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***Highlights (for review)**

- We derive a new map of annual mean wind speeds across Greater London
- Results used to assess the best location for small wind turbine installations
- Small wind turbines perform better towards outskirts of Greater London
- Distance from city centre is a useful parameter for siting small wind turbines
- Very few sites identified which meet threshold wind speed outlined in literature

Estimating the potential yield of small wind turbines in urban areas: A case study for Greater London, UK.

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Abstract

To optimise the placement of small wind turbines in urban areas a detailed understanding of the spatial variability of the wind resource is required. At present, due to a lack of observations, the NOABL wind speed database is frequently used to estimate the wind resource at a potential site. However, recent work has shown that this tends to overestimate the wind speed in urban areas. This paper suggests a method for adjusting the predictions of the NOABL in urban areas by considering the impact of the underlying surface on a neighbourhood scale. In which, the nature of the surface is characterised on a 1 km^2 resolution using an urban morphology database.

The model was then used to estimate the variability of the annual mean wind speed across Greater London at a height typical of current small wind turbine installations. Initial validation of the results suggests that the predicted wind speeds are considerably more accurate than the NOABL values. The derived wind map therefore currently provides the best opportunity to identify the neighbourhoods in Greater London at which small wind turbines yield their highest energy production.

The results showed that the wind speed predicted across London is relatively low, exceeding 4 ms^{-1} at only 27% of the neighbourhoods in the city. Of these sites less than 10% are within 10 km of the city centre, with the majority over 20 km from the city centre. Consequently, it is predicted that small wind turbines tend to perform better towards the outskirts of the city, therefore for cities which fit the Burgess concentric ring model, such as Greater London, 'distance from city centre' is a useful parameter for siting small wind turbines. However, there are a number of neighbourhoods close to the city centre at which the wind speed is relatively high and these sites can only been identified with a detailed representation of the urban surface, such as that developed in this study.

KEYWORDS: wind, energy, micro-generation, urban, boundary layer, roughness length, morphology

1. Introduction

To reduce the carbon emissions associated with the electricity delivered to the built environment, the UK government has developed a number of schemes to incentivise the growth of micro-generation technologies, including the Low Carbon Buildings Programme, the Code for Sustainable Homes and the Feed-in tariffs Order (Allen et al., 2008; Walker, 2011). As a result there has been an increase in the number of micro-generation technology installations in the UK, including micro-wind turbines (Bergman and Jardine, 2009; RenewableUK, 2011). However, a number of high profile field studies have shown that currently, small wind turbines installed in urban areas in the UK generally produce less energy than expected prior to installation. This has raised doubts about their potential, both in the context of the financial benefits to the owner and with respect to decarbonising the UK energy supply (Encraft, 2009; James et al., 2010).

The literature suggests the reason for the poor performance is twofold: Firstly, the majority of the turbines installed in urban areas are designed without taking into account the complex nature of the wind resource at roof level. Consequently, a number of recent studies have focused on designing wind turbines specifically for urban applications (Booker et al., 2010; Henriques et al., 2009; Muller et al., 2009). Secondly, due to the difficulty estimating the wind resource in an urban area there has been poor placement of the turbines. To optimise the placement of the turbines an accurate method of assessing the variability of the wind resource across a wide urban area is required.

For large-scale wind turbine installations extensive wind monitoring is generally conducted to identify potential sites, however, due to financial constraints, this is rarely possible for small urban installations. Bahaj et al. (2007) and Allen et al. (2008) assessed the performance of small wind turbines in urban areas using wind speed data collected at Met Office weather stations however such data are relatively scarce in urban areas. Consequently, to identify the best sites over a wide area there is a reliance on modelled wind speed data. There are several sources of wind resource information available in the UK. In recent years, the DECC wind speed database and Carbon Trust wind speed estimator have been the most commonly used tools. However, recent studies have shown there can be large inaccuracies in their predictions, particularly in urban areas (Encraft, 2009; James et al., 2010).

This paper aims to provide guidance for optimising the placement of small wind turbines in urban areas by developing an improved method of estimating the wind resource across a wide urban area. The first section discusses the tools currently used to estimate the wind resource at a potential site. This is followed by a discussion of the method developed in this study. Finally, the method has been applied to estimate the wind speed across Greater London, from which the best sites for small wind turbines (from an energy production perspective) have been identified.

2. Current Methods of estimating the wind resource in urban areas

The DECC wind speed database has been widely used by installers and planners for a number of years to identify sites for the installation of micro-wind turbines (James et al., 2010; Walker, 2011). It provides estimates of the annual mean wind speed at three heights (10, 25 and 45 m) on a 1 km resolution. It was produced by a mass consistent flow model, NOABL (Numerical Objective Analysis of the Boundary Layer), which interpolated wind speed data from 56 weather stations across the UK assuming a uniform surface (Burch and Ravenscroft, 1992). However, studies have shown that the database tends to overestimate the wind speed at urban locations (James et al., 2010). At 16 of the 25 sites considered in the Warwick wind trials the measured wind speed was over 40% lower than the NOABL prediction (Encraft, 2009). The inaccuracy of the database is indicative of the simplicity of the model and in particular the lack of representation of the impact of the underlying urban surface on the flow.

An urban surface affects the flow over a range of horizontal spatial scales: city scale (up to 10 or 20 km), neighbourhood scale (up to 1 or 2 km) and street scale (less than 100 to 200 m) (Britter and Hanna, 2003). At the street scale, interacting wakes are introduced by individual surface obstacles, hence at close proximity to buildings the nature of the flow is dependent on a number of local surface parameters such as building size, shape and orientation. This region of the urban boundary layer is known as the roughness sublayer and extends from the surface up to a height of approximately 2-5 times the mean building height (Roth, 2000).

Blackmore (2008) used wind tunnel experiments to consider flow around a range of different building designs and configurations in the roughness sublayer (i.e. on the street scale). Mertens et al. (2003) and Watson and Harding (2007) performed a similar analysis using CFD simulations. The results from these studies provide useful guidance as to the best location for small wind turbines above a specific building or within a given street. However due to cost and time constraints, it is not possible to apply this method to consider the wind speed across a wide urban area. Nevertheless, by considering the flow patterns in the roughness sublayer a modified NOABL estimation tool has been developed. The Micro-generation Installation Standard: MIS 3003 applies correction factors to the NOABL wind speed based on turbine height and urbanisation of the site, termed NOABL-MCS (MIS, 2009). While this approach considers the impact of the surface on the flow in the roughness sublayer, it does not consider the impact which occurs on larger scales. Consequently, James et al. (2010) showed that despite the adjustment, the NOABL-MCS still generally overestimates the wind resource in urban areas.

The region directly above the roughness sublayer is known as the inertial sublayer (ISL), which extends up to a height of approximately $0.1z_i$, where z_i is the height of the UBL. In this region the flow around individual buildings is averaged out, therefore the boundary layer has adapted to the integrated effect of the underlying urban surface (city scale). The wind speed in neutral conditions therefore is considered to be horizontally homogeneous and increases logarithmically with height

$$U(z) = \frac{u_*}{\kappa} \ln\left(\frac{z-d}{z_0}\right) \tag{1}$$

where U is the wind speed at a height z, u_* is the friction velocity and k is von Karman's constant. The roughness length, z_0, provides a measure of the drag exerted on the wind by the underlying surface, with a higher value indicating greater drag. When the surface obstacles are densely packed, such as in an urban area, they can be considered collectively as a canopy of mean height, h. This results in a vertical displacement to the wind profile, known as the displacement height, d. While equation 1 is strictly only valid in the ISL, Cheng and Castro (2002) and Coceal at al. (2006) have shown that it is also approximately satisfied down to the top of the canopy layer for spatially averaged flow.

The impact of the urban surface on the flow in the ISL forms the basis on the Carbon Trust wind resource assessment tool. The tool enables a user to specify their postcode and the proposed height of the turbine to obtain an estimate of the annual mean wind speed. The model is based on a wind climatology which has uniform validity across the country, derived from the National Climate Information Centre (NCIC) dataset. This is adjusted to the hub height of the turbine assuming a logarithmic wind profile and the presence of a blending height l_b (Best et al., 2008). Below l_b the wind profile is governed by the local surface characteristics, z_{0local} and d_{local}, while above l_b the wind profile is governed by the effective roughness of a number of surfaces z_{0eff}. Due to the increased consideration of the impact of the surface on the flow, the Carbon Trust tool generally provides more accurate predictions of the wind speed in urban areas than NOABL. However, a field trial carried out by the Energy Saving Trust showed that the tool tends to underestimate the wind resource with an error of up to 20% of the measured wind speed at some sites (Energy Saving Trust, 2009).

2.1 Internal Boundary Layer Approach

When flow encounters a change in surface roughness, such as a boundary between a rural and an urban area, it has to adjust to the new surface characteristics. Elliott (1958) and Panofsky and Dutton (1984) showed that the impact of the new surface gradually propagates upwards and a new boundary layer begins to grow, called an Internal Boundary Layer (IBL). Within the IBL, the wind profile is governed by the local surface characteristics, whereas above the height of the IBL, the wind profile remains characteristic of the upwind surface.

Mertens (2003) and Heath et al. (2007) considered the growth of an IBL at the boundary between a rural and urban surface to estimate the wind speed in an urban area from a reference rural wind speed. However both studies assumed a uniform roughness length for the whole urban area. In reality, while urban surfaces are very different from the surrounding rural surfaces, they are not internally uniform. Typically, because of common use, neighbourhoods (up to 1 or 2 km) tend to exhibit reasonably uniform surface characteristics (e.g. residential, industry, commercial, parkland). However variability of the surface on this scale has not been considered when estimating the wind speed in urban areas, therefore there is a clear need to develop a method of estimating the variability of the wind resource across an urban area on a neighbourhood scale.

3. Development of a new wind speed estimation method

This study uses the IBL approach outlined in Mertens (2003) to estimate the wind speed across Greater London taking into account the variability of the urban surface on a neighbourhood scale. The derived wind data was then combined with the characteristics of a number of small wind turbines to estimate the neighbourhoods across the city at which their energy production is greatest.

3.1 Neighbourhood scale variability

To represent the nature of the surface on a neighbourhood scale, Greater London was divided into 1 km^2 gridboxes. Each gridbox was then characterised by an estimate of z_0 and d. A common approach of estimating the magnitude of z_0 and d over a wide area is to use land use as a proxy (Barlow et al., 2008; Boehme and Wallace, 2008; Rooney, 2001). However, the problem for those interested in urban areas is that land use categories are usually very broad as they have to cover all types of land use (Britter and Hanna, 2003). For example, there are only two urban categories (urban and suburban) in the land use data used by the Carbon Trust model. A further problem with this approach is the assumption that pre-determined surface parameter values are applicable to different surfaces (i.e. all city centre surfaces are assigned the same z_0 value). In reality, the surface characteristics of one urban surface are likely to be different from that of another and consequently there can be large variability in the magnitude of the surface parameters (Wieringa, 1993).

More precise estimates of z_0 and d can be made using information about the size and spacing of the buildings, this is known as a morphological approach (Britter and Hanna, 2003). This study has estimated the magnitude of z_0 and d using expressions derived by Macdonald et al. (1998)

$$\frac{z_0}{h} = \left(1 - \frac{d}{h}\right) \exp\left\{-\left[0.5\beta \frac{C_D}{\kappa^2}\left(1 - \frac{d}{h}\right)\lambda_F\right]^{-0.5}\right\} \tag{2}$$

$$\frac{d}{h} = 1 + A^{-\lambda_P}(\lambda_P - 1) \tag{3}$$

where C_D is the drag coefficient of a single obstacle, A is a coefficient derived from experimental evidence and β is a parameter which modifies the drag coefficient to a value more appropriate to the particular configuration of obstacles. For this study, these values were taken to be, β=0.55, A=3.59 and C_D=1.2.

The expressions are dependent on three building morphology parameters, h the mean building height, λ_p the plan area ratio (the ratio of the total plan area of the surface obstacles to the total plan area) and λ_f the frontal area ratio. These parameters were computed for Greater London on a 1 km^2 resolution as part of the LUCID project (Evans, 2009). Even though λ_f was only derived for two wind directions 180° (Southerly) and 270° (Westerly), Evans (2009) showed that the frontal area for a particular wind direction is almost identical to the value for the opposite direction, irrespective of building shape. Consequently, the magnitude of the roughness length calculated for westerly flow $z_0(270)$ can be considered to be equivalent to that for easterly flow $z_0(90)$ (similarly $z_0(180) \approx z_0(360)$).

Figure 1 shows that the derived displacement height tends to decrease with distance from the city centre. At the city centre, where the buildings are relatively tall and densely packed, the displacement height peaks at a magnitude of 19.5 m, which equates to 0.8h. In the surrounding suburban region, where the buildings tend to be shorter and less densely packed, the magnitude of d is lower, generally between 2 and 4 m. Figure 2 shows a similar relationship is displayed for the roughness length for both wind directions, z_0 peaks in the city centre (1.4 m for Westerly flow and 1.3 for Southerly flow) and tends to decrease to a minimum value on the outskirts. Padhra (2010) suggested that the symmetry of the surface parameter plots shows that the spatial structure and organisation of Greater London fits the concentric ring model proposed by Burgess (1924). However, the figures also show that there are some regions of low z_0 and d relatively close to the city centre, these areas are generally parkland (such as Hyde Park, Regents Park and Richmond Park).

3.2 Internal Boundary Layer Model

By considering the growth of an IBL at a roughness change boundary, Mertens (2003) showed that the wind speed, U, in an urban area can be estimated from a reference upwind rural wind speed U_A, (measured at a height z_A) from

$$U(z) = \frac{\left(\ln\left[\frac{\delta - d_1}{z_{01}}\right] \ln\left[\frac{z - d_2}{z_{02}}\right]\right)}{\left(\ln\left[\frac{z_A - d_1}{z_{01}}\right] \ln\left[\frac{\delta - d_2}{z_{02}}\right]\right)} U_A(z_A) \tag{4}$$

where z_{01} and z_{02} are the roughness lengths and d_1 and d_2 are the displacement heights of the upwind and downwind surfaces respectively, and δ is the height of the internal boundary layer given by

$$\delta(x) = 0.28z_{02}\left[\frac{x}{z_{02}}\right]^{0.8} \quad (5)$$

where x is the distance from the roughness change boundary (Elliott, 1958).

While Mertens (2003) assumed that a single IBL grows at the rural/urban boundary, this study assumes that an IBL develops at the boundary between neighbourhoods of different roughness. Equation 4 is therefore used to estimate the annual mean wind speed of each gridbox for each of the 4 wind directions. As the wind speed calculated using equation 4 is dependent on the distance from the roughness change boundary, x, the wind speed was calculated at a range of x values (at 50 m intervals from 50 – 950 m therefore n=19). The gridbox mean wind speed, U is then calculated from

$$U(z) = \frac{1}{n}\sum_{i=1}^{n} u_i(z) \quad (6)$$

To apply the IBL formula for the first gridbox within the city boundary, a reference rural wind speed is required. This has been sourced from the NOABL wind speed database; this approach is consistent with that of Heath et al. (2007). For the downstream gridboxes, the mean wind speed derived for the previous gridbox is used as the reference wind speed.

To obtain an estimate of the overall annual mean wind speed for each gridbox, the wind speed for each of the 4 directions has been weighted based on the frequency of the wind from each direction measured at the Met Office weather station at Heathrow between 1990 and 2011 (located on the Western outskirts of Greater London at 51.479, -0.449) (UK Meteorological Office, 2012).

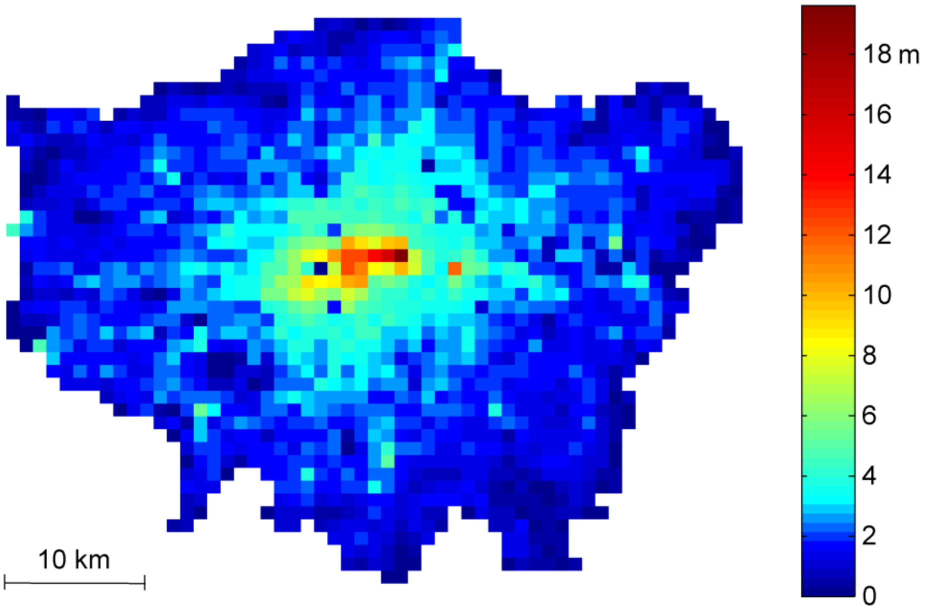

Figure 1 Displacement height (m) of Greater London derived from urban morphology database on a 1 km2 resolution.

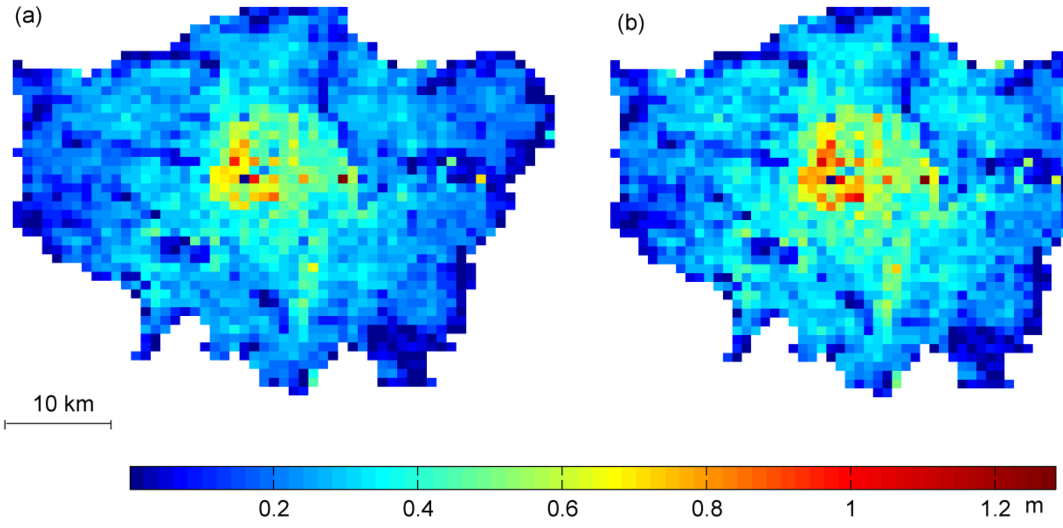

Figure 2 Roughness length (m) derived from urban morphology on a 1 km resolution (a) southerly/northerly flow (b) westerly/easterly flow.

3.3 Performance of small wind turbines

The model was used to estimate the annual mean wind speed at a hub height typical of that recommended for a number of rooftop turbines, z_{hub}. This was taken to be either 5 m above the mean building height or 10 m for the sites at which h=0 (i.e. no buildings). To estimate the potential energy production of a wind turbine at each gridbox, a Weibull distribution has been assumed to represent the variability of the hourly mean wind speed.

The Weibull probability density function is given by

$$f(v) = \left(\frac{k}{C}\right)\left(\frac{v}{C}\right)^{k-1} exp\left[-\left(\frac{v}{C}\right)^{k}\right] \tag{7}$$

where C and k are known as the scale and shape parameters respectively. This study assumes that the wind speed for each gridbox fits a Rayleigh distribution, which is a special case of the Weibull distribution, which occurs when k=2 (Lun and Lam, 2000; Ramrez and Carta, 2005).

The annual energy production of a range of different small wind turbines was estimated at each gridbox by combining the turbine’s power output P(v), (given by the power curve) with the Weibull probability density function for all of the velocities within the operating range of the turbine

$$E = t\int_{v_{cut-in}}^{v_{cut-out}} P(v)f(v)dv \tag{8}$$

where t is the number of hours in a year.

Figure 3 shows the details of the 30 wind turbines considered in this study. The selection was considered to represent the full range of systems currently available in the UK, both in terms of size and design. The figure shows that 21 horizontal axis wind turbines (HAWTs) and 9 Vertical axis wind turbines (VAWTs) with a rated power ranging from 0.056 to 9.8 kW have been considered.

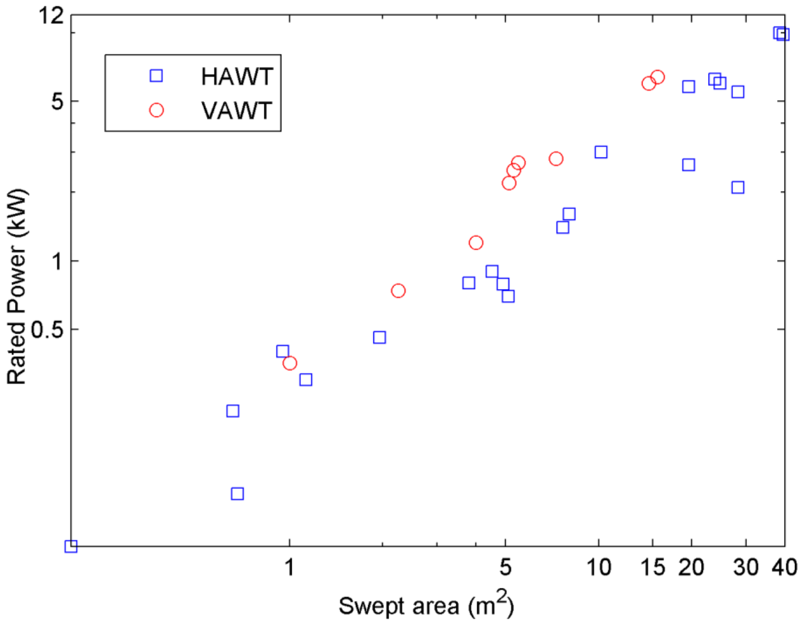

Figure 3 Details of the swept area and the rated power of the 30 turbines used in this study.

4. Wind resource results

Figure 4 shows the predicted annual mean wind speed at z_{hub} is generally higher on the outskirts of Greater London than the city centre region. The wind speed was estimated to be highest on the south west outskirts, with a value of approximately 5 ms^{-1}. The lowest wind speeds were predicted in and around the city centre, with a magnitude of 3.3 ms^{-1}. However, there are some regions close to the city centre with a relatively high wind speed which therefore do not fit this relationship, these equate to the regions of low z_0 and d values (i.e. such as Hyde Park and Richmond Park).

4.1 Validation

Ideally the mean wind speed predictions of the model would be validated with measured data. However, of the 8 Met Office weather stations in Greater London with wind speed observations only two are currently operational and hold wind data for a minimum of 10 years; Heathrow and Northolt, both of which are located towards the outskirts of the region. For both sites, the model has been used to estimate the wind speed at a height of 10 m, the results have then been compared with the measured wind speed data averaged over the period 2000-2010. To have further confidence in the model, the predictions have also been compared with the predictions of the NOABL wind speed database and Carbon Trust tool.

At both sites, the method outlined in this study produces a prediction of the annual mean wind speed within one standard deviation of the measured value. At the Northolt site the model overestimates the measured annual mean wind speed by only 3%. In comparison, the NOABL database overestimates by 27% and the Carbon Trust tool underestimates by 16%. A similar result was shown at the Heathrow site, with the model overestimating the annual mean wind speed by only 1% in comparison to an 18% overestimate by NOABL and 31% underestimate by the Carbon Trust tool.

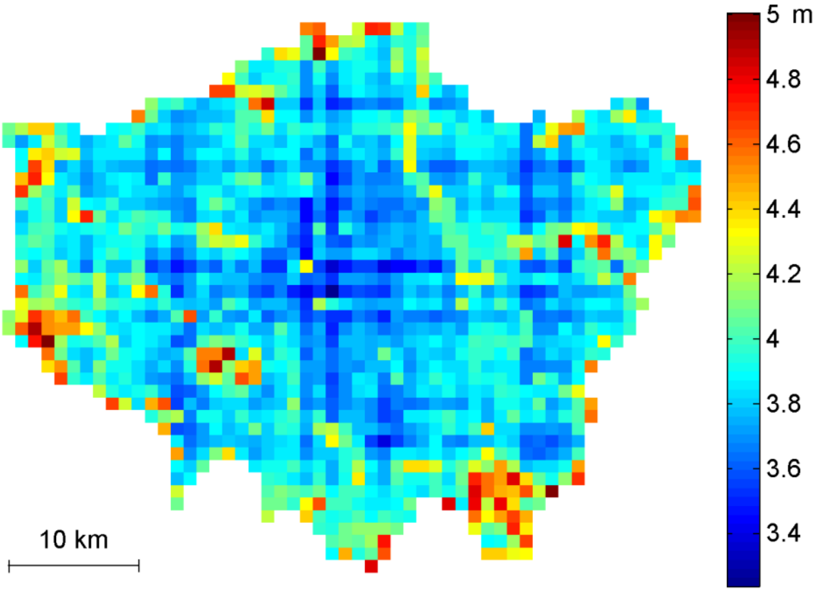

Figure 4 The annual mean wind speed, U, at zhub, based on the NOABL climatology upstream.

5. Implications for small wind turbines in urban areas

The wind map of Greater London has been used to estimate the potential annual energy production of 30 small wind turbines at each of the 1 km neighbourhoods across Greater London (using the method outlined in section 3.3). To allow comparison between the turbines, the performance has been expressed in the form of a capacity factor. This is defined as the ratio of the actual energy production in a given period, to the hypothetical maximum possible.

5.1 Using the new wind map to investigate the performance of small wind turbines in Greater London

Figure 5 provides an analysis of the magnitude of the capacity factor for the 30 turbines, estimated for each gridbox across the 1650 km^2 of Greater London. It shows there is large variability in the annual energy production of the different turbines across the city, with the HAWTs generally performing better. For all 9 VAWTs the median capacity factor does not exceed 6.4%, with a mean value of 4.4%. In contrast, the median capacity factor is below this value for only two of the HAWTs and the mean value over the 21 turbines is 10.6%. This result is largely due to the higher cut-in wind speed of the VAWTs. The figure also shows that there is not a clear trend between turbine size and the predicted median capacity factor.

In general, the performance of the turbines across Greater London is relatively poor compared to large wind turbines in open areas, with the median capacity factor exceeding 15% for only two turbines (turbine 19 and 29). Further analysis showed that for all gridboxes, these two turbines were predicted to produce the highest capacity factors. This suggests that, assuming the power curves are accurate, of the turbines considered one of these two turbines should be selected. Figure 5 also shows that there is large variability in the magnitude of the capacity factor of each turbine, indicating that the turbine performance varies significantly from one location within an urban area to another. This is also seen in figure 6 which shows the mean capacity factor averaged across all 30 turbines for each 1 km^2. These results imply that as expected the siting of a small wind turbine is important.

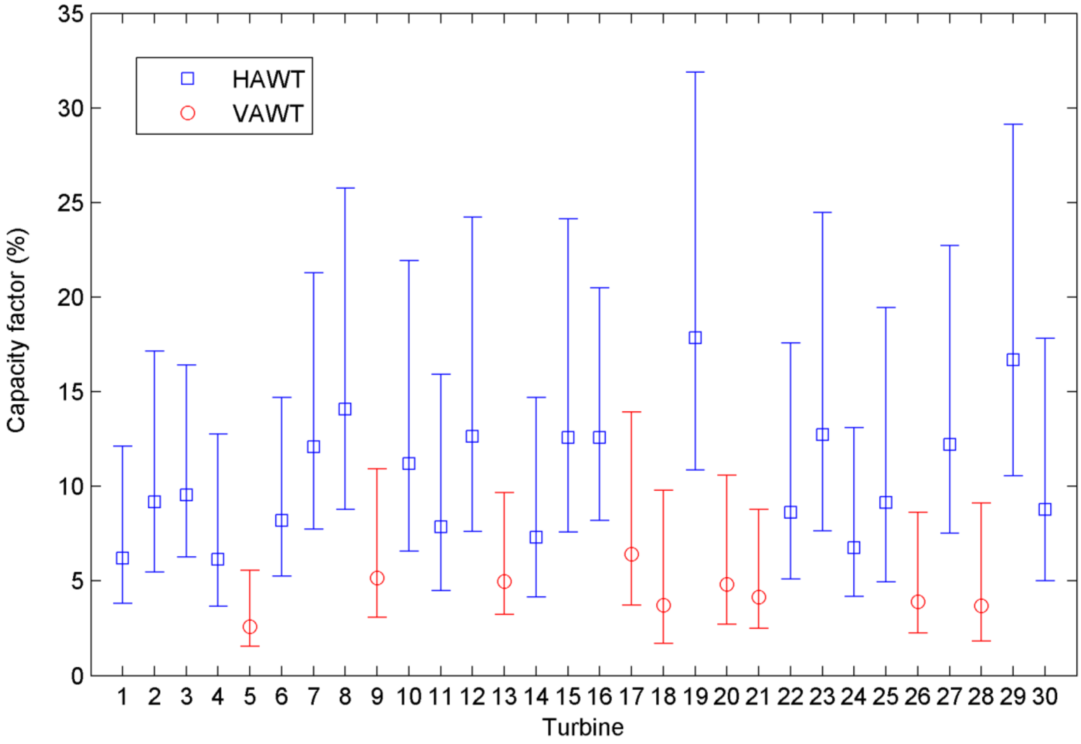

Figure 5 Estimated capacity factor for 30 turbines across Greater London, if installed at zhub. Median, minimum and maximum values across the 1650 1 km2 neighbourhoods are represented, with the turbines ordered by increasing rated power.

5.2 How does energy production vary with location?

The energy production of the turbines tends to increase with distance from the city centre, (due to the increase in wind speed). To explore this relationship further the magnitude of the mean capacity factor (across 30 turbines) along 15 transects (from 0 to 360° every 24°) through Greater London has been considered. Figure 7 shows the mean capacity factor averaged across the 15 transects as a function of distance from the city centre, as well as the minimum and maximum values. The values have been normalised by the mean capacity factor for the rural gridbox at the start of each transect. The figure shows that the mean capacity factor generally peaks towards the outskirts of the city before decreasing to a minimum value in the city centre. A similar relationship is shown for the minimum value. These results suggest that for cities which fit the Burgess concentric ring model, such as Greater London, ‘distance from city centre’ is a useful parameter for siting small wind turbines. However, figure 7 also shows that there is large variability in the maximum value of the mean capacity factor across the transects; there are sites close to the city centre at which the mean capacity factor is relatively high. This suggests that to identify the best sites for small wind turbines (in terms of energy production) further siting parameters, such as z_0 and d, are required on a neighbourhood scale.

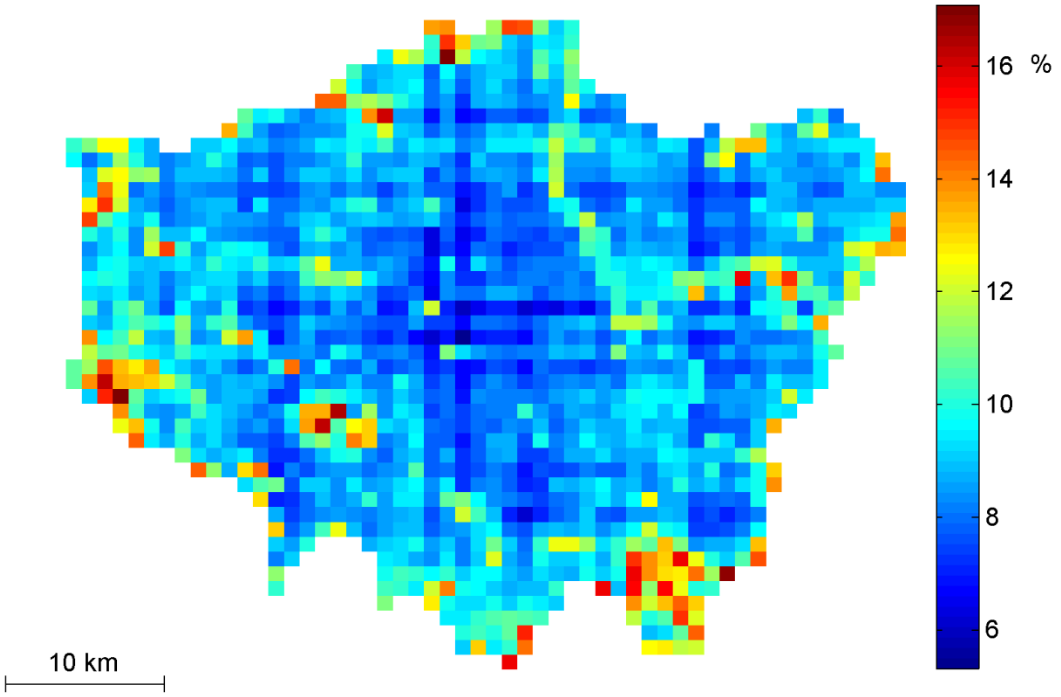

Figure 6 Mean capacity factor of the 34 turbines at zhub for each 1 km2 neighbourhood in Greater London.

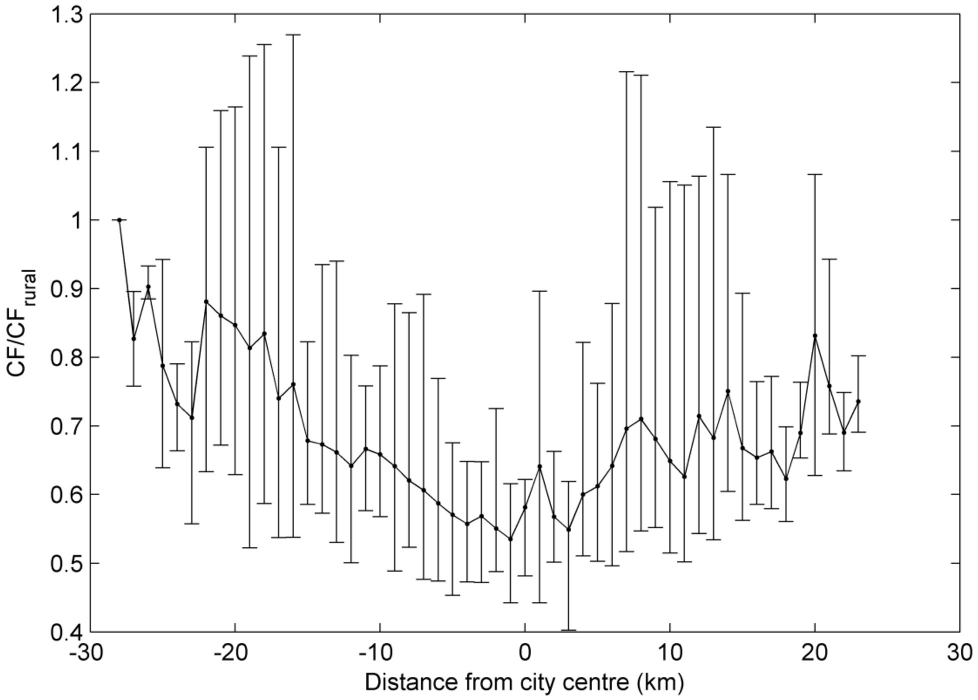

Figure 7 Mean capacity factor of 34 turbines estimated at zhub averaged along 15 transects through Greater London. The values have been normalised by the mean capacity factor at the rural site at the start of each transect.

5.3 What proportion of sites meet the RenewableUK criteria?

RenewableUK guidance states that it is generally worthwhile installing a small wind turbine at a site with a mean wind speed of 4-5 ms^{-1} (RenewableUK, 2012). This study predicts that the mean wind speed at z_{hub} exceeds the threshold of 4 ms^{-1} at only 28% of the 1 km^2 neighbourhoods in Greater London. Of these neighbourhoods, the majority are located towards the outskirts of the city, figure 8 shows that 50% are over 22 km from the city centre. Furthermore, the wind speed exceeds the threshold at only two gridboxes within a distance of 5 km of the city centre (which correspond to Hyde Park). The figure also shows that only 6% of the neighbourhoods have an annual mean wind speed in excess of 4.5 ms^{-1}, all of which are at a distance of more than 10 km from the city centre. Finally, if the threshold wind speed is taken to be 5 ms^{-1}, small wind turbines could only be installed in two neighbourhoods in Greater London, both of which are on the western outskirts of the city.

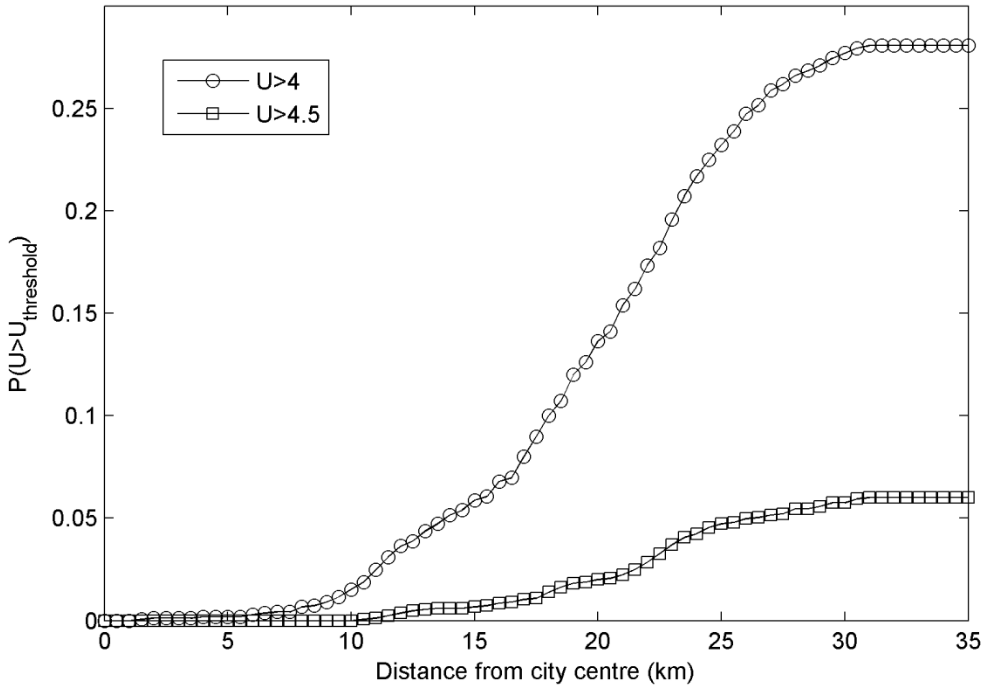

Figure 8 Probability of finding a neighbourhoods for which the predicted annual mean wind speed at zhub exceeds the threshold wind speed as a function of distance from the city centre.

5. Conclusions

Urban areas have largely been considered poor sites for small wind turbines, this conclusion has generally been drawn from observations of the wind resource at point locations. However, there has been little work optimising the placement of the turbines. This study has developed a method for estimating the variability of the annual mean wind speed across an urban area by considering the impact of the surface on a neighbourhood scale, in order to identify the best sites for small wind turbine installations.

The method has been applied to estimate the wind resource across Greater London, UK. Due to a lack of measured wind data in the city, there has been limited validation of the model's predictions. However, for the two sites with wind data available, the predictions were shown to be within one standard deviation of the measured wind speed data and considerably more accurate than both of the alternative site assessment tools (NOABL and Carbon Trust tool). These results suggest that the wind map developed in this study therefore presents the best opportunity to assess the performance of small wind turbines in Greater London.

The results show that generally the wind speed across London is relatively low. Of the 1650 1 km^2 neighbourhoods within the city, only 28% exceed the guideline threshold wind speed of 4 ms^{-1} at turbine hub height, outlined by RenewableUK. Of these sites less than 10% are within 10 km of the city centre, with the majority over 20 km from the city centre. The performance of small wind turbines therefore tends to be better on the outskirts of the city, particularly in the boroughs of Hounslow in the west and Bromley in the south east. Consequently, for cities which fit the Burgess concentric ring model, such as Greater London, 'distance from city centre' is a useful parameter for siting small wind turbines. However, there are some regions close to the city centre at which the wind speed is relatively high and these sites can only be identified by representing the urban surface on a neighbourhood scale.

The results also show that for each neighbourhood there is large variability in the performance of the different turbines, with the HAWTs generally performing better than VAWTs. Averaged across all neighbourhoods in London, the median capacity factor does not exceed 6.4% for any of the VAWTs. In contrast, the median capacity factor is below this value for only two of the HAWTs.

The approach outlined in this study, has thus far only been applied to Greater London, but could be replicated for all cities for which urban morphology data is available. It could therefore provide a useful tool for optimising the placement of small wind turbines in urban areas for the whole of the UK. The model however does not consider the impact of individual obstacles on the flow and therefore does not consider the variability of the wind speed at close proximity to buildings. The results can therefore be used to identify the best neighbourhoods for small wind turbines, in terms of the wind resource. However, to identify the best locations within each region, scaling factors need to be applied to the wind speed to account for the impact of individual buildings on the flow.

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Figure Captions

Figure 1 Displacement height (m) of Greater London derived from urban morphology database on a 1 km^2 resolution.

Figure 2 Roughness length (m) derived from urban morphology on a 1 km resolution (a) southerly/northerly flow (b) westerly/easterly flow.

Figure 3 Details of the swept area and the rated power of the 30 turbines used in this study

Figure 4 The annual mean wind speed, U, at z_{hub}, based on the NOABL climatology upstream

Figure 5 Estimated capacity factor for 30 turbines across Greater London, if installed at z_{hub}. Median, minimum and maximum values across the 1650 1 km^2 neighbourhoods are represented, with the turbines ordered by increasing rated power.

Figure 6 Mean capacity factor of the 34 turbines at z_{hub} for each 1 km^2 neighbourhood in Greater London.

Figure 7 Mean capacity factor of 34 turbines estimated at z_{hub} averaged along 15 transects through Greater London. The values have been normalised by the mean capacity factor at the rural site at the start of each transect.

Figure 8 Probability of finding a neighbourhoods for which the predicted annual mean wind speed at z_{hub} exceeds the threshold wind speed as a function of distance from the city centre.

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Figure1

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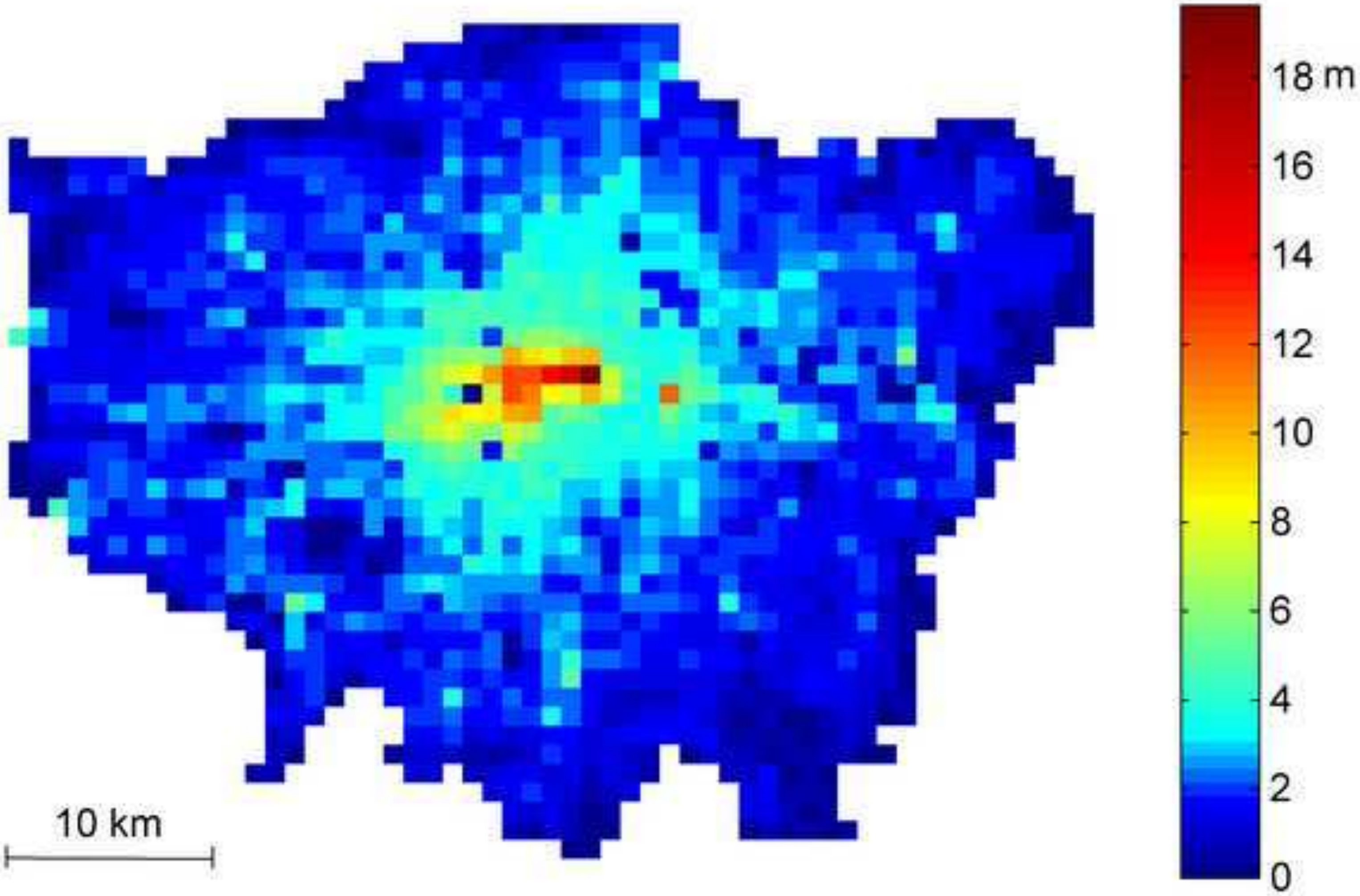

Figure2

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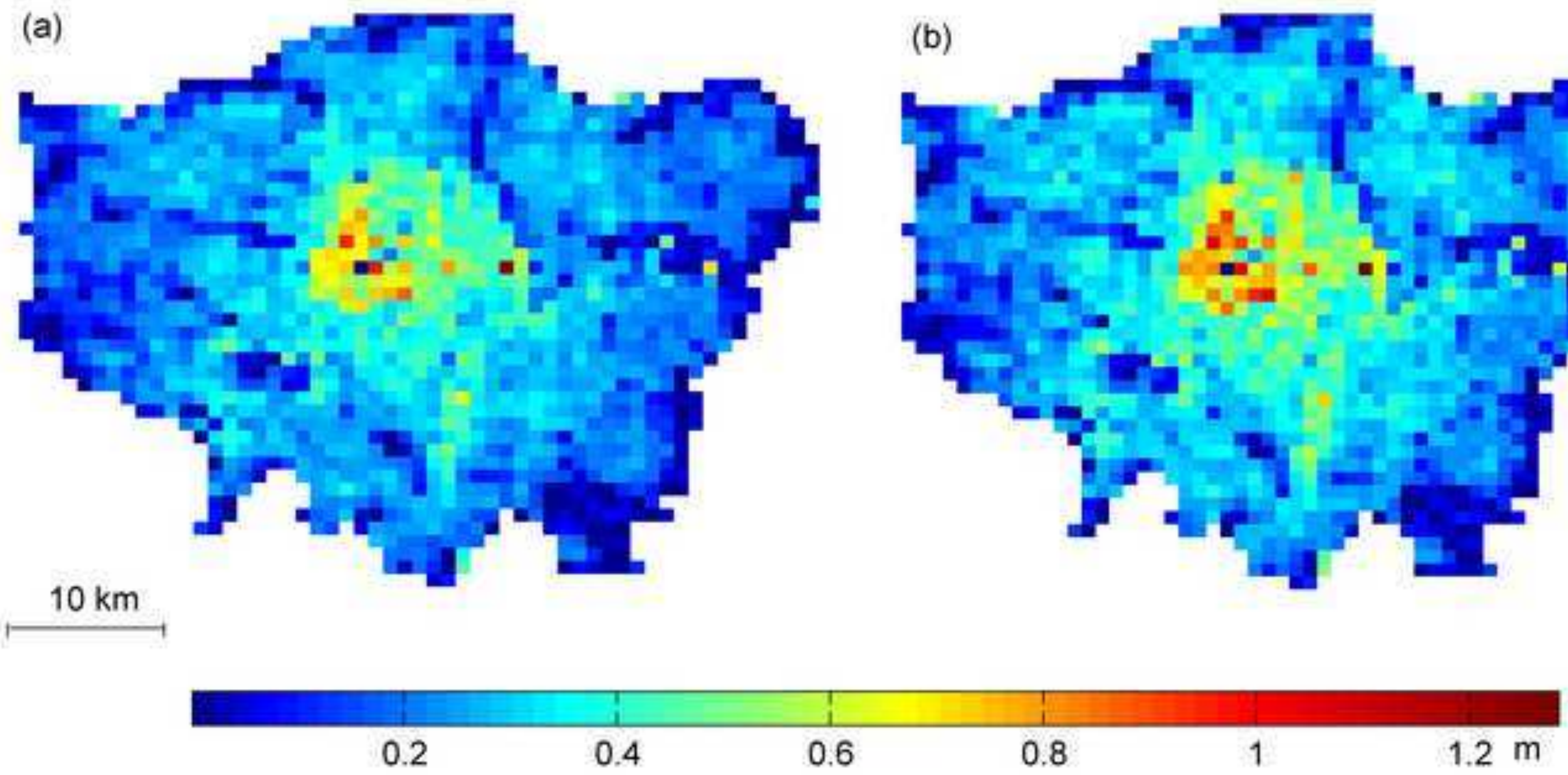

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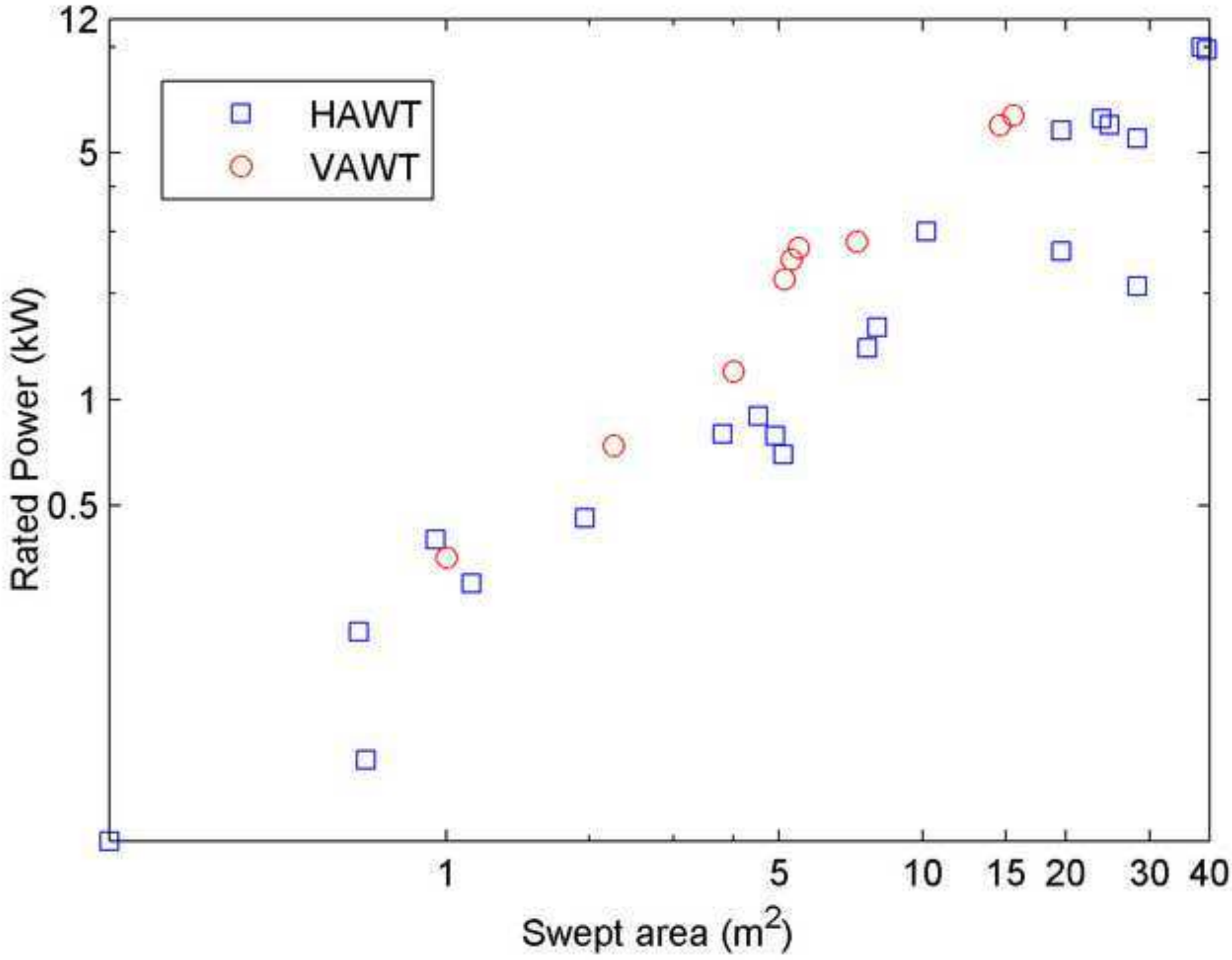

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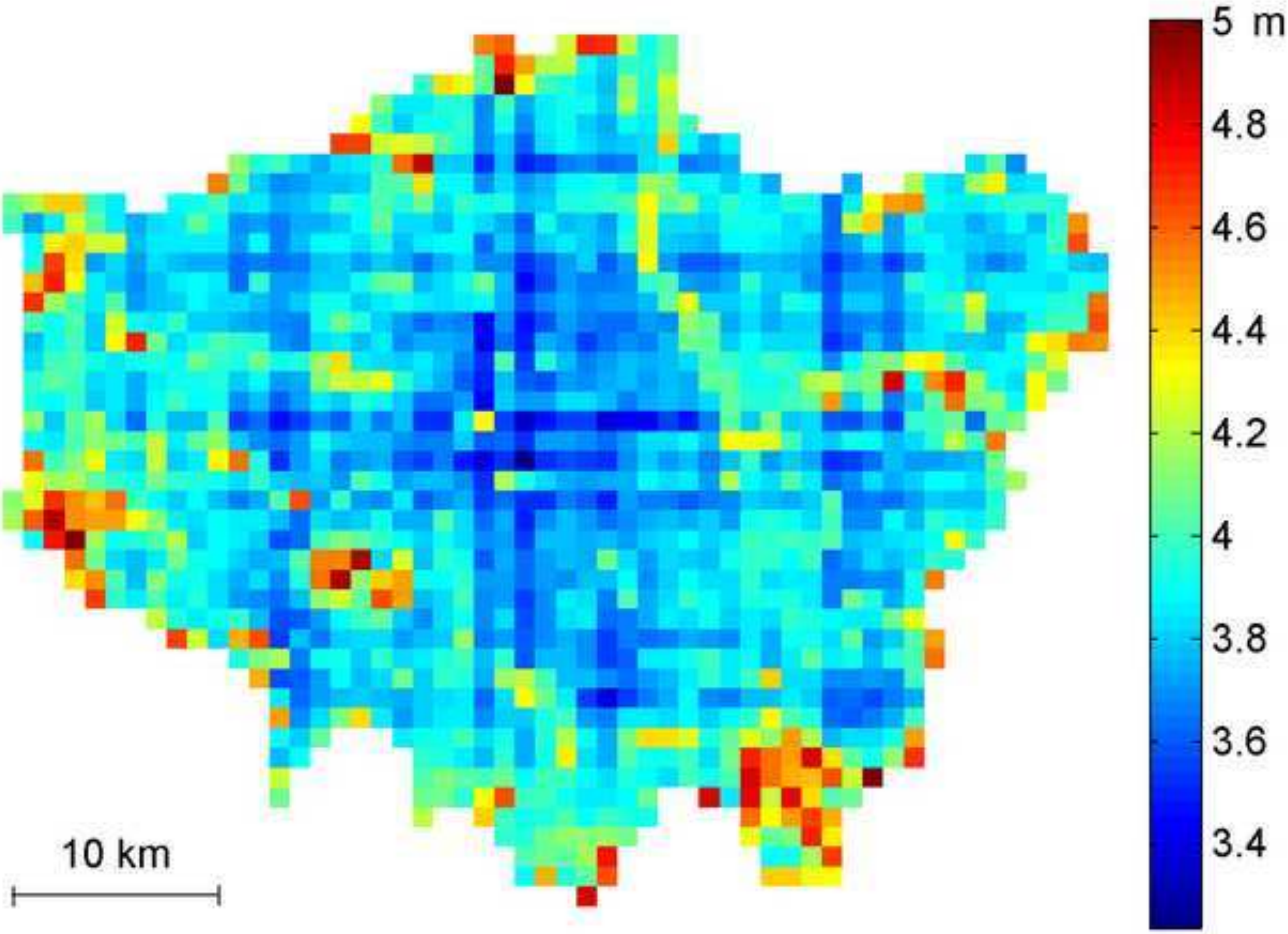

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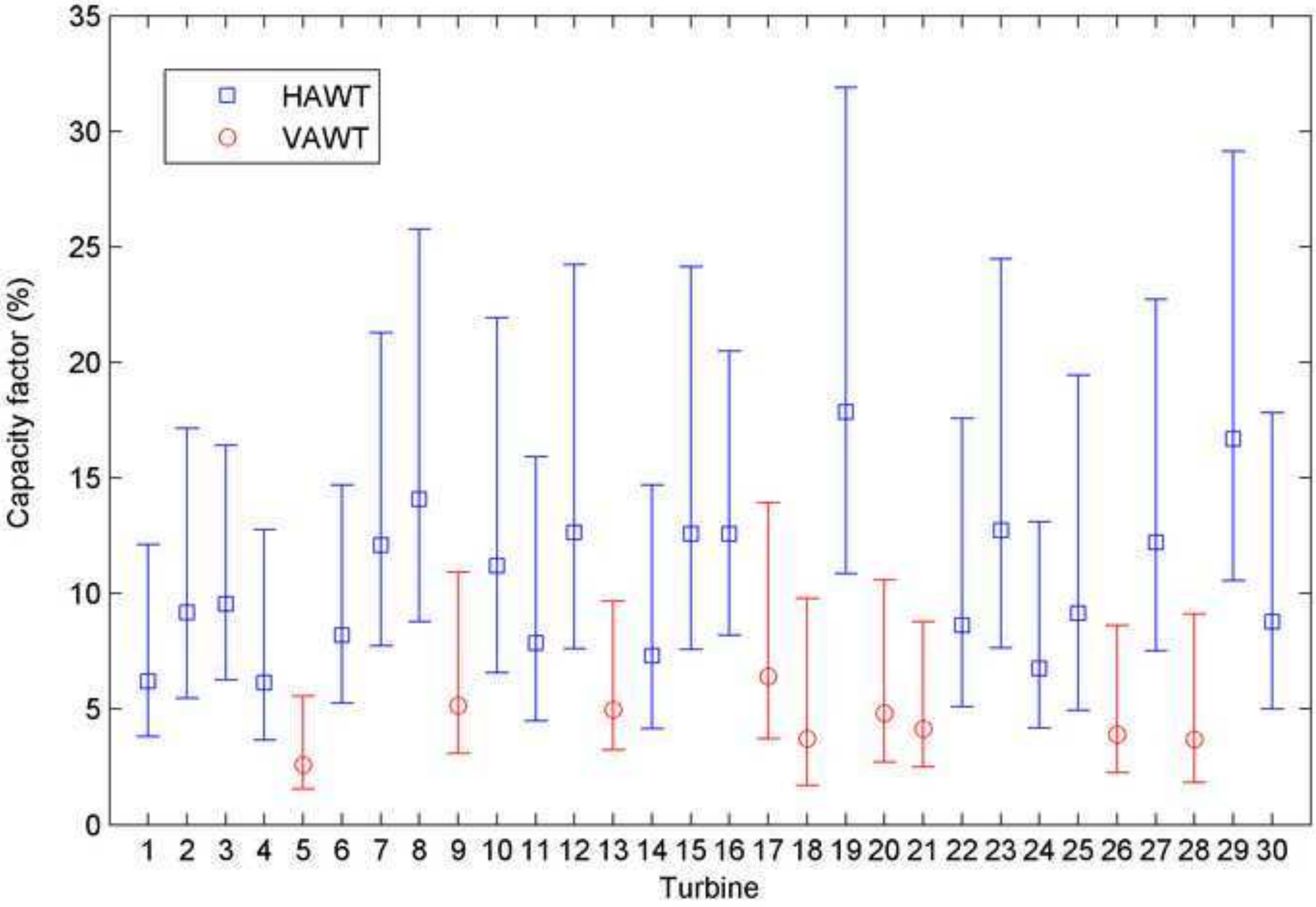

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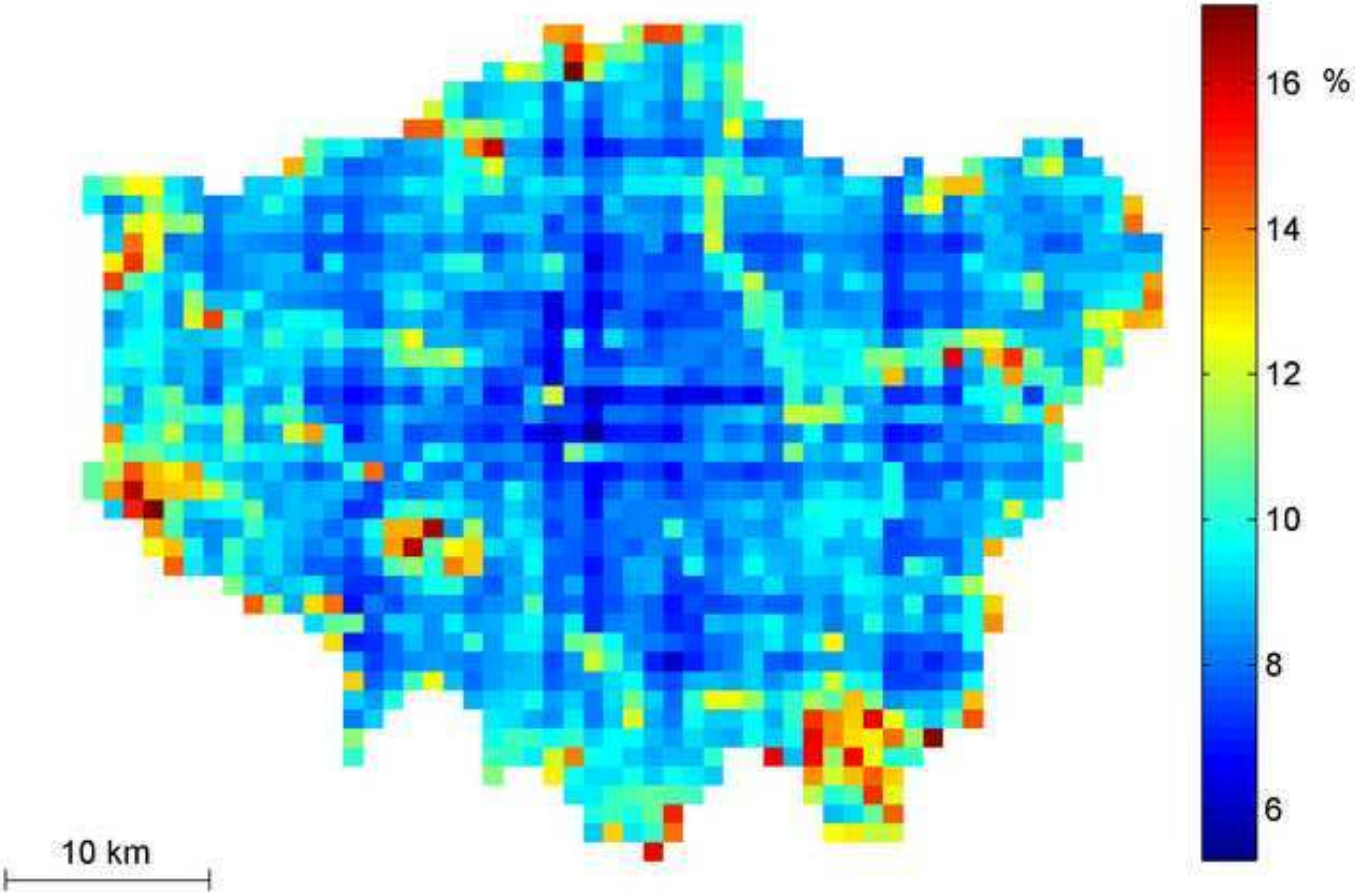

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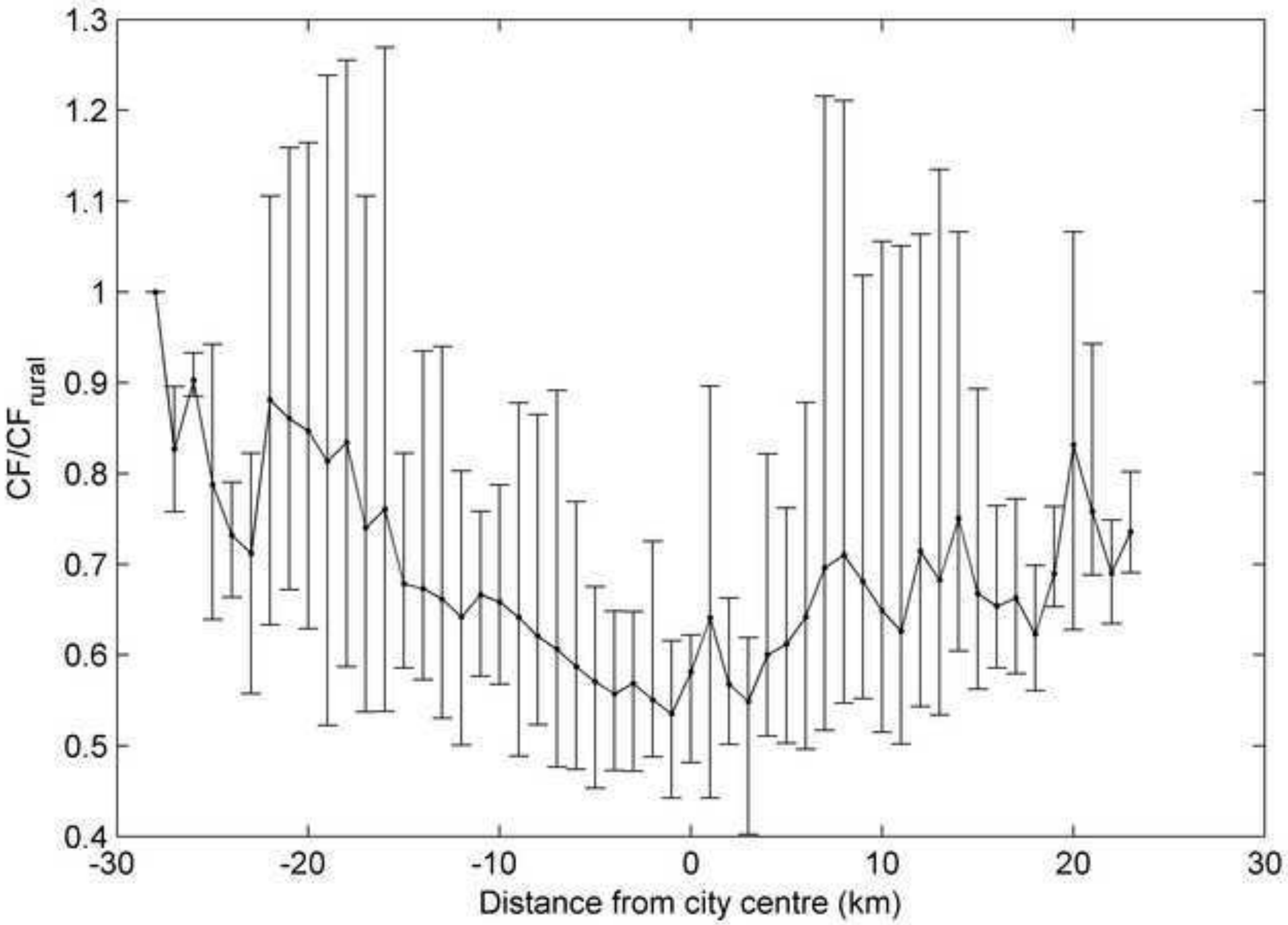
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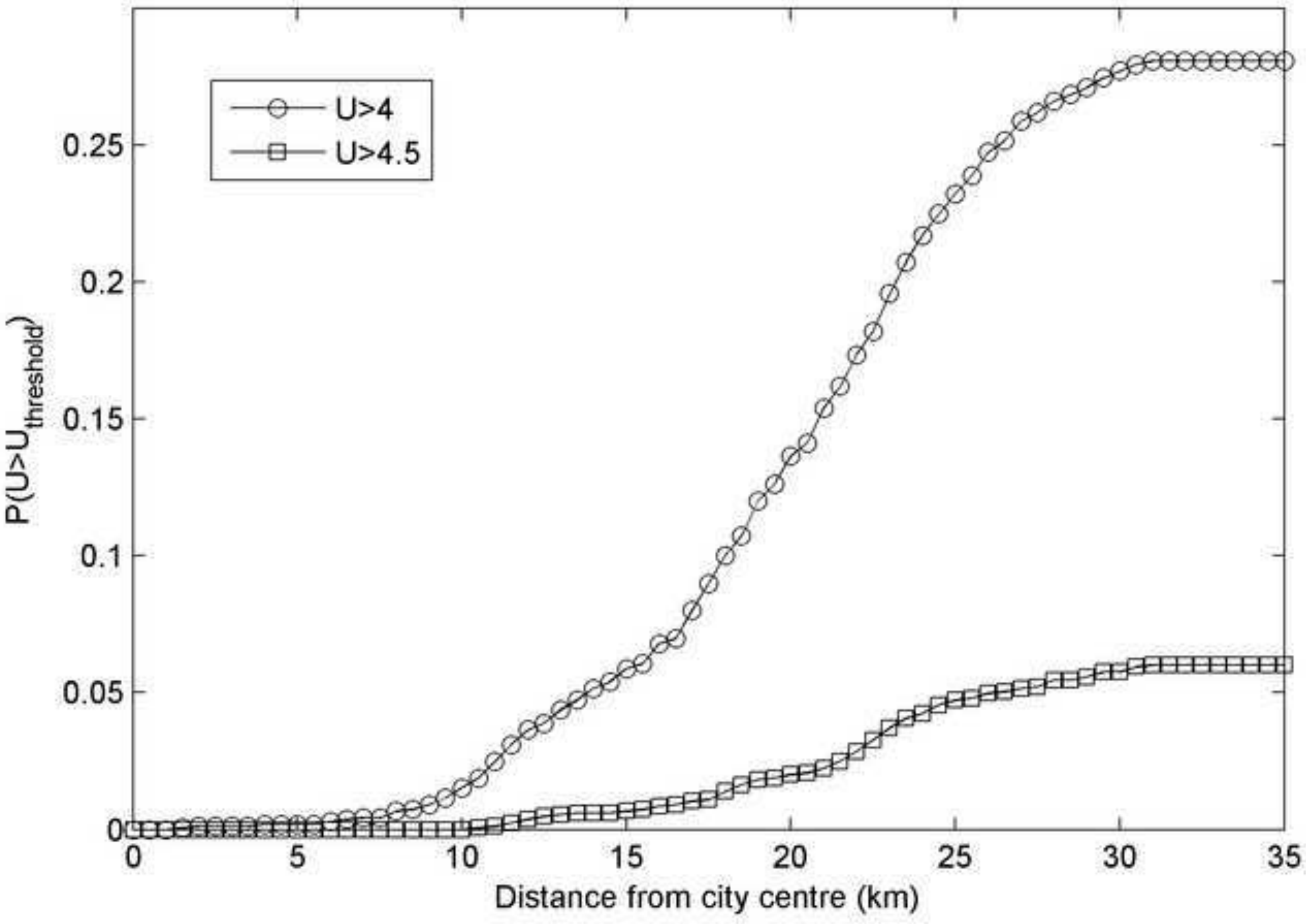
Distance from city centre (km)

Figure8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Distance from city centre (km)