DOI: http://dx.doi.org/10.21123/bsj.2021.18.2(Suppl.).1048

Investigating the Aerodynamic Surface Roughness Length over Baghdad City Utilizing Remote Sensing and GIS Techniques

Al-Zahraa A. Mohsen * *Monim H. Al-Jiboori* *Yaseen K. Al-Timimi*

Department of Atmospheric sciences, College of sciences, University of Mustansiriyah, Baghdad, Iraq
Corresponding author: alzahraa95adil@gmail.com, monim.atmsc@uomustansiriyah.edu.iq, yaseen.altimimi.atmsc@uomustansiriyah.edu.iq
*ORCID ID: https://orcid.org/0000-0001-6353-7217, https://orcid.org/0000-0002-0816-3918, https://orcid.org/0000-0001-5820-0345

Received 23/9/2020, Accepted 9/3/2021, Published 20/6/2021

Abstract:

This study calculated the surface roughness length (Z_o), zero-displacement length (Z_d) and height of the roughness elements (Z_H) using GIS applications. The practical benefit of this study is to classify the development of Baghdad, choose the appropriate places for installing wind turbines, improve urban planning, find rates of turbulence, pollution and others. The surface roughness length (Z_o) of Baghdad city was estimated based on the data of the wind speed obtained from an automatic weather station installed at Al-Mustansiriyah University, the data of the satellite images digital elevation model (DEM), and the digital surface model (DSM), utilizing Remote Sensing Techniques. The study area was divided into 15 municipalities (Rasheed, Mansour, Shulaa, Karrada, Shaab, Adhamiyah, Sadre 2, Sadre 1, Rusafa, Alghadeer, Baghdad Aljadeedah, Karkh, Kadhumiya, Green zone, and Dora). The results indicated that the variations in Z_o depend strongly on zero-displacement length (Z_d) and the roughness element height (Z_H) and wind speed. The research results demonstrated that Baghdad Aljadeedah has the largest (Z_o) with 0.43 m and Rasheed has the lowest value of (Z_o) with 0.19 m.; the average (Z_o) of Baghdad city was 0.32 m.

Key words: Baghdad, DEM, DSM, GIS, Surface Roughness Length, Wind Speed.

Introduction:

The roughness length (Z_o) has a direct impact on the atmospheric boundary layer structure and evolution; besides, it is important for describing the development of the urban cities, urban wind energy, urban air pollution and so on (1). In general, (Z_o) is known as a length scale describing the loss of wind momentum caused by the surface roughness to the height above the ground surface where the settled horizontal wind velocity decreases to 0 (2).

The methods to analyze any natural and manmade surfaces can be classified to major methods first requiring observations of wind, and second based on the morphology and spatial arrangement of surface roughness elements (referred to as morphometric analysis) (3).

The process of city growth has led to decreasing the rates of wind speed urbanization and to increasing the surface friction: as a result, the wind speed is reduced (4).

The Digital Elevation Model (DEM) and the Digital Surface Model (DSM) are satellite images; both have 1(m) of spatial resolution, and they are among the most important spatial datasets known in many geographical information systems (GIS) (5). A DEM is a “bare” land surface model, which is supposedly free of trees, buildings or other objects whereas a DSM is an elevation model that includes the tops of everything, including buildings, trees, and ground (6). The height resulted from the difference between the DSM and DEM which is known as Digital Height Model (DHM). It represents the height surface element (Z_H) (7).

These paramount parameters have urged many researchers in urban studies to examine the roughness of the surface (8). Grimmond and Oke (1999) studied the characteristics of urban wind movement and examined the shape of the surface divided by the methods used by previous researchers in eleven cities in seven American states (9). Grimmond, et al., (2019) calculated the morphology and aerodynamic roughness parameters utilized by three global digital elevation models (GDEM). The parameters are calculated for eight directional sectors of 1 km grid-squares (10). Al-Draji and Al-Jiboori, (2010) calculated Z_o for Bab Al-Mhadham area at the center of Baghdad city, utilizing the meteorological observations for wind speed. They concluded that the values ranged from 0.7 to 1.7 m, with 1.2 m average value (11).

In the recent research study conducted by Al-Jiboori and Haraji in 2019, the length of the surface roughness for eight sections was calculated by using the ultrasonic anemometer which was installed at Al-Mustansiriyah University. The results demonstrated that the ranges of the above variables are (0.24-0.48) m (1). The primary objective of this study is to use Remote Sensing and GIS: ArcGIS 10.4.1 software to estimate surface roughness length over Baghdad's chosen municipality and to design a map for the spatial analysis of the distribution Z_o data by inverse distance weighted (IDW) technique.

Methods

Calculating Zero-displacement length

In this study, many equations are used to calculate the roughness parameters. The height resulted from the difference between the DSM and DEM is defined as the Digital Height Model (DHM) which represents Z_H, as shown in Eq.1 (12).

$$DSM - DEM = DHM \quad (1)$$

The method that depends on the plan aerial index λ_P is used to describe the density and the fraction of the plan area; it can be expressed by Eq. 2:

$$\lambda_P = \frac{A_P}{A_T} \quad (2)$$

Where A_P is the plan surface of the roughness elements (km^2), and A_T is the total surface area (km^2) (13). The plan area index is attached to the significance of the interfering space between the roughness elements. An excess in λ_P will lead to an excess in the displacement height and to a reduction in the roughness of the obstacle array, at λ_P which tends to be 1; this means that the elements are merged because they are so close to each other and they form a new surface (1). The ratio of the displacement height over the roughness element Z_d (m) is evidenced by Eq. 3:

$$\frac{Z_d}{Z_H} = 1 + \alpha^{-\lambda P}(1 - \lambda_P) \quad (3)$$

Z_H is the height of the roughness elements (m); α is Empirical coefficient in equation equal to 4.43, and λ_p is the Plan area ratio of the roughness elements (14).

Calculating the Length of the Surface Roughness

From the law of logarithmic wind speed and converting that into an exponential function, the length of the surface roughness during neutral atmospheric stability can be determined by Eq. 4 (15).

$$Z_o = (Z - Z_d)\exp\left(\frac{-u_z k}{u_*}\right) \quad (4)$$

Where u_* is the friction velocity, k is equal to (0.38) and it is defined by von Karman's constant (16), Z_o is the surface roughness length (m), and Z represents the height over the surface, from which the wind (m) is measured.

It was found from the manual and the empirical evidence that the ratio between the standard deviation of the average wind speed σ_u to u_* ($\emptyset_u = \frac{\sigma_u}{u_*}$) is constant under neutral atmosphere conditions, whose value is (2.2-2.5) as mentioned before (17), so yields Eq. 5:

$$Z_o = (Z - Z_d)\exp\left(\frac{-u_z \emptyset_u k}{\sigma_u}\right) \quad (5)$$

The engineers have generally preferred to estimate the wind speed at heights higher than the height of roughness element (18), so the Exponential engineering law is used for the winds as shown by Eq. 6:

$$\frac{u_r}{u_z} = \left(\frac{Z}{Z_r}\right)^{\alpha} \quad (6)$$

Where u_r: represents the wind speed at a specified height and α is the exponent whose value changes depending on the atmospheric stability and surface roughness, as the value in urban areas reached to 0.25, whilst it decreases to 0.14 for non-rough surfaces and at neutral conditions (19).

Description of Surface Roughness Length Analysis Model

The best method of interpolation for estimating the surface roughness length in Baghdad city is the inverse distance weighted IDW (20). Figure 1 shows the steps to obtain map of Z_o spatial analysis.

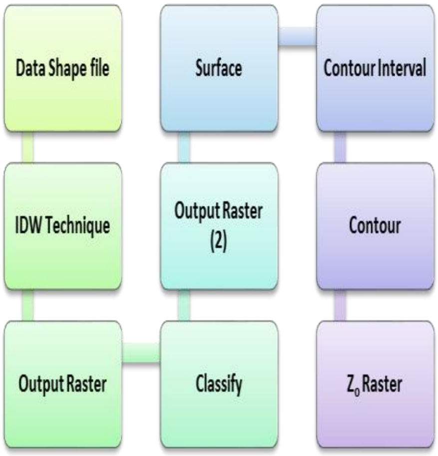

Figure 1. Methodology to design a map of the spatial analysis of distribution Z_o data in ArcGIS.

Study Area:

Baghdad is the capital of the Iraqi Republic, and it is situated on the banks of Tigris River in the central region (21). The terrain of the city is that it is roughly flat and a low-lying land adjacent to a stream alluvial plain (22). Baghdad includes fifteen municipalities, seven of them are situated in Karkh, east of the Tigris, (Kadhumiya, Shulaa, Mansour, Karkh, Green zone, Rasheed, and Dora) and eight lie in Rusafa, west of the Tigris, (Shaab, Adhamiyah, Sader 1, Sader 2, Rusafa, Alghadeer, Baghdad ALjadeedah, and Karrada), as shown in Fig.2. Geographically, Baghdad is situated at latitude (33.22^o – 33.48^o) N, longitude (44.17^o – 44.50^o) E and (30 – 38 m) above the mean sea level; the area of Baghdad city is 877 km^2 (23). The architecture of Baghdad ranges from traditional two or three story brick houses to modern steel, glass and concrete structures, and it has about 12 bridges spanning the river and joining the east and west parts of the city, with many universities and institutes (24). The climate of Baghdad is characterized as subtropical, continental and semiarid, with cool winter, short spring, dry and long summer and very hot. For the last 30 years, the average temperature 25°C and average rainfall per year is approximately 140 mm with no rain at summertime (25).

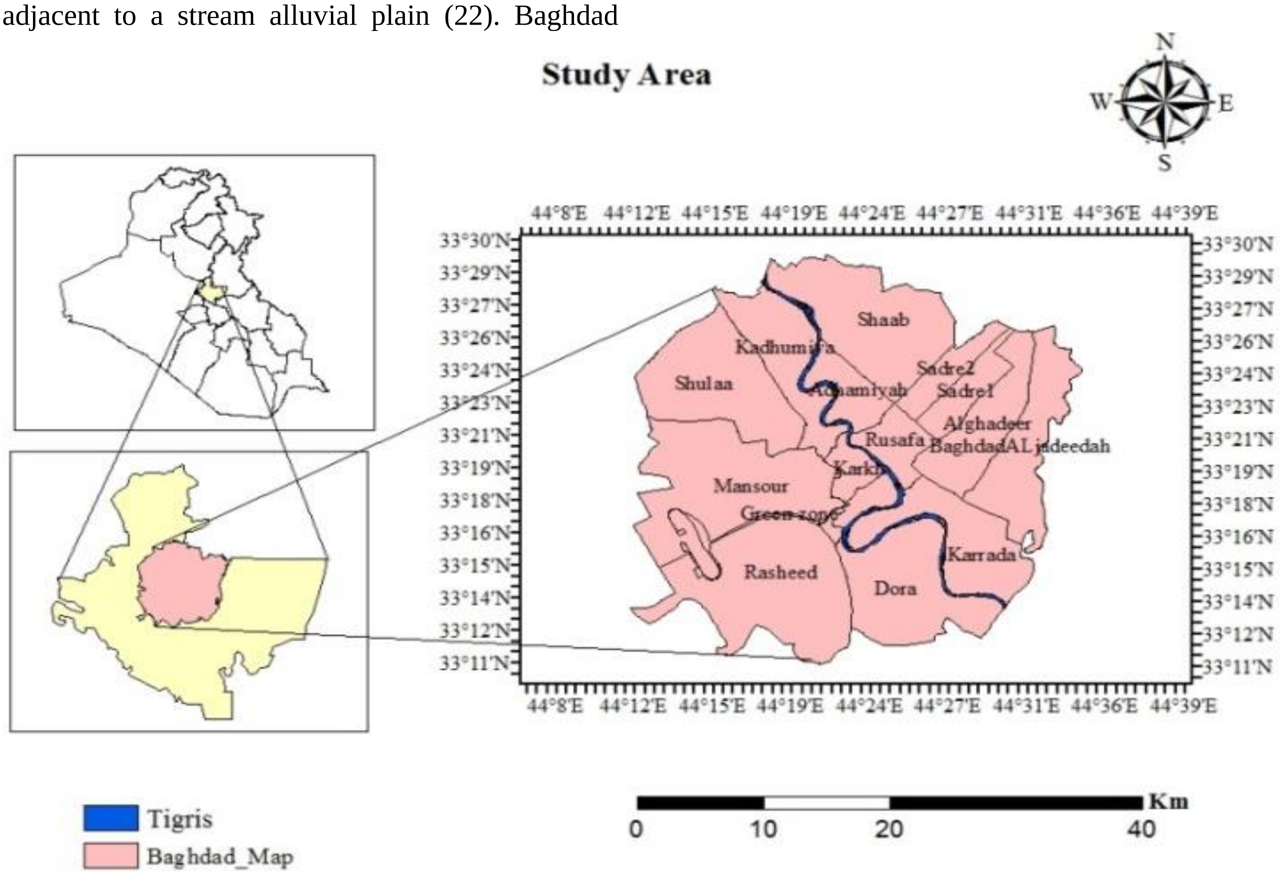

Figure 2. Maps of Iraq Baghdad city.

Data Source

Data have been acquired mainly from four sources. Firstly, from the digital surface model (DSM) images for Baghdad, derived from the satellite ALOS Global Digital Surface Model "ALOS World 3D – 30M" (AW3D30), on 5/7/2019, as shown in Fig.3. Secondly, from the digital elevation model (DEM) images for Baghdad derived from the USGS earth explorer website, on 2/7/2019, as displayed in Fig.4. And third from the Shape file of the boundary of Baghdad city municipalities which comprises fifteen municipalities obtained from Baghdad Municipality. Finally, from a meteorological data of wind speed and direction obtained from the automatic station of the College of Science Atmospheric Department of Al-Mustansiriyah University for the period (2019/1/2 – 2019/12/16). The Rusafa municipality was chosen as a study center for its proximity to the city center of Baghdad as shown in Fig.5, when the automatic weather station installed in Al-Mustansiriyah University which is located in Rusafa.

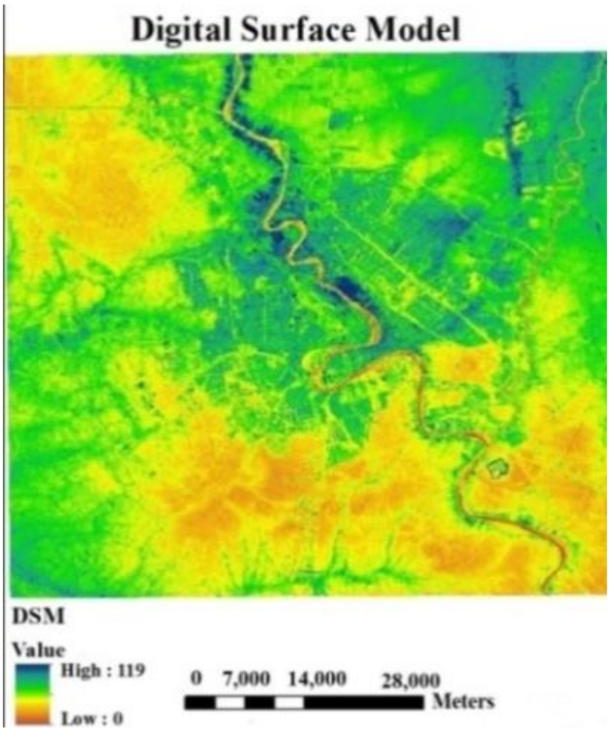

Figure 3. Digital Surface Model image for Baghdad at 5/7/2019.

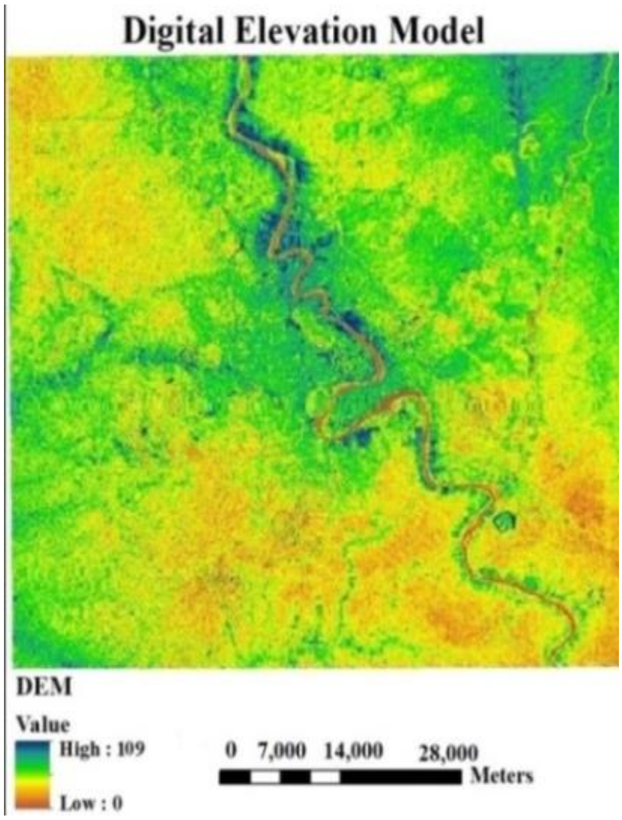

Figure 4. Digital Elevation Model image for Baghdad at 5/7/2019.

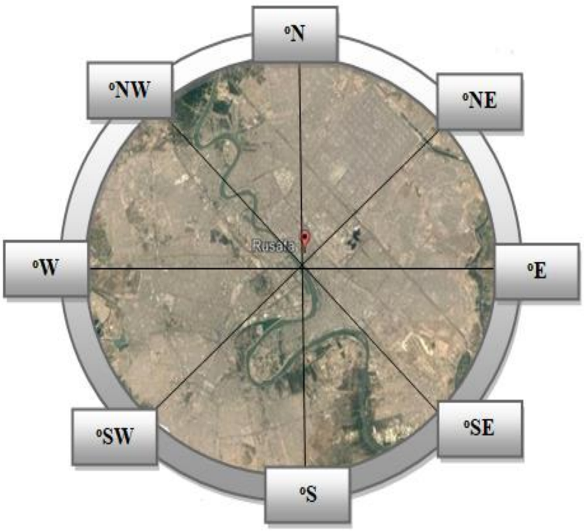

Figure 5. The city of Baghdad and the effective wind direction, considering Rusafa is the center.

Results and Discussion:

Zero-displacement length (Z_d)

The Zero displacement value Z_d is essential for calculating surface roughness which is based on the Z_H and λ_P values. The height resulting from the difference between the DSM and DEM is defined as DHM by Eq.1. Also, it represents the height of the roughness element Z_H (13). The area of interest (Baghdad city) was extracted from the satellite images DSM and DEM. Finally, the data for each municipality were extracted and they became ready for statistical analysis; the difference between them was calculated to get Z_H for each municipality by ArcGIS Algepra tool, which represents the average height of all buildings and the roughness elements present in the area of each municipality, λ_P is calculated by applying Eq.2, when the plan area A_P (km^2) of the roughness elements which represent the area occupied by elevations such as buildings and trees also calculated using ArcGIS by classifying the height data from the DHM images of the roughness elements with heights greater or equal to 2, then by taking the number of pixels for each municipality where the required heights are present, calculating and converting them in a (km^2) per municipality. This classification was chosen ensuring that low-level street furniture (e.g. signage), vehicles, etc. are removed, to determine the plan area index consistent with the study of Kent et al., (2019) (10), and A_T (km^2) representing the total area , after that calculated Z_d by Eq.3 Table 1 exhibits the results of the values of A_P, A_T, λ_P, Z_H, and Z_d for Baghdad and its municipalities, where it is clear that the relationship between Z_H and Z_d is positive and that the relationship between λ_P and Z_d is positive as well. The average values of Z_H and Z_d of Baghdad city were (14.46 m), (8.34 m).

Table 1. Values of Z_H, A_P, A_T, λ_P and Z_d.

Municipalities	A_p (km^2)	A_T (km^2)	λ_P	$Z_{H\,(m)}$	Z_d(m)
Rasheed	36.3	123.3	0.29	18.4	10
Mansour	36.3	123.3	0.29	28.7	15.6
Shulaa	24.6	90.2	0.27	10	5.1
Karrada	18.6	69.3	0.27	14.1	7.2
Shaab	35.6	99.2	0.36	10.2	6.3
Adhamiyah	8.3	27.3	0.3	12.1	6.7
Sadre 2	10.7	20.9	0.51	8.6	6.7
Sadre 1	14.5	23	0.63	8.7	7.5
Rusafa	9.1	23.7	0.39	24.2	15.8
Alghadeer	27.2	51.5	0.53	14.6	11.5
Baghdad Aljadeedah	29.9	65.3	0.46	9.5	6.9
Karkh	3.9	51.5	0.26	18.5	9.2
Kadhumiya	16.3	56.1	0.29	12.6	6.8
Green zone	2.8	16.7	0.17	14.5	5.1
Dora	15.2	82.1	0.19	12.2	4.7

Surface roughness length (Z_o)

After calculating Z_d and classifying the air stability based on the data obtained from the automatic weather station, we chose the wind data for the neutral conditions only by relying on the Pasquill schedule of stability (26). The values of the surface roughness length Z_o were obtained by applying the logarithmic wind speed method, Eq.5. In the municipalities of Russafa and Mansour, we needed to calibrate the height of the automatic weather station because it is set to a height less than the height of the roughness elements in these two municipalities by using Eq.6. Table 2 below presents the results of the surface roughness length.

Table 2. values of Z_o with municipalities.

Municipalities	Z_o (m)
Rasheed	0.19
Mansour	0.37
Shulaa	0.33
Karrada	0.35
Shaab	0.35
Adhamiyah	0.31
Sader2	0.28
Sader1	0.4
Rusafa	0.33
Alghadeer	0.26
Baghdad Aljadeedah	0.43
Karkh	0.21
Kadhumiya	0.3
Green zone	0.29
Dora	0.37
Baghdad	0.32

Figure 6 shows Z_o values of all municipalities, as it was found that the values varied among the municipalities. They highest value of Z_o in Baghdad Aljadeedah was (4.3 m) and the lowest value of Z_o in Rasheed was (1.9 m). Consequently, Baghdad's total value of surface roughness length appeared to be equal to (0.32 m).

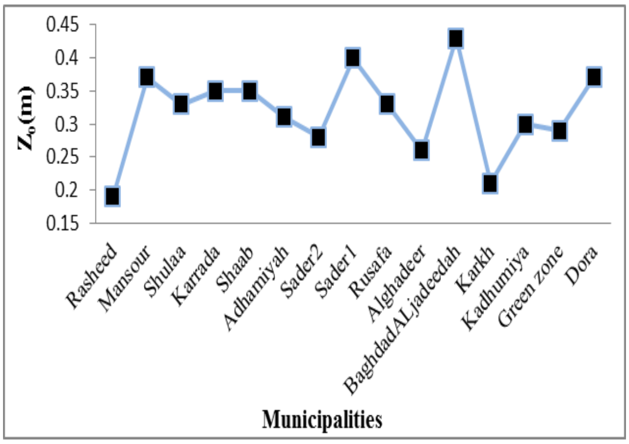

Figure 6. Variation of surface roughness length with municipalities.

Figure 7 reveals the values of the length of the roughness surface with the front area index, where the values of Z_o varied with λ_p from one municipality to another; the largest value of Z_o was (0.43 m) of Baghdad ALjadeedah municipality: the value of $\lambda_{p=}$ 0.46, while the least value of Z_o was (0.19 m) of Rasheed municipality when $\lambda_{p=}$ 0.29.

From this Figure, we conclude that the relationship between the variable Surface roughness length Z_o and the front area index λ_p is positive correlation, as we noticed an increase in Z_o value with an increase in λ_p value.

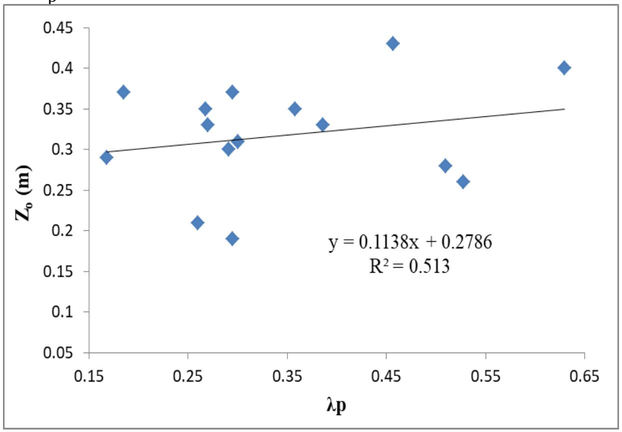

Figure 7. variation of Z_o (m) with λ_P.

Figure 8 displays the contour map for for all Baghdad municipalities. It can be seen that the highest roughness length appears in the municipality of Baghdad Aljadeedah with a value of (0.43) m, followed by Sader1 municipality with a value of (0.4) m, and the lowest roughness length appears in Rasheed municipality with a value of (0.19) m, followed by Karkh municipality with a value of (0.21) m.

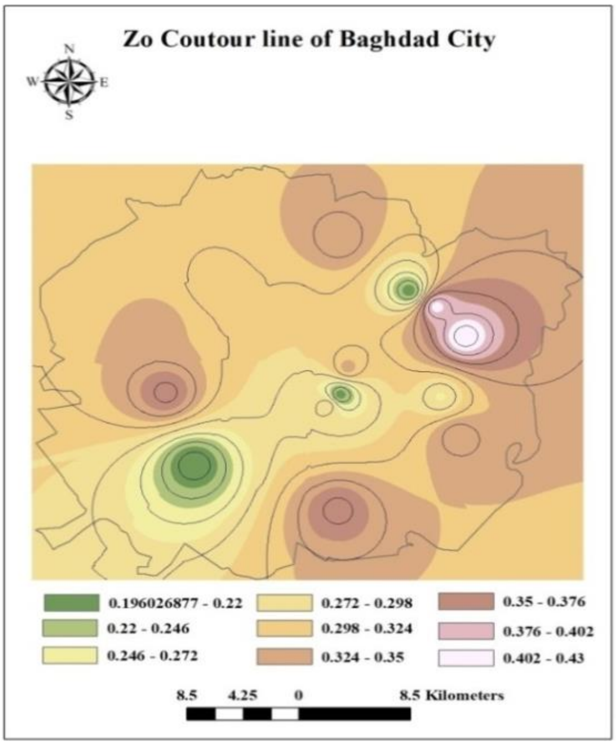

Figure 8. contour distribution of Surface roughness length for Baghdad city.

There are two previous studies that calculated surface roughness length in Baghdad. The first was conducted by Al-Draji and Al-Jiboori (2010); it calculated Z_o for Bab Al-Mhadham; the result was 1.2 m (11). The second study carried out by Al-Jiboori and Haraji, (2019) was confined to Al-Mustansiriya University and its surroundings with an area of 1 km, where the average Z_o was equal to 0.8 m (1). The two examined areas of the previous studies are part of the Rusafa municipality which covers an area of 23.7 km; Z_o is estimated within the study area points for this research; it was equal to 0.33 m, the values differed due to the differences in the areas covered, as well as the difference in the presence of roughness elements in terms of height and density.

Conclusion:

Based on the satellite image data and the wind data obtained from the automatic weather station and with the help of the ArcGIS 10.4.1 software, the length of the surface roughness of Baghdad city and its 15 municipalities by the logarithm of wind law under neutral conditions have been estimated. Consequently, the following results: are reached the average value of the height of roughness element Z_H of Baghdad city is (14.46 m), the values of zero displacement length Z_d range from (4.7 m to 15.8 m), the Z_d average value of Baghdad city is (8.43 m), and the Z_o values of Baghdad municipalities range from (0.19 to 0.43 m) with the average value of Z_o (0.32 m) of Baghdad city. It can be proved that the length of roughness strongly depends on the spatial density of the surface elements. Depending on the values of the roughness parameters, Baghdad is classified as medium in height and density of urban surface form. This result is proportionate with results of Grimmond and Oke in 1999 (9). Finally, we designed a map viewing the spatial analysis of the surface roughness length data of Baghdad using the IDW interpolation tool. This map can be used to find the values of Z_o for some unknown places, such as whether it is on the edge of Baghdad or a point between two municipalities through the spatial distribution of values, where these values are important in urban planning, classifying cities and calculating evaporation rates.

Authors' declaration:

- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are mine ours. Besides, the Figures and images, which are not mine ours, have been given the permission for re-publication attached with the manuscript.

- Ethical Clearance: The project was approved by the local ethical committee in University of Mustansiriyah.

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التحقيق في خشونة السطح الأيروديناميكية الهوائية فوق مدينة بغداد باستخدام تقنيات الاستشعار عن بعد ونظم المعلومات الجغرافية

الزهراء عادل محسن **منعم حكيم خلف** **ياسين كاظم عباس**

قسم علوم الجو، كلية العلوم، الجامعة المستنصرية، بغداد، العراق.

الخلاصة:

في هذه الدراسة تم حساب طول خشونة السطح (Z_o), طول الازاحة الصفرية (Z_d) وارتفاع عناصرالخشونة (Z_H) باستخدام تطبيقات GIS. الفائدة العملية من هذه الدراسة هي تصنيف تطور بغداد ،اختيار الأماكن المناسبة لتركيب توربينات الرياح، التخطيط الحضري، إيجاد معدلات الاضطراب والتلوث وغيرها. تم تقدير طول خشونة السطح (Z_o) فوق مدينة بغداد بناءاً على بيانات سرعة الرياح التي تم الحصول عليها من محطة أرصاد جوية آلية مثبتة في الجامعة المستنصرية ، بيانات صور الأقمار الصناعية نموذج الارتفاع الرقمي (DEM) ، ونموذج السطح الرقمي (DSM) ، باستخدام تقنيات الاستشعار عن بعد. تم تقسيم منطقة الدراسة إلى 15 بلدية (الرشيد ، المنصور ، الشعلة ، الكرادة ، الشعب ، الأعظمية ، الصدر 2 ، الصدر 1 ، الرصافة ، الغدير ، بغداد الجديدة ، الكرخ ، الكاظمية ، المنطقة الخضراء ، الدورة). أظهرت النتائج إلى أن الاختلافات في Zo تعتمد بشدة على طول الإزاحة الصفرية (Z_d) وارتفاع عنصر الخشونة (Z_H) وسرعة الرياح. وأظهرت نتائج البحث أن منطقة بغداد الجديدة لديها أكبر قيمة Z_o بحدود (0.43 م) واقل قيمة الى Z_o كانت في بلدية الرشيد وبحدود (0.19 م). حين بلغ معدل (Z_o) لمدينة بغداد (0.32 م).

الكلمات المفتاحية: بغداد، خشونة السطح، سرعة الرياح، نظم المعلومات الجغرافية، نموذج الأرتفاع الرقمي، نموذج السطح الرقمي.