. Introduction

Today, 54 % of the world's population is living in urban areas and it is expected to reach 66% by 2050, of which 90% increase is projected in Asian and African countries (*Source: www.un.org*). The complete urban geometry is changing and there is an increasing trend of high-rise structures to accommodate this growing population. This upward change in urban roughness alters microclimate patterns in urban areas. Understanding surface roughness is of worldwide interest and their estimation can be utilized to study some important urban phenomenon like detection of urban ventilation paths, dispersion modeling and heat flux exchange in an urban area. Several parameters have been suggested for overall estimation of urban roughness such as Zero-Plane Displacement Height (z_d) , Roughness Length (z_o) (Lettau, 1969), Plan Area Density (λ_p), Frontal Area Index (λ_f) (Grimmond and Oke, 1999; Burian et al.,2002,Wong et al., 2010)**,** Frontal Area Density (Yaun et al., 2014),Depth of the Roughness Sub-layer (z_r) (Bottema, 1997; Grimmond and Oke. 1999)and the Effective Height (h_{eff}) (Matzarakis and Mayer,2008) etc. The displacement height (z_d) and roughness length (z_o) are considered as key parameters in the logarithmic velocity profile and are commonly used in many models to specify the boundary conditions above built-up areas (Burian et al, 2002). Another important parameter is Frontal Area Index and has a strong relationship between Surface Roughness (z_o). Frontal area index is suggested as a good indicator for mesoscale meteorological and urban dispersions models (Burian et al., 2002).

History of roughness estimation goes well back to 1930's when Nikaradse (1933), studied the flow of fluid inside pipes which roughened with grains of sand and derived the relationship of the roughness length ($z_{0)}$ with roughness height. Later Jensen's (1958), Ariel and Kliwchnikova (1960) and Hanna (1969) made their contribution to surface roughness evaluation however some of these studies lacked inclusion of zero plane displacement height and for some studies like that of Jenson(1958), surface length of study area (Copenhagen) was abnormally high. However the more recent studies (Dong et al., 1992; Blumberg and Greeley, 1993) question the approach used by Nikaradse (1933) as according to them the urban surfaces are much more complex and surface attributes and topography also needs to be considered for estimation of roughness parameters. Studies on aerodynamic parameters, $z_0$and$z_d$for urban areas with varying geometry conditions have been carried out through various methodologies, including wind tunnel experiments and numerical simulations for several decades (Zaki et al., 2014). From then, till today a lot of advancements have been made in the estimation of roughness parameters that includes technological and methodological advancements and also there has been a considerable increase in the number of parameters that are today used to denote roughness of an urban area (Burian et al., 2002). Methods to estimate roughness parameters can be broadly categorized under two categories: Micrometeorological (Anemometric) and Morphometric (Geometric) (Grimmond and Oke, 1999). The methods has their advantages and disadvantages. Hence, this paper attempts to review the methods, their pros and cons and applicability in urban areas.

2. Micrometeorological Methods

Micrometeorological method depends largely on extensive in-situ measurements which includes observations of wind direction and speed at different heights. Later, this field data is used for computations using log-law on which micrometeorological methods usually depend.

$$\text{Log Law: } \frac{u(z)}{u} = \frac{1}{k} ln \frac{z - z_d}{z_0} \quad (1)$$

Here u(z) is averaged wind speed at height z, u is frictional velocity, k is von Karman's constant and z_d and z_o are zero-plane displacement height and roughness length respectively. This method requires large amount of field data for whichobservation towers need to be installed (Gal andSumeghy, 2007).

Studies using field observations to examine the upper and lower atmosphere for the wind profile dates back to 100 years(Roth,2000). The first documented measurement of urban turbulence was performedin October 1946 from the tower of Central Meteorological Observatory, Tokyo (Roth, 2000). These early studies focused on the upper higher layer while studies starting from early 1970's concentrated on the lower atmosphere. To take field observations many approaches were used such as measurements on Eiffel tower (Taylor,1918), meteorological towers (Shiotani and Yamamoto,1950), TV towers (Soma,1964; Arakawa and Tsutsumi, 1967), hot air balloons (Angel et al. 1974), and helicopters (McCormick and Kurfis, 1966; Taylor, 1918).

Jones et al.(1971) used a captive baloon to take measurements 1000 ft. above two urban areas and established a relationship between velocity profile index and lapse rate. Marullaz (1975) used 60 m high masts in Nantes, France and these measurments further used in Davenport(1963) emphirical law to determinevariation of mean wind speed. The roughness values computed were found to be very high. The equation proposed by Marullaz (1975) was as follows:

$$\frac{u(z)}{u(z_1)} = \left(\frac{z}{z_1}\right)\alpha \qquad (2)$$

Here u(z) is mean wind speed at z altitude and $u(z_1)$ is mean wind speed at z_1 altitude and α is roughness.

Ackerman and Hildehrand (1978) used aircraft to measure turbulances and fluxes at three different heights and Oikawa and Meng (1995) conducted field measurements using ultrasonic anemometer within and above urban canopy in Sapporo, Japan. Extensive measurements of wind structure over a particular site were recorded and results led to roughness length half the mast's height.

Site charactristics are very important for roughness value estimationusing micro meteorological methods (Wieringa ,1992 and Bottema ,1997) , which requireterrain to be flat , tower construction should be slender and open enough to avoid wake interferences, instruments must be equipped to accurately measure wind and turbulance measurements, measurement height must be above roughness sublayer but low enough to be in an adjusted boundary layer. Atleast three levels for recommended for measurements, which should allow sampling into mean values over a period of time, should be neutral to or should be atmospherically stable and there should be inclusion of zero plane displacement. Different methods were used to determine the range of values that could be estimated using commonly accepted methods for estimating surface roughness length. Along with surface roughness length, the displacement height (z_d) was also estimated. However most of the early studies lacked consideration of displacement length (z_d) which led to large values of z_0. This was very effectively proved by Hanna(1969) in the reanalysis of Ariel and Kliwchnikova (1960). Grimmond and Oke (1999) applied the criterias adapted from Wieringa (1992) and Bottema (1997) to 60 field studies and surprisingly only 9 could pass the test. Majority of studies failed due to non inculsion of z_d and high value of z_0.

Lettau (1969) also discussed various problems that micrometeorological applications deal with, one of them was the masts used for measurements were itself acting like a roughness element. The determination of roughness values using wind profile measurements is troublesome as the instrumental errors need to be eliminated and major problem arises when the true reference point log law is not known in prior, making determination of Z_d in addition to Z_0.

Besides, micrometeorological methods required an exhaustive site prepration and extensive setup of observation towers for taking wind measurements. The application of these methods for estimation of roughness values is limited only to few points in an urban area , underrepresenting the large variability present in urban areas. The urban areas are often not suitable for installing observation towers as per the site requirements and also requires under canopy realization of wind dynamics. Besides, the installation of a large number of towers in urban areas to capture the high variability requires extensive and costly setup of observation towers. Micrometerological methods are most accurate and no other method can surpass them in terms of accuracy however due to the constraints of execution and cost involved, they are not extensively used in urban areas.

3. **Morphometric Methods**

The estimation of Roughness parameters to a great extent depends on the shape, size, density and height of the roughness elements (Grimmond and Oke, 1999). This is equally proved by the various wind tunnel studies, numerical methods and analytical methods (Wieringa, 1992;Bottema 1995a,1995b, 1997).

Morphometric methods are based on the morphology of urban area anduse height and density of urban structures for calculation of roughness parameters (Bottema,1997) ,however the sophisticated methods of determining urban roughness make use of many other parameters including frontal area index, height, width and density of roughness elements (Grimmond and Oke. 1999). Morphometric methods have the advantage that values can be determined without the need of tall towers and instrumentationand high cost of investment. Table 1lists various morphometric parameters used by researchers to compute urban surface roughness.

3.1 Wind tunnel studies

Marshall (1971) used a homogeneous array to estimate roughness values using computed values of frontal area of the roughness elements.Counihan(1971) used following relationship using the area of interest and roughness elements to estimate roughness length using velocity profiles and measured cubic elements in a wind tunnel.

$$z_0 = h^* \left[1.08 \frac{A_r}{A} - 0.08\right]$$

(3)

Here A_r is total plan area of roughness elements, A is area of interest and h^* is average height of roughness elements

Raupach (1994) estimated roughness values for a vegetated area based on the canopy height(h) and area index (A). He analysed the behavior of z_0/h with roughness density where roughness elements were of varying heights.Macdonald (1998) analysed the methods used by Lettau (1969), Counehan (1971) andRaupach (1994) and further used their fundamental priniciple to derive a new approch. Macdonald (1998) and Lettau (1969) used homogeneous array of roughness elements. Similarly Couhenan (1971) also tested his methods against homogeneous arrays in a wind tunnel. The method yeilds z_d and z_0 using the below mentioned equation:

$$\frac{z_d}{z_h} = 1 + \alpha^{-\lambda_p}\left(\lambda_p - 1\right) \quad (4)$$

$$\frac{z_0}{z_h} = \left(1 - \frac{z_d}{z_h}\right) exp\left\{-\left[0.5\beta \frac{C_D}{k^2}\left(1 - \frac{z_d}{z_h}\right)\lambda_F\right]^{-0.5}\right\} \quad (5)$$

where α is an empirical coefficient, C_D is a drag coefficient, k is von Karman's constant, and β is a correction factor for the drag coefficient (the net correction for several variables, including velocity profile shape, incident turbulence intensity, turbulence length scale, and incident wind angle, and for rounded corners), λ_p is plan aerial fraction, λ_f is frontal area Z_d/Z_h is height normalized value of zero plane displacement and Z_0 /Z_h is height normalized roughness length.

As discussed above, a number of empirical formulas have been used to compute the urban roughness parameters directly based on realtionships derived in wind tunnel studies. The major limitation to these methods are that they become computation intensive as study areasize increases. It is costly and almost impossible to test the model of whole urban area in wind tunnel.Besides, these methods are based on idealized flows such that the flows are constant in direction normal to the roughness elements and the array of elements is regular. However, these kind of situations are totaly different from real urban areas where roughness elements are in all shapes and also the wind direction is constantly changing (Grimmond and Oke. 1999).

3.2 Remote sensing and GIS based methods

With the advent of higher computation capabilities, advent of new technologies such that Remote Sensing, GIS and availability of 3D urban databases have led to an easy estimation of roughness values. However these recent techniques rely on the algorithms using drag force and force around buildings (Ratti et al.,2005).As height data for many urban areas is not available easily therefore many studies (Su et al.,2008; Tian et al.,2011; Wong et al.,2011; Schaudt and Dickinson,2000; Yuan et al.,2014) used remotely sensed data for estimation of roughness values of a urban area. Using remote sensing technologies such as photogrammetry and GIS, the height of urban features was estimated, then a detailed urban database was genetated which was further used to calculate urban roughness elements. However, some of the researchers (Burian et al.,2002; Ratti et al., 2005; Gal and Unger,2009; Wong et al.,2010) used existing 3D building datasets.

Burian et al. (2004) gave a comprehensivereview of various roughness parameters and also demonstrated calculation for the sample area of downtown Los Angeles, CA. 3D urban database, DEM and Land use/ Land cover data was used and analyzed in a GIS environment. Ratti et al. (2005) computed $\lambda_{f,}$ λ_p and Z_H using a Digital Elevation Model (DEM). Shadow casting and sky view factors were obtained using basic image processing techniques. Gal and Unger(2009) divided the study area of Szeged, Hungary in irregular polygons and applied modified Bottema(1995) equation for irregular building groups.The final results were achieved by developing a avenue script in ArcView 3.2 software by using the assign proximity function of the Spatial analyst module. Su et al.(2008) used high resolution ortho photos for deriving the height of urban structures in Vancouver, Canada. Land use regression models were used to finally compute urban roughness parameters. Wong et al. (2011) proposed a GIS based technique to investigate urban roughness along the coastof Kowloon peninsula of Honk Kong. Using a building database on a grid of 100m,urban structures were analysed and roughness values were computed. Later, using Least Cost Path (LCP) analysis on a GIS platform, ventilation pathways were found. Wong et al. (2011) also performed scenario analysis for validating the wall effect by removing the frontal building of the area. Table 2 lists various equations for computing different morphometric parameters used in different studies.

Today, extensive avaialabilty of sub meter resolution remote sensing data in 3D domain has opened up a new era where reserachers are generating large area 3D models and databases of urban areas. Apart from that , support for different programming and scripting language in various GIS platforms have changed the strategy adopted earlier for roughness parameter estimation. Extensive use of computer programming language to automate the task of urban roughness estimation which was once a computation intensive task is frequenty used by researchers today.Thie field holds a promising future as growing number of data availability and computation capabilities make it easier for generating the various parameters required (frontal area index , height , width and density of roughness elements) for compuation of roughness parameters.

4. Conclusions

The study of roughness elements in an urban area is vital and holds the key to the future urban climate researches. Micrometeorological methods for roughness studies are based on site measurements values and morphological methods use estimated values and empirical relationshipsfor computation of roughness values. Micrometeorological methods are one of its kind that use actual wind flow measurements using high end anemometers. The measured values go through numerical simulations to determine a roughness value that is most accurateamong values estimated by morphomatric methods. However, studies proved that micrometeorological studies require huge setup which requires a good amount of financial investment. Talking in context to urban studies the methods do not look feasible as installing towers and masts above the urban canopy layer is difficult to execute.

On the other hand, morphometric methods use estimated values and empirical relationships, hence it is less accurate as compared to micrometorological methods. Morphological methods use the underlying principle of wind tunnel experiments. Wind tunnel experiments assumed idealized flow of winds and also assumed the roughness elements to be of regular orientation. The assumptions of wind tunnel experiments vary completely when the roughness needs to be estimated for an urban area, where the wind flow is not idealized and roughness elements exist in all shapes and sizes. Howevre, morphometric methods do have there own advantages asthese methods do not require installation of towers, masts and high end devices for taking measurements hence finding there applicability in urban areas. Morphometric methods specially remote sensing and GIS based methods incurs less cost as compared to micrometeorological methods. Morphometric studies are alleviated by the use of thecurrent technologies that includes high end computation devices, remote sensing and GIS. These technologies have led to availability of three dimensional urban databases which can be very easily exploited for roughness parameter estimation. Among the morphometric method, the methods based on remote sensed data and GIS, have now surpassed the limitations of wind tunnel based methods. Now nonregular building arrays and non idealized flows can be equally considered. The methodology of execution of these methods is surely going to change with the use of satellite data, 3D database and inclusion of GIS based processing.

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Table1: Nomenclature of the Terminology used for different Morphometric Parameters

S. No.	Parameter	Parameter Description
1	$\bar{h}$	Mean Building Height
2	s_h	Standard Deviation of Building Height
3	h_i	Height of Building i
4	N	No. of Buildings
5	$\bar{h}_{AW}$	Mean Building Height
6	A_i	Plan Area
7	λ_p	Building Plan Area Fraction
8	A_p	Plan Area of Buildings at Ground Level
9	A_T	Total Plan Area
10	$a_p(z)$	Building Plan Area Density
11	Z	Specified Elevation Above Ground
12	z_{ref}	Logarithmic Height Range
13	Δz	Height Increment
14	$a_r(z)$	Roof Area Density
15	$L(z)$	Building Area Index
16	h_c	Canopy Height
17	λ_f	Building Frontal Area Index
18	A_{proj}	Area Projected to Wind
19	Θ	Wind Angle
20	$\bar{L}_y$	Mean Breadth of Roughness Elements
21	$\bar{H}$	Mean Roughness Element Height
22	ρ_d	Roughness Element Density
23	$A(\theta)_{proj(\Delta z)}$	Area Projected to Wind at Θ Direction at a Height Increment Z
24	a_f	Frontal Area
25	λ_C	Complete Aspect Ratio
26	A_c	Combined Surface Area of Buildings and Ground Exposed
27	A_R	Roof Area
28	A_G	Area of Exposed Ground
29	A_W	Wall Surface Area
30	λ_B	Building Surface Area to Plan Area Ratio
31	λ_S	Height to Width Ratio
32	H_1	Height of Upward Building
33	H_2	Height of Downward Building
34	z_d	Displacement Height
35	z_0	Roughness Length
36	f_d & f_0	Empirical Coefficients: f_d =0.5 & f_0 = 0.1, for Urban Areas
37	c_{d1}	Free Parameter (c_{d1}=7.5)
38	ψ_k	Roughness Sub Layer Influence Function
39	u_*	Frictional Velocity
40	U	Large Scale Wind Speed
41	c_s, c_r	Drag Coefficients; c_s=0.003, c_r=0.3
42	K	Von Karman's Constant (K=0.4)
43	α	Empirical Coefficient (4.43 For Staggered Array)
44	β	Correlation Factor for Drag Coefficient (1.0 for Staggered Array)
45	C_D	Drag Coefficient (1.2)
46	C_{dh}	Drag Coefficient Dependent On Obstacle Shape
47	S_{12}	Distance Between Building 1 And Building 2

Table 2: Equations for Evaluating Different Morphometric Parameters, Z_0 and Z_d

S. No.	Equation	Equation Definition	Equation Source
1	$\bar{h} = \frac{\sum_{i=1}^{N} h_i}{N}$	Mean Building Height	Burian et al. (2004)
2	$s_h = \sqrt{\frac{\sum_{i=1}^{N}(h_i - \bar{h})^2}{N-1}}$	Standard Deviation of Building Height	
3	$\bar{h}_{AW} = \frac{\sum_{i=1}^{N} A_i h_i}{\sum_{i=1}^{N} A_i}$	Average Building Height weighted by Building Plan Area	
5	$a_p(z) = \frac{\lambda_p(z)}{\Delta z}$	Building Plan Area Density	
6	$a_r(z) = \frac{A_p\left[z - \frac{\Delta z}{2}\right] - A_p\left[z - \frac{\Delta z}{2}\right]}{A_T . \Delta z}$	Roof Area Density	
7	$L(z) = \int_{z}^{h_c} a_r(z) dz'$	Building Area Index	
8	$\lambda_f(\theta) = \frac{A_{proj}}{A_T}$	Building Frontal Area Index	
9	$\lambda_f = \overline{L_y}\overline{H}\rho_d$	Building height characteristics	
10	$a_f(z, \theta) = \frac{A(\theta)_{proj(\Delta z)}}{A_T \Delta z}$	Frontal Area Density	
11	$\lambda_c = \frac{A_C}{A_T} = \frac{A_W + A_R + A_G}{A_T}$	Complete Aspect Ratio	
12	$\lambda_B = \frac{A_R + A_W}{A_T}$	Building Surface Area to Plan Area Ratio	
13	$\lambda_S = \frac{H_1 + H_2/2}{S_{12}}$	Height to Width Ratio	
14	$z_d = f_d \overline{z_H}$ $z_0 = f_0 \overline{z_H}$	Displacement height Roughness Length	Gimmound and Oke (1999):
15	$\frac{z_d}{z_H} = 1 - \left\{\frac{1 - exp\left[-(c_{d1} 2\lambda_f)^{0.5}\right]}{(c_{d1} 2\lambda_f)^{0.5}}\right\}$ $\frac{z_0}{z_H} = (1 - \frac{z_d}{z_H})\, exp\,(-k\frac{U}{u_*} + \psi_k)$ $\frac{u_*}{U} = min\left[(c_s + c_R\lambda_f)^{0.5}, \left(\frac{u_*}{U}\right)_{max}\right]$	Height Normalized Zero Plane Displacement Height Height Normalized Roughness Length	Raupach (1994)
16	$\frac{z_d}{z_H} = 1 + \alpha^{\lambda_p}(\lambda_p - 1)$ $\frac{z_0}{z_H} = \left(1 - \frac{z_d}{z_H}\right) exp\left\{-\left(0.5\beta\frac{C_D}{k^2}\left(1 - \frac{z_d}{z_H}\right)\lambda_f\right)^{-0.5}\right\}$	Height Normalized Zero Plane Displacement Height Height Normalized Roughness Length	Macdonald et al. (1998)
17	$z_0 = (z_{ref} - z_d)\exp\left(-\frac{k}{\sqrt{0.5\lambda_f C_{dh}}}\right)$	Roughness Length	Bottema (1997)
18	$z_0 = (z_{ref} - z_d) exp\left(-\sqrt{\frac{0.4}{\lambda_f}}\right)$	Roughness Length	Gal and Unger (2009)