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Assessment of Aerodynamic Roughness Length Using Remotely Sensed Land Cover Features and MODIS

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Abstract. Wind speed profile has a significant role in environmental transport phenomena whereby Roughness length is a governing factor that determines wind speed profile. Normally, relatively crude estimates of roughness length are used in global climate models based on constant values for each specific land cover category. However, a significant variation may exist within any one of these land cover categories. For this reason, it is necessary to derive detailed roughness length distribution over areas under consideration. Satellite observations can be used to assess the details of roughness length distribution. The aim of the present study was to develop method for roughness length assessment based on remotely sensed Normalized Difference Vegetation Index (NDVI) and landscape images for the entire Iraq area. The NDVI was generated using MODIS data (MOD13Q1) at 250 m resolution acquired on 23th April 2015 for whole Iraq. And the landscape images were classified based on land use and land cover (LU/LC) that relates general classes of LU/LC and values of roughness length coefficient. Taking into consideration a specific range of NDVI values of each landscape category, a correlation analysis was used to determine the aerodynamic roughness between the values of (NDVI) and the aerodynamic roughness based on the European Wind Atlas classification and the Royal Netherlands Meteorological Institute. A quantitative relationship was set up to retrieve the aerodynamic roughness length from MODIS data (MOD13Q1) where $R^2 = 0.96$. Experiments prove that the proposed methodology can provide accurate roughness length estimations for the spatial and temporal analysis of land surface. The findings of this study will enhance sustainability in Iraq and many other regions of the world, thus, supporting the Sustainable Development Goals (SDGs) through the establishment of wind farms especially in countries with coastal areas that can serve as a major source of the national electricity.

Keywords: Roughness length, NDVI, Iraq, MODIS, land use/land cover.

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1.   Introduction

Iraq is recently classified as one of the most vulnerable countries affected by the global climate change. In the recent decades, drought, desertification and dusty storms are more severe in Iraq (Marfleet, 2011), therefore studying the interaction between land surface and atmosphere has become a necessity. Land surface roughness characterized by roughness length (z_0 m) is a governing factor in dust emission process (Prigent et al., 2005). In many applications of surface hydrology and meteorology, the aerodynamic roughness length is a very important parameter. Aerodynamic roughness length z_0 m is a surface parameter that scales the vertical profile of the horizontal component of wind speed and characterizes the ability of the surface to absorb momentum from airflow (Chen et al., 2015). As well as the aerodynamic roughness, length is one of the main parameters which determine heat exchange between the atmosphere and the land surface (Sun et al., 2016). Many simulations have revealed the importance of z_0 m implementations in the atmospheric environment models. Early in 1980, studies on atmospheric modeling showed that changes in surface sensible and latent heat fluxes is a result of changes in the surface roughness length. This trigger near-surface climate changes and atmospheric circulation patterns (Sud et al., 1988; Beljaars and Viterbo, 1994; Maynard and Royer, 2004; Reijmer et al., 2004; Cao and Lin, 2014), as well as water consumption through evapotranspiration from irrigated areas (Hansen, 1993). Accurate knowledge of the aerodynamic characteristics of cities is vital to describe, model and forecast the behaviour of urban winds, turbulence and the dispersion of pollutants at all scales.

In the past decades, several approaches for the estimation of z_0 m at the regional scale based on the structural features of canopy have been included in the literature. Aerodynamic roughness depends mainly on the geometric features as well as the distributions of the roughness elements (Maurer et al., 2013). The mean canopy height, the canopy structure as well as plant density are key variables particularly for vegetated surfaces (Yu et al., 2016). During the growing season, z_0 m and canopy structure of agricultural lands change rapidly. Maps of time-dependent aerodynamic roughness length are useful to model land-atmosphere interactions (Chen et al., 2015). In the past two decades, the development of satellite remote sensing (RS) emerged as an effective way of retrieving information about the surface as well as parameterizing aerodynamic roughness on the regional or global scale (Hasager and Jensen, 1999 Menenti et al., 1996; Menenti and Ritchie, 1994; Yu et al., 2016). Many models have been developed for z0m as a function of vegetation physical structural parameters such as leaf area index (LAI) (Choudhury and Monteith, 1988; Myneni et al., 2002), canopy area index (CAI) and frontal area index (FAI) ((Schaudt and Dickinson 2000; Yu et al., 2016; Raupach, 1994). Besides, optical parameters such as normalized difference vegetation index (NDVI) estimated by remote sensing have been widely used for z_0 m estimation ((Yu et al., 2016; Schaudt and Dickinson, 2000; Zhang et al., 2010). Time series of the NDVI or the LAI acquired from a variety of optical satellites, which include Landsat, Sentinel and MODIS, have been used mainly for z0m estimations of forests and farmlands (Bastiaanssen et al., 1998; Schaudt et al., 2000; Borak et al., 2005; Cho, et al., 2012). During crop growing periods, NDVI is correlated closely with z0m for cropland (Li and Menenti, 1999; Schaudt and Dickinson, 2000), Gupta et al. and Moran et al. described the relationship between z0m and NDVI as z0m = exp (a + b NDVI) (Gupta et al., 2002; Yu et al., 2016). So, based on the scientific literature, there are two main factors, they are closely correlated to each other, which are NDVI and z0m. To understand this relationship, need to know the mathematical concept of Roughness length (z_0) as well as know how the European Wind Atlas and the Royal Netherlands Meteorological Institute (KNMI) classified z0m values on each type of surface component.

1.1   The Mathematical Concept of Roughness Length (Z_0).

Average wind speed is normally increased with height from earth surface due to frictional forces. The common profile of wind speed variation with height from earth surface V (z) is as follows (Ramli et al., 2009):

$$V (z) = U*/k \ln (z/z_o) \ldots\ldots..\ldots\ldots\ldots\ldots\ldots. (1)$$

Where:

$U*$ is friction velocity, k is Von Karman constant (~ 0.4), z is height above the ground surface and z_o is aerodynamic surface roughness length.

The aerodynamic roughness length is in close relation with the geometric features and distribution of roughness elements on earth surface that is normally affected by land use. Categorizing land use is a very useful method of surface roughness length estimation. The categories could be quite effective in the establishment of representative roughness lengths. Additionally, the land-use includes terrain features like hills and mountains which result in a form drag contribution to surface roughness (Hansen, 1993).

1.2   European Wind Atlas and Royal Netherlands Meteorological Institute (KNMI)

Roughness length varies for different type of terrains. There are basically four major types of terrain classifications used by major codes of practice (Ramli et al., 2009) as follow:

1)   Water surfaces such as those of seas and lake.
2)   Earth structures which have open surface area with slight obstruction.
3)   Sub-urban areas with average obstructions like buildings and trees with a height of 10 meters from the surface.
4)   Urban areas or high vegetation crops.

Local roughness length can be determined by the use of experimental data that was obtained using masts and towers. However, remote sensing data products are capable of providing wide spatial coverage and efficient sampling of vegetation canopies temporally, paving way for parameterization of Z_0 at regional scales (Chen et al., 2015). Thus, multi-spectral data provide the possibility to distinguish different ground features from each other, thereby making it possible for the preparation of thematic maps from these data (Lu et al., 2009).

Some researchers have discovered significant correlation between roughness length coefficient and NDVI (Bastiaansen et al., 1998). And pointed out that the relationship can be used to estimate roughness length coefficient (Z_0). Data based Land Surface Processes (LSP) parameters ware carried out using NDVI for the computation of roughness length (Z_0) (Gupta et al., 2002). For instance, in a study, z_0 m at high spatial resolution (30 m) was obtained from classified satellite images. Another study noted that z0m = 0.13 h for a homogeneous vegetation canopy, where h represents the height of the vegetation (Chen et al., 2015). Jia et al. (1999) used the Normalized Difference Vegetation Index (NDVI) to parameterize z0m using an empirical relationship (Li and Menenti, 1999). Other study used the obstacle height and frontal area index to derive Z0m (Chen et al., 2015).

The primary objective of this study is to develop a method to determine time-dependent patterns of aerodynamic roughness at the regional scale using remote sensing data. This paper proposed an aerodynamic roughness estimation methodology based on the concept of footprint weighting method, where Zom over the whole experimental field is aggregated (Lu et al., 2009). Based on the scales of European Wind Atlas (Troen and Petersen, 1989) and the Royal Netherlands Meteorological Institute (KNMI) for Z_0 m values on each type of surface component (Silva et al., 2007), as well as using the characteristic parameters of the roughness elements which include vegetation density from MODIS data. Later to create a model to calculate (Z_0 m) to test the statistical correlation between NDVI and roughness length coefficient to find the best value of R-squared. It is worth noting, that in this study have a new Innovate, by using (google earth) to get on the types landscapes for the experimental field is aggregated, which they need later to compare with the both of the scales of European Wind Atlas and the Royal Netherlands Meteorological Institute (KNMI) for getting on Z_0 m values on each type of surface component.

In the European Wind Atlas, the roughness length class is defined on the basis of the roughness length in m z_0, that is, the height above ground level where the wind speed is theoretically zero (see Troen and Petersen, 1989).

Whereas the Royal Netherlands Meteorological Institute (KNM I) classified roughness was also considered for validation purposes (Silva et al., 2007). Table 1 shows the types of classes land use/land cover and values of roughness length coefficient for each one based on both European Wind Atlas classification.

Table 1. Roughness length scale.

Roughness Class	Roughness Length, z_0 in m	Energy Index (%)	Land Scape
0	0.0002	100	Water surface
0.5	0.0024	73	Open terrain such as runways with smooth surface
1	0.03	52	Agricultural area, no fences or hedges, scattered buildings,
1.5	0.055	45	Agricultural area, hedges with min. 1250m/¾ mile distance and some houses
2	0.1	39	Agricultural area, very few of houses, hedges with min. 500m/¼ mile distance
2.5	0.2	31	The agricultural areas with shrubs, houses, trees and hedges with min. 250m distance
3	0.4	24	Villages, very rough and uneven terrain
3.5	0.8	18	Large cities with high rise buildings
4	1.6	13	Very large cities with high rise buildings

2.   The Study Area

In this research, the study area covers the entirety of Iraq. It is located at Latitude and Longitude 29° 5̄ N - 37° 22̄ N., 38̄ E - 45° 48̄ E respectively. Iraq occupies a total area of 437,072 km2 (168,754 sq. miles). These areas comprise of water bodies (4,910 km2) and land (432,162 km2). There are six countries along Iraq's border. Turkey, Jordan, Syria, Kuwait, Saudi Arabia and Iran: along 331 km, 181 km, 605 km, 814 km, 242 km and 1,458 km respectively (Mahmoud, 2004).

Based on the geographic features, Iraq could be divided into four main regions as follows (see Figure 1):

1)   The desert (west of Euphrates):
It is an extension of the Syrian Desert which covers areas in Jordan and Syria. Saudi Arabia is located to the west of the Euphrates River (Held, 2000).

2)   Mesopotamia/ Al Jazirah (between the upper parts of Tigris and the Euphrates Rivers). The uplands region Al Jazirah, also known as "the island," is a desert plateau located to the north of Samarra (a Tigris city) (Euphrates city). It is an upland region and it extends into Syria.

3)   The Iraqi Kurdistan is the northern highlands:
This is the northern highlands of Iraq which comprises of mountains that rise to over 3,600 m near the Iranian and Turkish borders (Held, 2000).

4)   Lower Mesopotamia, the alluvial plain.
This alluvial plain extends from Iraq's middle region, northern Baghdad to the Arab Gulf. It was formed over centuries due to the deposition of silt from the Tigris, Euphrates, and other rivers in their deltas (Library of Congress, 1988; Held, 2000; Abbas et al., 2015; Abbas et al., 2020).

Figure 1. Map of Iraq. (Source –Library of Congress. 1988)

3.   Satellite data

MODIS data, product (MOD13Q1) at 250 m resolution acquired on 23 April 2015, was used to generate NDVI map of the study site (whole Iraq), where the data as follow:

1)   (MOD13Q1.A2015113.h21v05.006,Coordinates:35.0468,43.0305).
2)   (MOD13Q1.A2015113.h22v05.006,Coordinates:35.0484,55.3265).
3)   (MOD13Q1.A2015113.h22v06.006,Coordinates:25.0335,49.8704)
4)   (MOD13Q1.A2015113.h21v06.006,Coordinates:25.0326 ,38.7904).

The MOD13Q1 Version 6 product gives a Vegetation Index (VI) esteem on for every pixel premise. There are 2 essential vegetation layers. NDVI is the first and is alluded as the continuity index to the existing National Oceanic and Atmospheric Administration-Advanced Very High-Resolution Radiometer (NOAA-AVHRR) derived NDVI. The Enhanced Vegetation Index (EVI) is the second vegetation layer, which has enhanced affectability over high biomass districts (USGS, 2012).

4.   Methodology

Vertical wind profiles and micrometeorological theories are normally used to estimate roughness length for local sites. Individual Z_0 m over each patch (surface component) is calculated firstly using the characteristic parameters of the roughness elements which include: leaf area index, vegetation height etc., then using the footprint weighting method , Z_0 m over the whole experimental field is aggregated (Lu et al., 2009). Later to create a model to calculate (Z_0 m) to test the statistical correlation between NDVI and roughness length coefficient to find the best value of R-squared as in the following approach:

❖   First phase:

NDVI raster for the whole Iraq was created using MODIS data product (MOD13Q1). Using four MODIS images product (which were previously mentioned in the section of satellite data used) by mosaicking technique to generate NDVI map for whole Iraq area. The NDVI (Kriegler et al., 1969) is a simple numerical indicator and one of the most widely used and accepted vegetation indexes (Rouse

et al., 1974). It can also be used as an indicator of relative biomass and greenness (Boone et al., 2000). Additionally, NDVI uses higher reflectance values of vegetation in the near Infrared (NIR) region and lower reflectance values in the red region. It is based on a ratio of the NIR and the red bands as given in equation 4.

NDVI = (NIR – R)/ (NIR+R) ……………….………… (4)

The values of NDVI for a given pixel range from -1 to +1. Where zero means no vegetation and 0.8 - 0.9 (close to +1) indicates the highest possible density of green leaves. Several locations (points) were chosen in Iraq which have different landscape and various value of roughness, length coefficient. These areas have different values of NDVI and can get the roughness length classification as shown in table (1) and NDVI raster for all Iraq area using GIS software.

❖   Second phase:
The statistical correlation between NDVI and roughness length coefficient were used to find the best value of R-squared. Excel software was used to get the best final mathematical model which describes the relationship between NDVI and roughness length coefficient. This mathematical model was used to create the roughness length map for Iraq area.

❖   Third phase:
This phase involved classification of the land use / land cover of Iraq and comparing them with both the European Wind Atlas classification and Royal Netherlands Meteorological Institute classification using Google Earth software. The different definitions of Iraq's land cover (ILC) were studied. Based on the particular terrain characteristics, the grouping was not always obvious compared with the general well-known references of roughness classification. There are different landscapes in the local areas of Iraq and another major goal of this current study is to classify the general land use and landscape.

❖   Fourth phase (Image Processing Techniques):
The Iterative Self-Organizing Data Analysis Technique (ISODATA), roughness length coefficient map for Iraq area and Density Slicing technique were used to generate the range of roughness length coefficient map for the study site. ISODATA Clustering Algorithm: The ISODATA (Jensen, 2007) is an iterative unsupervised classification scheme (Lillisand et al., 2000). This algorithm minimizes the within cluster variability and categorizes the pixels into a number of classes based on statistics.

5.   Results and discussion

The result of NDVI map for whole Iraq area is shown in figure (2). Based on the second step in the methodology section, a mathematical model of (Z_0) was created for the whole Iraq's area using a semi-empirical approach that incorporates both quantitative remote sensing information from NDVI map, and qualitative information (land cover classification) using Google Earth software. This was followed by solution of the equations (2&3) to get the roughness length values and making comparisons with table (1). There is a difference of 39 points as shown in table (2). Finally, the mathematical model showed the relationships between NDVI and Z_0 (equation 5), which was used to create roughness length map for the whole of Iraq's areas. The model shows good correlation (R^2 = 0.9678) see figure (3).

$$Z_0 = 0.0206 \, e^{7.6978 * NDVI} \qquad ……………………………. (5)$$
Where: Z_0=Roughness length.

N	Value Of	Values Of (Z_0)	Class	Coordinates of Selected Experimental Ground Points	N	Value Of NDVI	Values of (Z_0)	Class	Coordinates of Selected Experimental Ground Points

Table 2. Roughness length values response to the NDVI values.

	NDVI			latitude (N)	Longitude (E)					latitude (N)	Longitude (E)
1	0.1085	0.047716	1.385	32.681	41.22	*21*	0.331	0.31	2.94	31.777	44.548
2	0.1125	0.049244	1.412	32.047	40.543	*22*	0.337	0.32	2.966	31.622	44.825
3	0.1139	0.04979	1.421	33.57	40.468	*23*	0.321	0.3	2.912	31.832	44.544
4	0.1087	0.047792	1.387	30.955	44.626	*24*	0.267	0.149	2.331	31.733	44.566
5	0.1417	0.059867	1.574	34.783	44.167	*25*	0.213	0.145	2.309	31.527	45.188
6	0.1179	0.057329	1.538	33.954	40.909	*26*	0.219	0.145	2.309	31.398	45.168
7	0.141	0.061638	1.598	34.219	45.357	*27*	0.258	0.148	2.326	31.297	45.386
8	0.1285	0.055858	1.516	34.272	44.897	*28*	0.274	0.149	2.331	31.949	45.652
9	0.1315	0.057194	1.536	34.484	44.675	*29*	0.293	0.15	2.337	32.397	45.646
10	0.169	0.073416	1.743	32.128	45.845	*30*	0.13	0.06	1.576	32.421	46.102
11	0.163	0.0777	1.79	31.887	46.009	*31*	0.136	0.06	1.576	32.286	46.536
12	0.1928	0.071308	1.719	31.27	46.38	*32*	0.122	0.049	1.408	34.108	42.527
13	0.1588	0.070915	1.715	32.829	44.993	*33*	0.139	0.065	1.642001	35.145	43.194
14	0.1821	0.074172	1.752	32.972	44.49	*34*	0.114	0.045	1.337	35.831	41.87
15	0.2033	0.100687	2.0060	33.881	44.107	*35*	0.122	0.049	1.408	30.329	43.836
16	0.2658	0.164733	2.415	33.858	44.993	*36*	0.134	0.06	1.576	32.031	46.227
17	0.2851	0.139618	2.277	34.072	44.751	*37*	0.124	0.05	1.424	31.822	46.357
18	0.39	0.43	3.212	37.099	44.136	*38*	0.136	0.06	1.576	32.264	46.593
19	0.385	0.36	3.064	37.09	44.135	*39*	0.128	0.053	1.473	32.008	46.981
20	0.371	0.35	3.041	36.796	43.609						

5.1 *Roughness length map:*

The mathematical model of roughness length (equation No.5) was used to create the roughness length map for the whole of Iraq's area. The interactive classification scheme was used to re-classify the range values of roughness length based on classes and type of (land use/land cover). See figure (4).

The result of ILC (types of the landscape) which has been created was based on both European Wind Atlas classification and Royal Netherlands Meteorological Institute classification. It is shown in table (3) and table (4). It explains the proposed value of roughness length coefficient for each land cover classes. The 57 different ILC Classes were grouped into 13 roughness Classes.
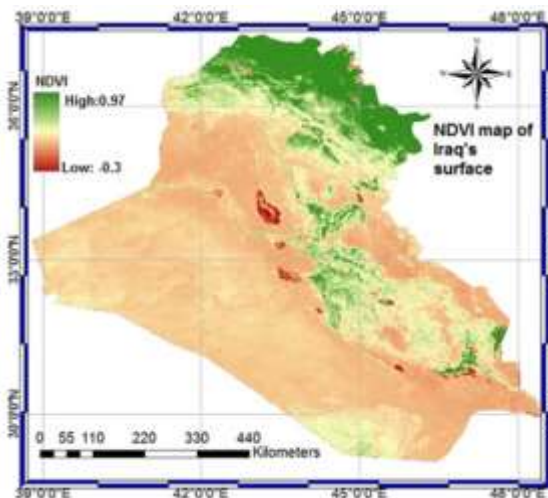
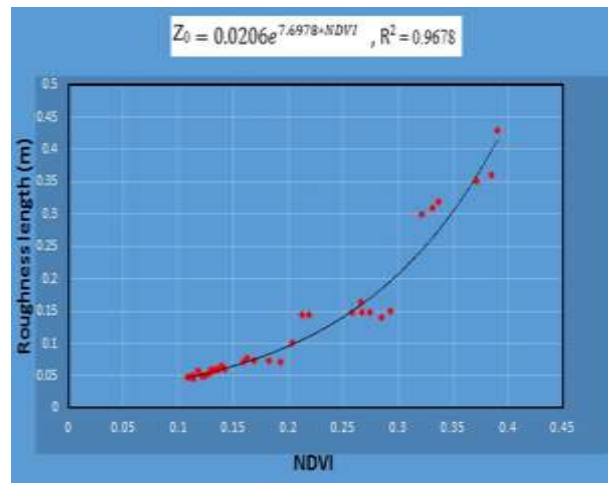**Figure 2**. NDVI map of Iraq's surface -April 2015.

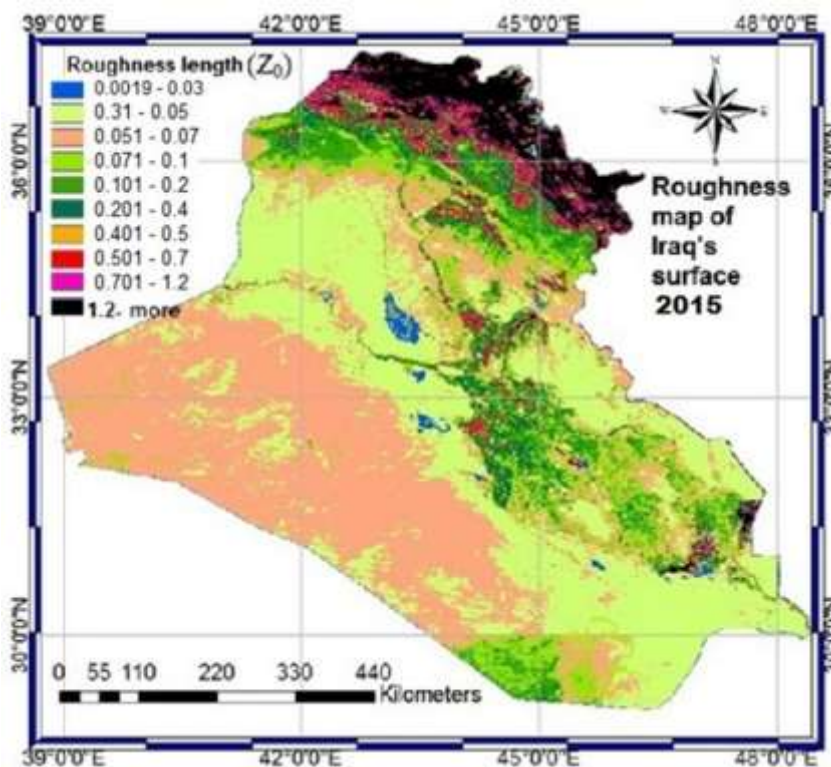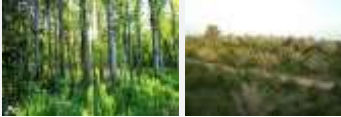**Figure 3.** The Mathematical relationship between roughness length factor and NDVI.

Figure 4. Roughness map of Iraq's surface 2015.
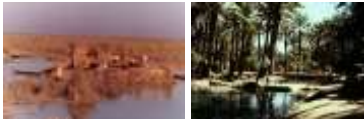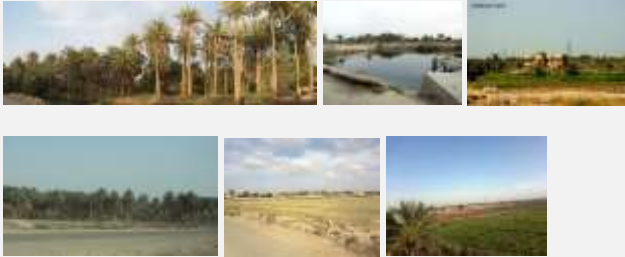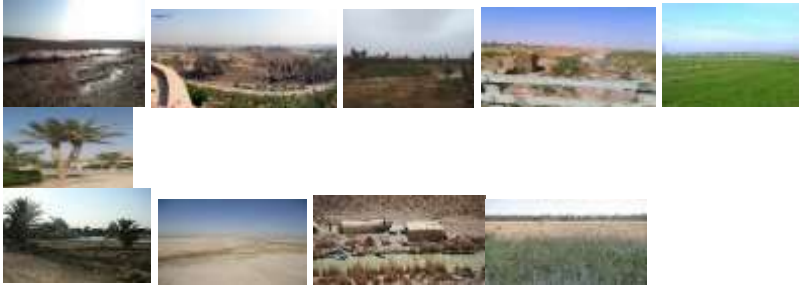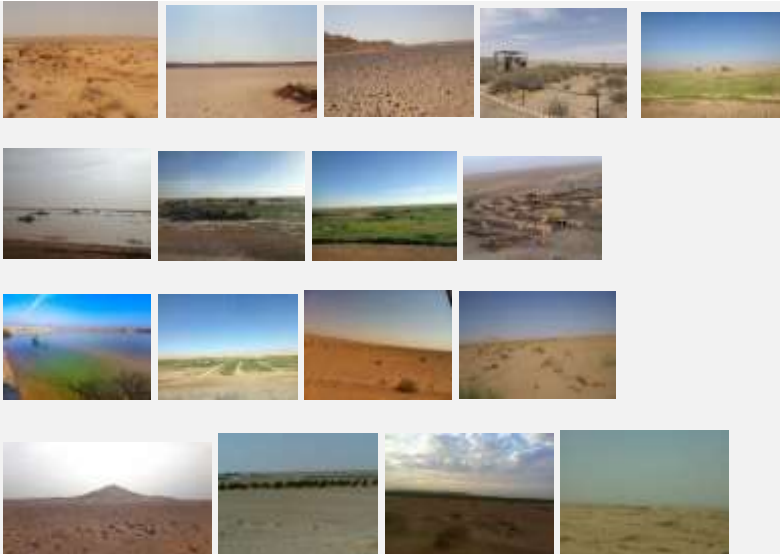
Table 3. Proposed ILC (types of the landscape) and Roughness classification of Iraq.
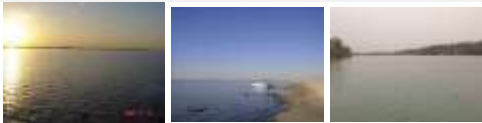
Description of Iraq land covers classes	Proposed ILC Roughness Classification	Other roughness classifications

	Value range	Most likely value	KNMI	European Wind Atlas
Mountain area	> 1.6	-	-	-
Continuos urban fabric	1.1 - 1.6	1.6	1.6	1
Coniferous woodland; Mixed Woodland	0.7-1.2	0.80	0.75	0.8
Green urban ranges; Transitional forest/bush regions	0.5 - 0.7	0.6	1.1	
Discontinuous urban range; Construction destinations; Mechanical or business units; Sport and relaxation areas; Port zones.	0.4 - 0.5	0.5	0.1 - 0.5	0.5
Agro-ranger service zones; Complex cultivation patterns; Land principally occupied by agriculture, with significant zones of natural vegetation.	0.2 - 0.4	0.3		0.1 - 0.3
Yearly products related with lasting yields; Fruit trees and berry plantations; Olive Trees;Vineyard	0.1 - 0.2	0.1	0.39	0.03 -0.1
Non-irrigated arable land; Permanently irrigated land; Rice fields; Salt marshes	0.05 - 0.1	0.05	0.03-0.07-0.17	0.03-0.05
Sclerophylous vegetation; Pastures Sclerophyllous; Natural grassland; Moors and heathland	0.03 -0.05	0.04	0.03	0.0075
Water courses; Coastal lagoons; Water bodies; Sea and ocean Estuaries.	0.001-0.030		0.001	0.0001

Table 4. ILC Roughness Length Scale Table**.**

Group No.	Type of land cover- land use	Value range of roughness classification
12		> 1.6
11		1.1 - 1.6
10		0.7-1.2
9	- - - - - - - - - - - ---- - - - - - - -	0.5 – 0.7
8		0.4 – 0.5

7		0.3 – 0.4
6		0.2 – 0.3
5		0.1 – 0.2
4		0.07 – 0.1
3		0.05 – 0.07
2		0.03 – 0.05

1				0.0019-0.03

6.   Validation of the Aerodynamic Roughness Length Results

The aerodynamic roughness length was estimated based on methodology presented in this work. To validate the remote sensing model results for the site (see Figure 5). The coefficient of correlation, R and the RMSE are used to evaluate the results. Overall, this methodology provided a good results to estimate aerodynamic roughness length to the area under consideration that were in consistence with standard of roughness length scale of by the European Wind Atlas and the Royal Netherlands Meteorological Institute (KNMI). For the types of the landscape of Iraq, the model performs well, with relatively high R-values and low RMSE values.
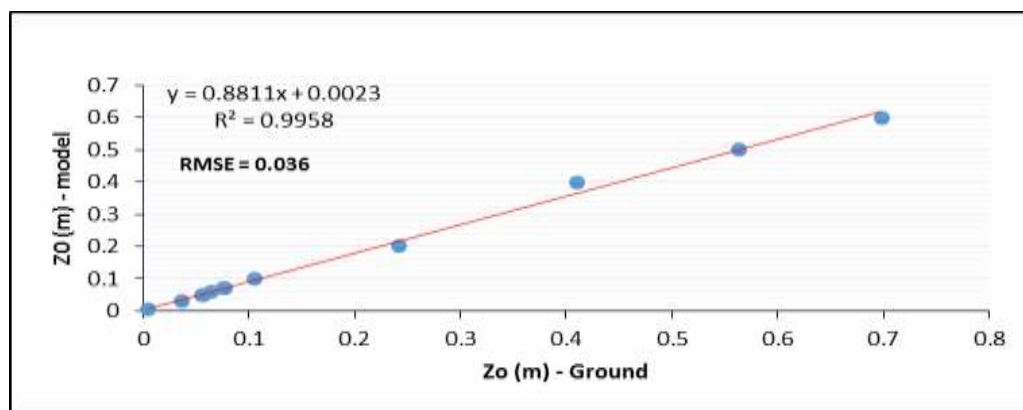

Figure 5. Validation of the estimated aerodynamic Roughness Length model.

7.   Conclusion

Roughness-length mapping based classification land cover (CLC) was obtained. The CLC enabled a good description of the site's roughness without any other specific local references. On the studied sites (Iraq's area), the soil and climatic qualities are distinct. Due to the differences in the predominant species from one region to another, different landscapes exist although they are associated with the same Land-cover class of Iraq. Most of the land covers would likely change with time, hence, special care must be given to landscape changes beyond the CLC description time window. In this study, the 250 m minimal resolution for the classification of a separate CLC Class will tend to be small, but they are quite important occurrences. This will happen mostly on transitional Classes. Integration of remote sensing and GIS provides an active tool with high efficiency in the identification and mapping land cover with a good resolution, in order to produce accurate roughness data sets. It is recommended that more studies at the local level should be carried out in order to obtain more detailed information about the whole area of Iraq so as to attain more accuracy. This will help in determining which area is suitable for the wind farms thereby contributing in achieving some of the SDGs (e.g. sustainable cities and communities) in Iraq.

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