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Development of an updated fundamental basic wind speed map for SANS 10160-3

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This paper evaluates the need for updating the strong wind climate stipulations of South Africa for the design of structures in accordance with SANS 10160-3:2010, as based on the latest information presented by Kruger *et al* (2013a; 2013b). The primary objective is to provide the geographic distribution of the characteristic gust wind speed by means of the fundamental value of the basic wind speed, stipulated as $v_{b,0}$ in SANS 10160-3. A reassessment of previously published information is made to incorporate additional wind speed modelling results and to investigate identified anomalies. The format of presentation, based on local municipal districts, is subsequently motivated, assessed and implemented. In order to provide for situations requiring the consideration of the dynamic effects of wind loading, similar information on characteristic hourly mean wind speed is provided. It is concluded that the presentation of wind speed on a district basis provides an effective balance between the spatial resolution of the available information and its use in operational standardised design.

INTRODUCTION

Stipulation of the geographical distribution of the free field wind speed across South Africa provides a direct link to the strong wind climate of the country and the design wind loads on structures. The nominal treatment of the map of the fundamental value of the basic wind speed $v_{b,0}$ was identified as one of the major deficiencies of the South African National Standard SANS 10160:2010 *Basis of structural design and actions for buildings and industrial structures* Part 3 *Wind Actions* (Goliger *et al* 2009). The publication of SANS 10160-3:2010 (reissued in 2011 with corrections) was therefore followed up with extensive investigations into the strong wind climate of South Africa and the statistical treatment of strong wind observations to derive extreme value probability models, and the compilation of representative free field wind speed maps (Kruger 2011; Kruger *et al* 2013a; 2013b).

Prior to the latest revisions of extreme wind statistics, a comprehensive strong wind analysis for the purpose of the South African loading standard was conducted in 1985 (Milford 1985a; 1985b). Considering that wind loading represents the dominant environmental action in South Africa to be considered in the design of structures, an accurate estimation of strong winds is of cardinal importance to the built environment, and should be updated as new information becomes available. A review of the historical development of climatic data for wind load design in South Africa is provided by Goliger *et al* (2017).

The updated maps and statistics not only take into account the historical increase in the availability of extreme wind data in South Africa (presently at least seven-fold), but also considers a range of the most widely applied statistical procedures utilised internationally in the estimation of extreme wind statistics. The choice of appropriate statistical methods depends largely on the length and quality of data records, the exposures of associated measuring instruments, the mixed strong wind climate of South Africa, as well as the averaging time scales. For example, there are fundamental differences between the methods suitable for the estimation of extreme hourly average wind speeds, which have high volumes of temporally interdependent strong wind values in their associated data sets, and gust speeds, which have lower interdependence.

This paper presents the background to the reassessment and application of the strong wind information in a format that is suitable for implementation in standardised structural design and thereby for incorporation into an update of SANS 10160-3. The stipulation of the basic wind speed provides the starting point for the process. The representation of $v_{b,0}$ as the gust wind speed constitutes the only rational way to resolve the differences between synoptic, convective thunderstorm and mixed climate strong wind. This implies that the introduction of $v_{b,0}$ as the 10-minute mean wind speed, in order to be consistent with the reference Eurocode standard EN 1991-1-4:2005, ought to be reversed to the practice followed in SABS 0160:1989. The stipulation of $v_{b,0}$ as

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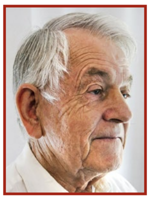

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the 1:50 year or 0.02 fractile of the annual extreme gust wind speed forms part of the reliability representation of strong wind occurrences. Although structural dynamic effects are beyond the scope of SANS 10160-3, mapping of the hourly mean characteristic wind speed is readily available from the background research, and is therefore included here as additional information on the South African strong wind climate.

An initial update of $v_{b,0}$ is presented by Kruger *et al* (2013b). The resultant map of v_k, the 1:50 year gust wind speed derived from automatic weather station data of the South African Weather Service (SAWS), is considered here as the basis of the update of statistics for $v_{b,0}$. However, reassessment is needed to review some anomalies that can be identified from the published maps in terms of apparent outliers. Additional metadata on the influence of terrain conditions on strong wind measurements are taken into account. Complementary information on strong wind occurrences, based on reanalysis of synoptic information during wind storms, provides extensions of the probability models based on annual extreme value observations. Reanalyses of the results are particularly useful for spatial interpolation of values and consideration of complex topography.

For implementation as a design wind map, a suitable format is needed to fully exploit the geographic resolution of strong wind information, whilst the stipulated wind speed is presented in an unambiguous normative manner for use in operational design. The selection of the areas corresponding to local municipal districts, as the units for the geographical description of $v_{b,0}$, is motivated and assessed. Alternative schemes are considered for selecting wind speed intervals to represent the continuum of values. Various constraints affecting the resolution of the format for the stipulation of $v_{b,0}$ are taken into account.

The main steps in compiling the map of the fundamental values of the basic wind speed can be summarised as:

i. the optimal selection of wind speed intervals,
ii. deriving optimal values to local municipalities with measurements, and
iii. assigning values to the remaining municipalities through interpolation.

Subsequently, the consistency of values is checked between contiguous areas, specifically the metropolitan regions, but also for smaller areas where high values were obtained. From the above it follows that an iterative process is necessary, with due consideration of the original measurements, to converge to a map that is consistent with the overall resolution of information and operational requirements.

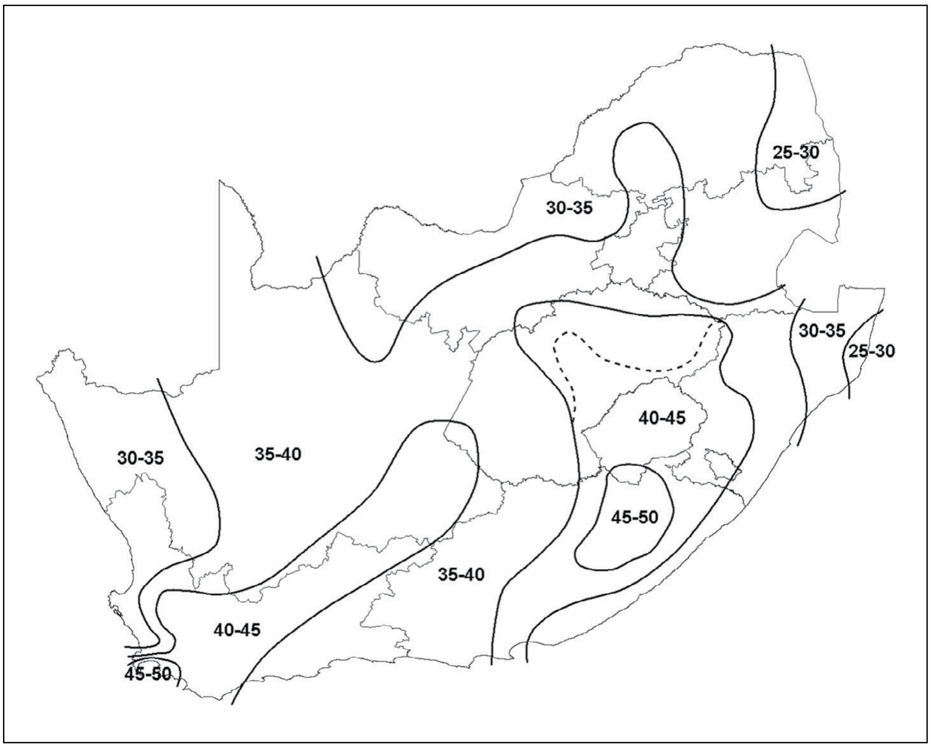

Figure 1: Map for 1:50 year gust speed (v_k) developed from measured data (Kruger *et al* 2013b)

The main features of the resulting map are summarised in conclusion, considering the advancement achieved compared to the present map. The potential for future updating is assessed, as based on extension of the dataset for both the present automatic weather station (AWS) records to improve the time variant probability models, and the inclusion of additional AWS data to extend the spatial resolution.

REASSESSMENT OF UPDATED STRONG WIND STATISTICS

Main features of revised maps for characteristic wind speed

The primary output of the updated statistical analysis and mapping of the South African strong wind climate is a map of the characteristic gust wind speed (v_k) shown in Figure 1 (Kruger *et al* 2013a; 2013b). Quality control measures and extreme value analysis to derive input values for this map are discussed in these references. As v_k is derived from the instantaneous wind speed measured from automatic weather stations (equipped with an RM Young propeller sensor), the time-resolution of the wind speed value obtained is 1 s, instead of the 2–3 s which is the conventional gust standard. Shorter duration gusts than the standard 3 s are more appropriate for structural design (Holmes & Ginger 2012; Holmes *et al* 2014). Differences in the response of the AWS and the structure are not accounted for in the map for $v_{b,0}$ on the assumption that it is included in the uncertainties provided for by the procedures for determining the wind load.

The main feature of this map, compared to the current map of the basic wind speed ($v_{b,0}$) given in SANS 10160-3:2010, is its increased complexity due to the improved resolution resulting from a spatially denser network of observations and consideration of the mixed strong wind climate. Values of v_k range from 45–50 m/s in the southwest extreme to 25–30 m/s in the northeastern regions; on a localised scale a range of 30–50 m/s is obtained within the Cape Town metropolitan district. Significant spatial features can be observed at intermediate scales, particularly for wind speeds above 40 m/s.

A critical assessment of Figure 1 in comparison to the underlying wind speed data indicates the smoothing effect of the interpolation needed to represent v_k as wind speed intervals, which may omit significant sub-regional trends. In addition to finding a suitable format for presenting v_k as the basic wind speed $v_{b,0}$, a reassessment and updating with new information is needed.

A direct comparison between the wind speed given by Figure 1 for v_k and for $v_{b,0}$ in SANS 10160-3:2010 is reported by Kruger *et al* (2013b), indicating a noticeable reduction over large regions of the country, particularly towards the north, including the metropolitan regions of Gauteng.

Moderation of updated gust statistics

The estimations of the design values developed in Kruger *et al* (2013a; 2013b) took into consideration:

i. The selection of appropriate statistical methodologies

ii. The provision for uncertainty in the results due to the use of short wind time series
iii. The spatial extents of relevant strong wind mechanisms (Kruger *et al* 2010; 2011a–b; 2013a)
iv. Adjustment of wind speed measurements to account for non-standard terrain roughness surrounding the AWSs (Kruger 2011).

The adjustment for terrain roughness was identified to be the most subjective, partly due to the limited metadata information on the roughness conditions surrounding each AWS. Assessment was limited to Google Earth aerial imaging, where roughness classification could not be based on inspection records or photographs for the surrounding environments for an AWS (Kruger 2011; Kruger *et al* 2013c). These roughness adjustments had a significant influence on the estimation of the extreme wind statistics, as reported by Kruger *et al* (2013a & b). The measurements at the Strand, Elliot and Umtata stations where v_k values exceed 45 m/s, were identified as requiring further scrutiny.

Recently SAWS has embarked on a comprehensive programme of updating all metadata in its AWS network. This involves documenting the environment around the AWS, including estimated distances to significant obstacles, tabulated assessments of surface roughness, nearby topography, and photographs of the AWS taken from each of the four main wind directions. This updated information made the objective reassessment of wind speed values possible, where adjustment of measured wind speed to an equivalent value for Terrain Category 2 terrain roughness made previously, could have been too conservative.

For the Strand, updated assessment based on photographic documentation (Figure 2), indicates standard roughness towards the northern sectors. Where wind speed was initially adjusted by as much as a factor of 1.67, a significant fraction of the measurements was used subsequently without adjustment. Consequently v_k could be reduced from 46.7 m/s to 41.0 m/s for this location.

The station at the Umtata Airport, which is well exposed, remained at 45 m/s. The value at Elliot could be re-estimated from 46.0 m/s to 44.7 m/s by extending the time series, effectively diluting the influence of a small number of relatively high annual maximum values.

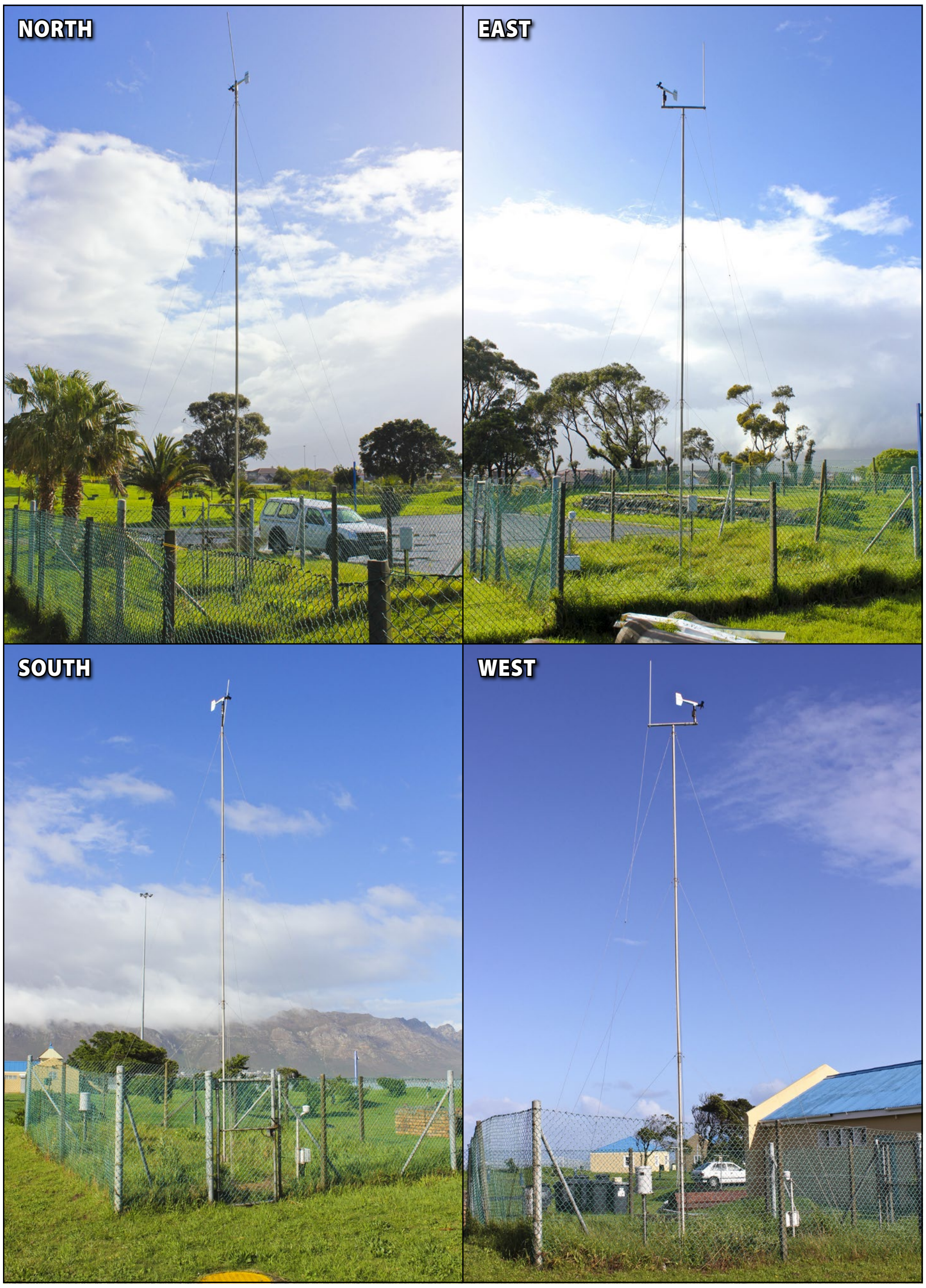

Figure 2: Photographs of the Strand weather station from the main wind directions as indicated

Input from the Wind Atlas project

The Wind Atlas for South Africa (WASA 2015) project is coordinated and run under the auspices of the South African National Energy Development Institute (SANEDI). The main aim of the project is to identify regions of high wind energy potential in the country. The project partnership includes SANEDI, the University of Cape Town (UCT), the Danish Technical University (DTU), the Council for Scientific and Industrial Research (CSIR) and SAWS.

The WASA project included a work package managed by SAWS and DTU, aimed at the development of information on extreme wind speeds. The class of wind turbine at a specific location is hence based on the extreme wind speed to be expected over a 50-year period. The atlas provides high-resolution maps for the project domain at two time scales, i.e. gust (2–3 s) and a 10-minute averaging period. An important component of the project relates to the integration of the extreme wind statistics derived from model and measured data, from which the final maps could be developed. Particularly the modelling part of the project required the development of new methodologies, to take into account the complex strong wind climate of South Africa (Kruger *et al* 2014; Larsén & Kruger 2014; Larsén *et al* 2013a and b; Larsén *et al* 2015). The verification of the modelled results comprised thorough comparisons with the results derived from measurements, i.e. those in Kruger *et al* (2013b). Where discrepancies occurred, particularly where the modelled results were significantly lower than those from the measurements, upward adjustments were made to the modelled data. In addition, all values were adjusted upwards to the closest 5 m/s interval above the specific values, accounting for the inherent uncertainty in extreme wind estimations, and also for simplification purposes, to produce the final statistics for the 1:50 year gust map at a resolution of about 4 km. These verified high-resolution outputs

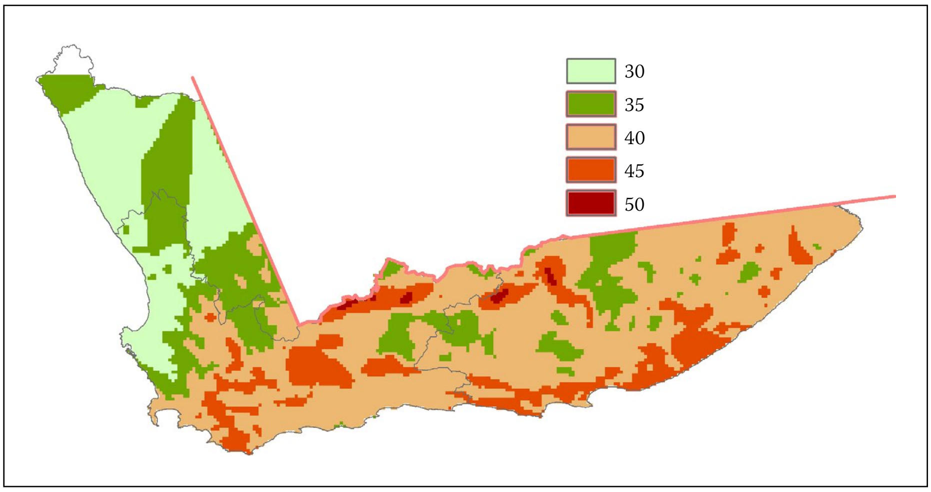

Figure 3: 1:50 year wind gust values developed in WASA Phase 1 (m/s)

proved to be invaluable for the assignment of return values, especially within sparsely populated and topographically complex regions, where results from measured data were scarce or non-existent.

Figure 3 presents the 1:50 year wind gust map for the spatial domain of WASA Phase 1, concluded in March 2014. Apparent from the map is that most values in the southwestern Cape and eastwards are 40–45 m/s, while to the north of the southwestern Cape it is lower at 30–35 m/s. This pattern broadly confirms the results produced from measurements (Kruger *et al* 2013b), but also emphasises the role of local topography as a significant factor in the potential of strong wind gusts to develop. Examples of these are especially visible in the northeast and east of the domain, e.g. the isolated values of 50 m/s in the Nuweveld Mountains north of Beaufort-West and the Sneeuberg mountain range to the north and northeast of Graaff-Reinet. In contrast, lower values are shown in areas with relatively lower elevation than the surrounding areas, e.g. between the Swartberg and Nuweveld mountain ranges to the south of Beaufort-West, and to the east of the Sneeuberg mountain range.

Considering the spatial variability of strong winds due to local topographical features, it is important to note that the design wind statistics to be implemented in the loading standard should provide a conservative estimation of 1:50 year gust values over flat terrain, which conforms to Terrain Category 2. Special provision, as stipulated in the code, has to be made for those cases that do not conform to the above criteria. The WASA gust map shown in Figure 3 provides realistic data on strong wind climatology over the project domain, and it reflects the topographical detail which is expected to be resolved separately in the loading standard. The WASA map is therefore used mainly for interpolation purposes, while drafting the map for SANS 10160-3. The information presented in Figure 3 nevertheless provides useful background information for any designs within that region, particularly for mountainous localities.

BASIC WIND SPEED FORMAT

The objective of formatting the data on the basic wind speed is to present the updated information on the characteristic wind speed v_k as the fundamental value of the basic wind speed $v_{b,0}$ unambiguously geographically across the country in terms of a stipulated wind speed interval. Whilst the map of v_k and the WASA reanalysis are taken as indicative of regional trends, the updated set of $v_{k,\mathrm{AWS}}$ wind speed values are considered as the basis for stipulating $v_{b,0}$. This provides a limit to the spatial resolution of the format, determined by the 74 AWS dataset used by Kruger *et al* (2013a and b). The resolution of the wind speed range of 29–45 m/s is limited by the record period of 10–18 years. Some enhancement is achieved through advanced extreme value probability modelling, including the peak-over-threshold method for the short time series, as well as the statistical assessment of the mixed strong wind climate. Constraints on the resolution are eventually mitigated by the reliability modelling that accounts for all residual uncertainties, in addition to the time-variant nature of windstorms.

Basis for spatial resolution – local municipal districts

Presentation of the basic wind speed $v_{b,0}$ on a scale similar to that implied by the point values derived from the network of 74 AWS records, $v_{k,\mathrm{AWS}}$ should ensure the optimal use of the underlying information. This is in contrast to the approach taken for the compilation of the latest map of v_k, where an extensive set of isophlets is derived through a process of interpolation, including a degree of subjectivity (see Figure 1). Although the geographical distribution of local authority districts may appear to be unrelated to the strong wind climate of the country, similarities in the scale are nevertheless apparent when it is noted that there are 52 metropolitan areas and district municipalities, with a total of 240 local municipality districts. Additional commonalities can also be identified, such as the placement of AWSs, concentration of structures, regulatory functions of district centres, and even the influence of topographical features, e.g. mountain ranges and valleys, often forming natural district boundaries.

The use of a combination of metropolitan and district municipality areas will result in a close match between map zones and $v_{k,\mathrm{AWS}}$ values. However, such coarse zoning would lead to an underutilisation of the available information. Furthermore, such zoning results in zero to five $v_{k,\mathrm{AWS}}$ values per zone, with multiple values obtained for both large districts, such as the Northern Cape Province, and smaller districts, resulting from the nature of geography or settlement. This format was therefore not investigated further.

Local municipal districts, together with metropolitan areas, were therefore selected as basis for zones to represent uniform values of $v_{b,0}$ per zone, as derived from $v_{k,\mathrm{AWS}}$ values obtained for the districts where the AWSs are situated. The average ratio of about three local municipalities to an AWS data point implies a mild degree of interpolation to estimate $v_{b,0}$ values for all zones across the country. The mapping process is thereby discretised into 240 zones across the country to use as footprint for each of the 74 AWS data points ($v_{k,\mathrm{AWS}}$), with discrete interpolation for the remaining zones.

Wind speed resolution

Wind speed is presented in discrete format as $v_{b,0}$ values to represent selected intervals of $v_{k,\mathrm{AWS}}$ values. The value of $v_{b,0}$ is selected at mid-range of the interval in order not to introduce a conservative bias into the format. The limit of 5 m/s applied to the v_k map (Figure 1) was relaxed to consider intervals of 4 m/s and 3 m/s. Such refinement was deemed to be justified by the simplification of the spatial zoning. Fragmentation of the discrete mapping of $v_{b,0}$ was used as basis for setting a lower limit of 3 m/s, to the wind speed intervals.

Assessment of discrete format

While there was a significant improvement in the availability of data for the development of the maps in Kruger *et al* (2013a & b) compared to when the previous map was developed by Milford (1985a & b), the eventual spatial resolution can still be considered as inadequate over many regions of the country, especially those with significant topographical variation. The use of only in-situ measurements, which is the case for the greatest part of South Africa, will, at best, be able to provide a general impression of the strong wind climate only.

However, it should be considered that the vast majority of weather stations are located close to main built-up centres, particularly towns. In many cases these stations are situated at the local airports, which are in open terrain but still relatively close to built-up centres. Therefore it can be argued that the measurements from weather stations can be considered to be biased towards the areas of densest population or of strategic/developmental importance. This justifies an assumption that the strong wind statistics from the weather stations are largely representative of the built-up areas of the local municipalities in which they are located. The development of new infrastructure is most often also biased towards these areas.

Referring to municipal borders, these follow, where possible, the local topography and other natural features. Figure 4 presents a map of the topography of South Africa, with the local municipal borders superimposed. It is apparent that some borders between provinces, e.g. between the Free State and KwaZulu-Natal, and the Western and Northern Cape provinces are defined by the topography, particularly the escarpment, which in turn dictates the municipal borders in the relevant areas. Especially in the Limpopo, Mpumalanga, Eastern Cape and Western Cape provinces many local municipal borders follow the regional topography.

A third important consideration, which is relevant to the practicality and user-friendliness of the final basic wind speed map, is that it would be convenient to unambiguously identify the appropriate basic wind speed value by only having to reference the value assigned to the local municipality where the structure is planned. This provides a direct link between the design process and the regulatory function of local authorities.

Adjacent regions of high economic activity

It is preferable that in contiguous regions of high economic activity the development should be subject to design criteria that are consistent across common municipal borders. It was therefore deemed sensible to assign single design values to those district municipalities or larger regions where economic activity is relatively high and integrated. These large metropolitan regions include Gauteng, south-western Cape, Port Elizabeth and Durban.

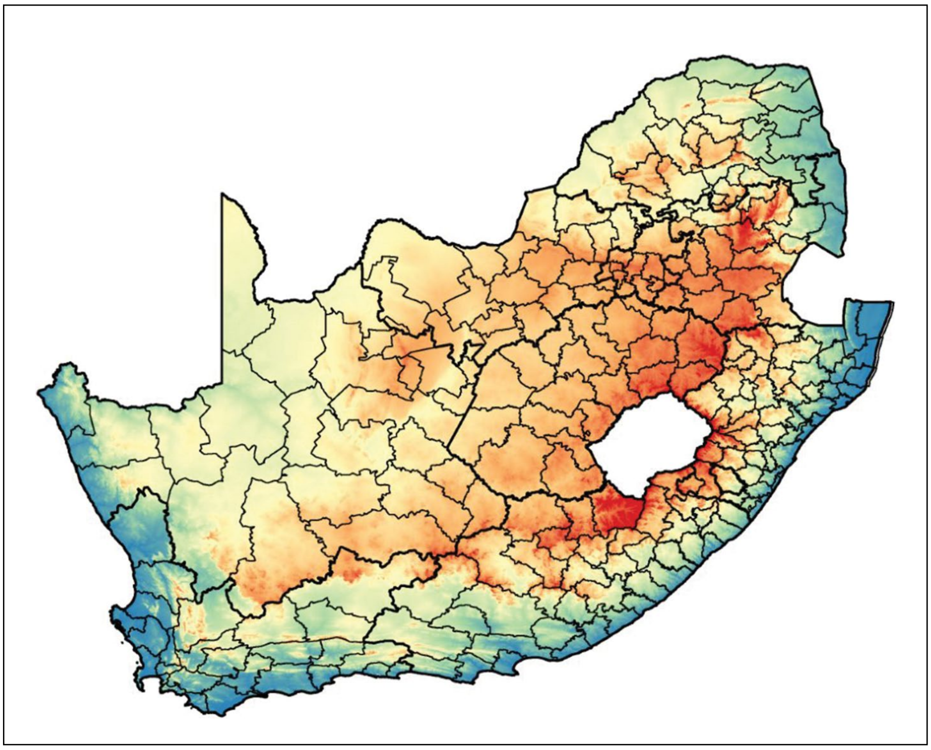

Figure 4: Topography of South Africa, with local municipal borders superimposed

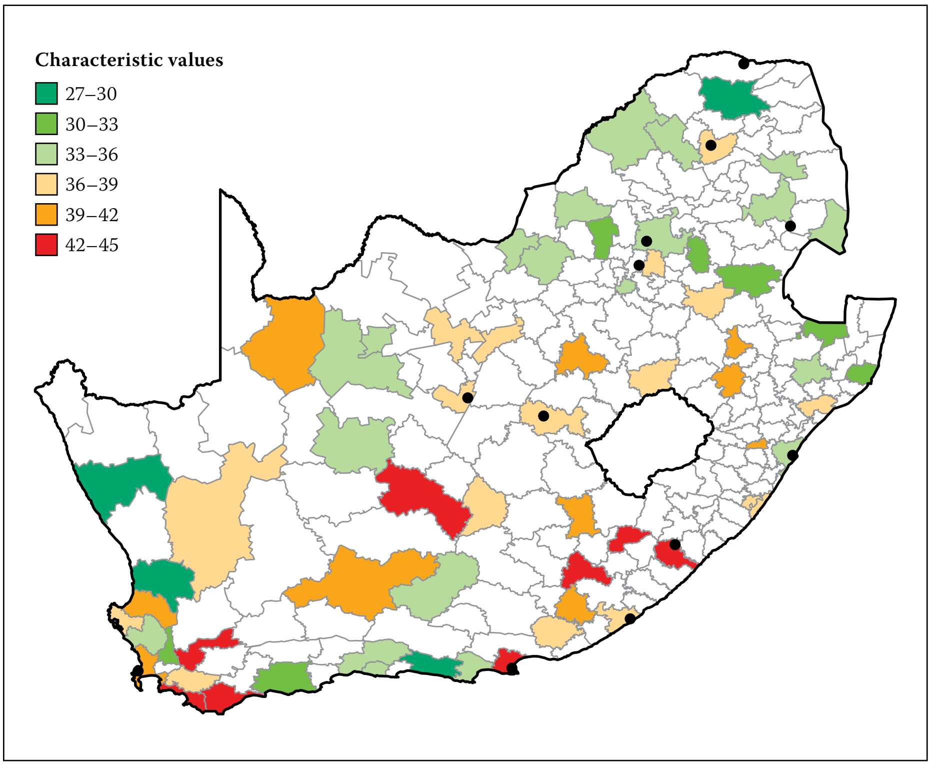

Figure 5: Basic map of $v_{k,AWS}$ values as assigned to zones within which AWSs are located

IMPLEMENTATION

The main steps for implementing the representation of $v_{b,0}$ according to the discrete spatial and wind speed format are as follows:

i. Set up a basic map of $v_{k,AWS}$ values for the zones representing the AWS positions.
ii. Derive the $v_{b,0}$ values from an appropriate set of wind speed intervals.
iii. Extend the basic map to all zones, considering related information, including some degree of simplification.

Basic map of $v_{k,AWS}$ values

The geographic input information of $v_{k,AWS}$ values that serve as the basic map for the implementation of the zone-based mapping of $v_{k,AWS}$ is shown in Figure 5, as arranged in 3 m/s intervals starting from the maximum value of v_k = 45 m/s (white areas reflect municipal regions in which no relevant/adequate wind speed records are available). The basic map provides information on the features of local districts, serving as discrete zones, sampling of $v_{k,AWS}$ values and the extension needed to stipulate $v_{b,0}$, the distribution of $v_{k,\text{AWS}}$ wind speed values.

Striking features of the district-based zones are the irregular shapes and size, ranging from dense networks to large zones, generally from east to west. A surprisingly large number of unpopulated zones, shown in blank, are adjacent to at least one AWS zone. The exception is a substantial region of KwaZulu-Natal and the Eastern Cape where the AWS network does not provide any measured data.

On a countrywide scale there is a clear trend of decreasing wind speed from south to north, with low to high values occurring in the southern third of the country, medium to low values for the central third, and generally low values for the northern third. The complexity of the southwestern part of the country is illustrated by the full range of six intervals of $v_{k,\text{AWS}}$ values over a small cluster of adjacent zones. A mild degree of fragmentation can also be observed over the central parts of the country, mostly in the Free State and Northern Cape provinces.

Set of stipulated $v_{b,0}$ values

The intervals of the isophlets on a map can be considered to be a compromise between the required detail and sufficient spatial information. For the map of design wind gust values, additional factors were considered, mainly:

i. The reassessed values in the Eastern and Western Cape
ii. The assignment of unique values at local municipal level
iii. The objective to assign the same values to larger regions with relatively high and integrated economic activity.

For the hourly map, to be provided as additional information in the revised code, reassessment of the characteristic hourly wind speed is not deemed to be necessary, so that only factors (ii) and (iii) are applicable.

Selection of characteristic values

The scale of values for $v_{b,0}$ selected to represent the range of $v_{k,\text{AWS}}$ values from 28.7 m/s to 45 m/s can be determined algorithmically by selecting the starting point, the interval and the assigned value within the interval. To be consistent with the reliability-based approach, $v_{b,0}$ is selected as the mid-value of the interval. As motivated above, the interval of 5 m/s used for the isopleth map could be reduced due to the area zoning used for $v_{b,0}$. Three intervals of 5 m/s, 4 m/s and 3 m/s were considered. Without rounding off, four $v_{b,0}$ values are needed to scale the range for 5 m/s and 4 m/s intervals and six values for 3 m/s interval.

The statistics of the ratio of $r = v_{b,0} / v_{k,\text{AWS}}$ per zone was used as a diagnostic tool to assess the consistency of the match between

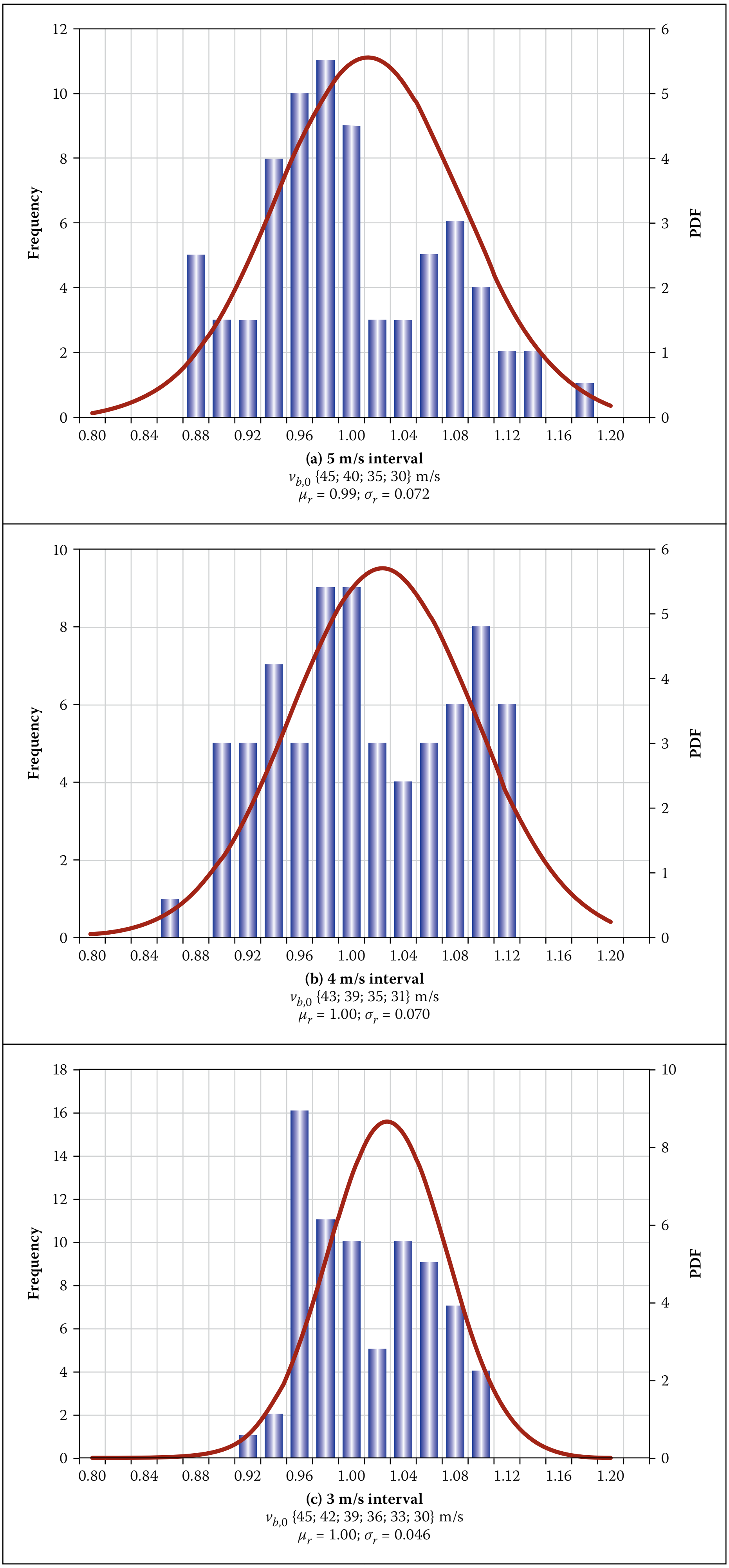

Figure 6: Match of $v_{b,0}$ to $v_{k,\text{AWS}}$ values for alternative wind speed intervals

the resulting $v_{b,0,\text{zone}}$ and input $v_{k,\text{AWS}}$ values. The mean of r (μ_r) is an indication of any bias, which is intended to be close to 1.0. The standard deviation (σ_r) indicates dispersion, aimed to be as small as possible. A uniform set of r values indicates an even spread across the interval. Indicative results are displayed in Figure 6.

The above results indicate no effective bias, comparable dispersion for 5 m/s and 4 m/s intervals, and a noticeable reduction in dispersion for the 3 m/s case. The 4 m/s case provides the closest approximation of a uniform distribution. The dispersion and uniformity of r values are relatively sensitive to the selected values of $v_{b,0}$, which are mostly influenced by small numbers of observations at the low and high extremes. For further analysis the set of values for a 4 m/s interval was adjusted to {44; 40; 36; 32} m/s rounded values, introducing bias from a longer lower tail, with μ_r = 0.98; σ_r = 0.075.

Spatial interpolation

The selection of the range of $v_{b,0}$ can be assessed quantitatively and rationally for the set of zones with AWSs, with uncertainties fully accounted for in the reliability assessment. Assignment of values to unpopulated zones is more difficult, requiring a strong element of judgement based on interrelated but indirect information. This process is complicated by the fragmented nature of the basic map of $v_{k,\text{AWS}}$ shown in Figure 5.

The first step of the process is to apply the $v_{b,0}$ values corresponding to 5, 4 and 3 m/s intervals to the AWS zones (see Figure 7). Close inspection shows virtually no difference for the two upper $v_{b,0}$ values for the 5 m/s and 4 m/s cases, relevant to the central and southern third regions of the country. The most significant changes are from the second lowest to the lowest interval for three zones in the far south and for six zones across the northern and northeastern regions. In spite of the difficulties of comparing four $v_{b,0}$ categories for the 4 m/s case, with the six categories for the 3 m/s interval, a similar pattern can be observed, with an increase in the number of zones in the lowest category corresponding to 3 m/s; in this case a few similar isolated changes occur for the midrange categories.

The basic $v_{b,0}$ map shown in Figure 7 was used to derive alternative trial maps for the three interval cases as shown in Figure 8. As a simplification of the 3 m/s map, the lowest two intervals (33 m/s and 36 m/s) were combined to result in the use of 5 intervals, with the lower limit for $v_{b,0}$ set at 33 m/s. This led to diagnostic statistics close to those of the 4 m/s format.

Since the reliability performance of the interpolation stage of the mapping process

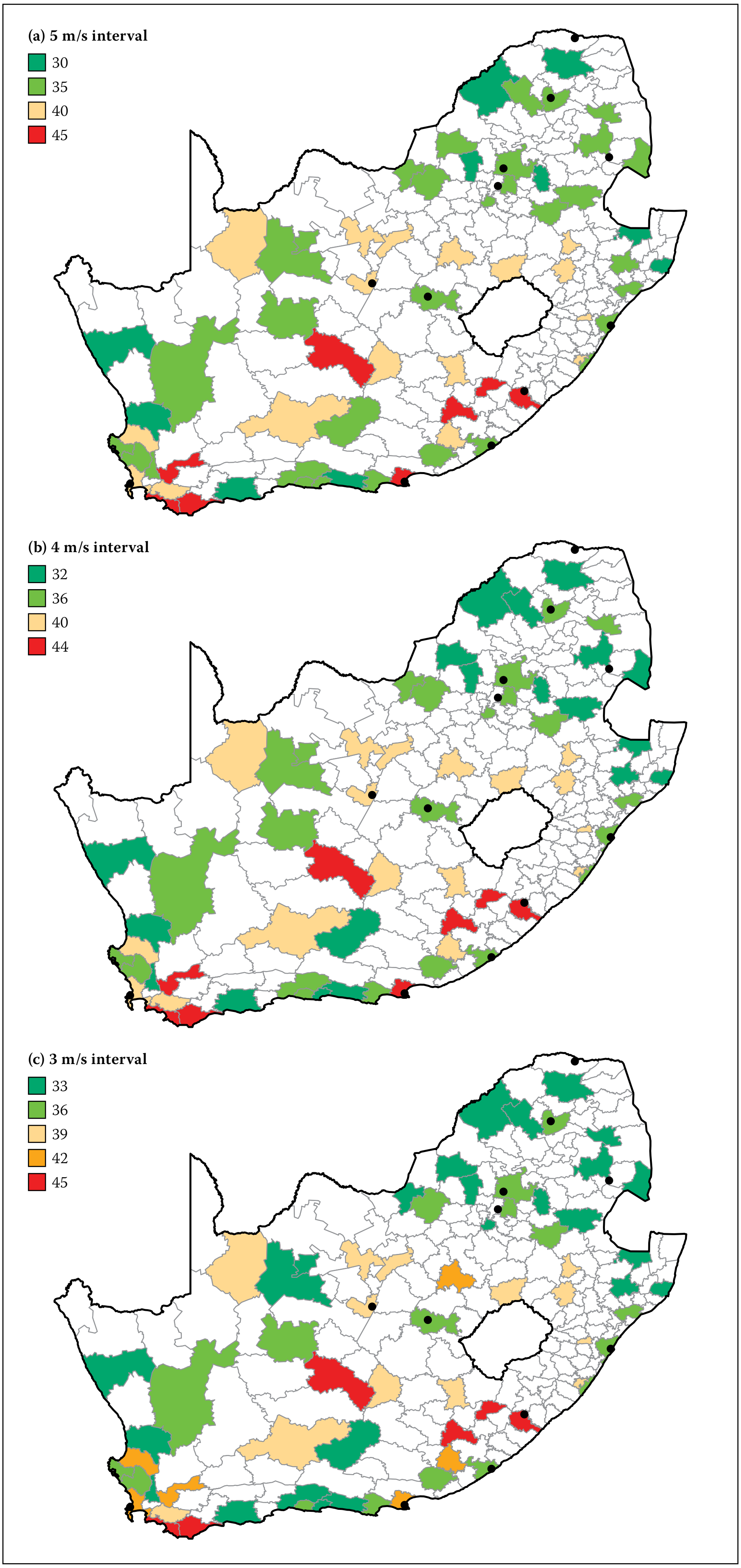

Figure 7: Basic map of $v_{b,0}$ values as assigned to AWS zones as a function of alternative cases of wind speed interval

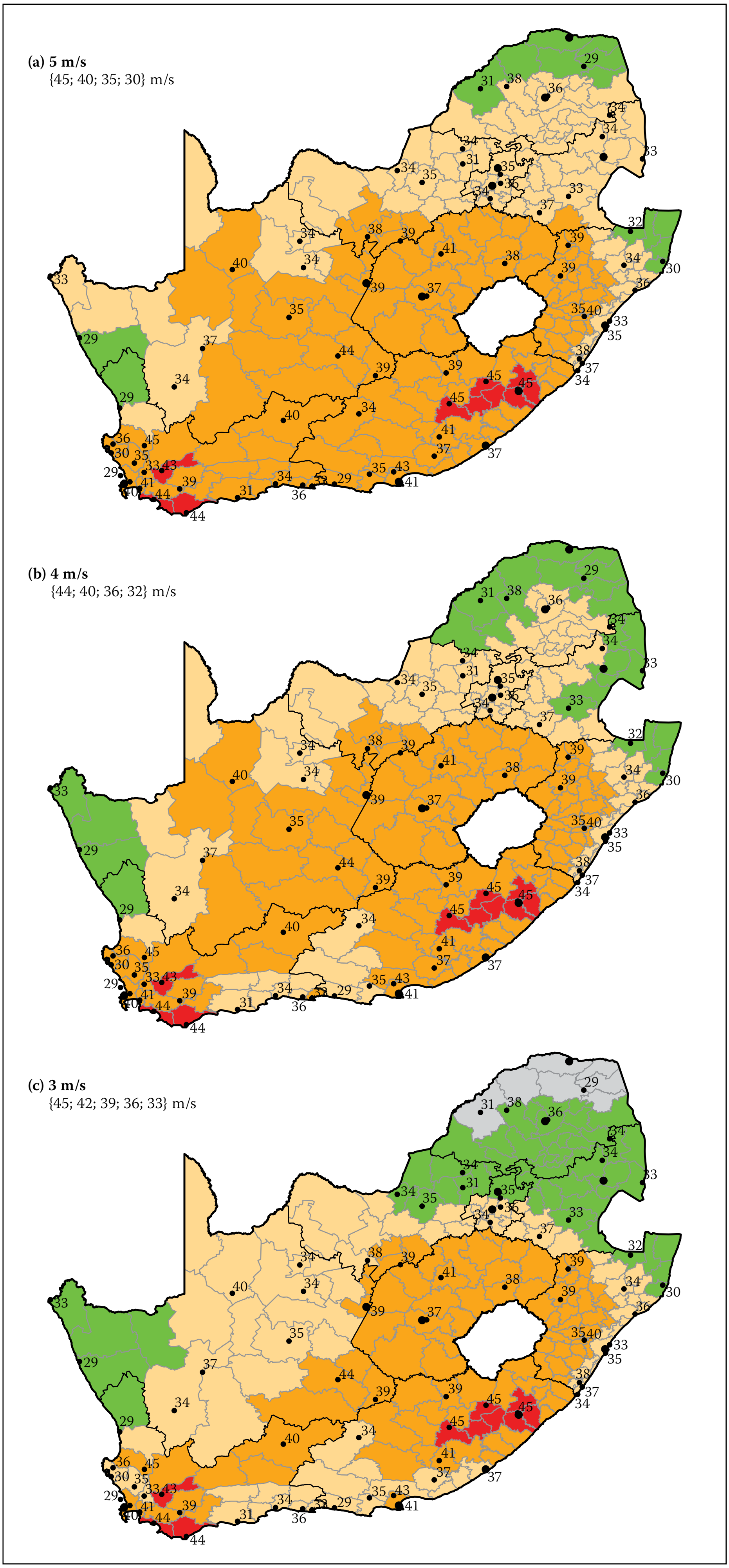

Figure 8: Trial maps of $v_{b,0}$ for South Africa

cannot be quantified, the tendency was adopted to adjudicate on the conservative side whenever the decision-making was not clear cut. Examples of a conservative approach are smoothing of the upper limit of the complex array of regions for the southwestern region, a safe value assigned to large uncharted regions of KwaZulu-Natal, and somewhat conservative treatment of the central regions of the country. A degree of smoothing out of the high value obtained for the AWS at De Aar is an example of some moderation that was applied.

Assessment

The following advantages and disadvantages of the interval selection were considered:

i. **3 m/s:** The map has the largest number of wind speed categories (five) and therefore it could better reflect the values at station level. However, a large fraction of the assigned values could not be backed up by the low spatial resolution of the values at station level; this increased the subjectivity in the development process of the map.

ii. **4 m/s:** The 4 m/s interval was just as effective to create adjacent regions with similar values as at the 3 m/s level. While the map has a smaller number of categories as with 3 m/s, it was deemed to be as effective to capture the design values at station level. Of the three options, the 4 m/s interval seemed to provide the optimal compromise between the number of categories, spatial amalgamation of same values, and representivity of the values at station level.

iii. **5 m/s:** With the 5 m/s it became more difficult to assign values that gave an acceptable reflection of the values at station level, also limiting the possibilities to justify large adjoining regions with the same values.

Proposed map of basic wind speed

The map based on 4 m/s intervals stipulated at the values for $v_{b,0}$ at {44; 40; 36; 32} m/s, as shown in Figure 9, is proposed to present the best balance between the underlying information and operational use in design. The information can effectively be tabulated per province as shown in Appendix A, and referenced back to the geographical distribution in Figure 9. The geographic map and the tabulated list are related by assigning a common code to each district.

There are two regions where the design gust values assigned are higher than in the map included in the 1989 version of the standard, i.e. in the Breede Valley municipality (Worcester), and an extensive region in the eastern interior of the Eastern Cape Province. In the case of the former, a 1 in 50 year gust value obtained from statistical

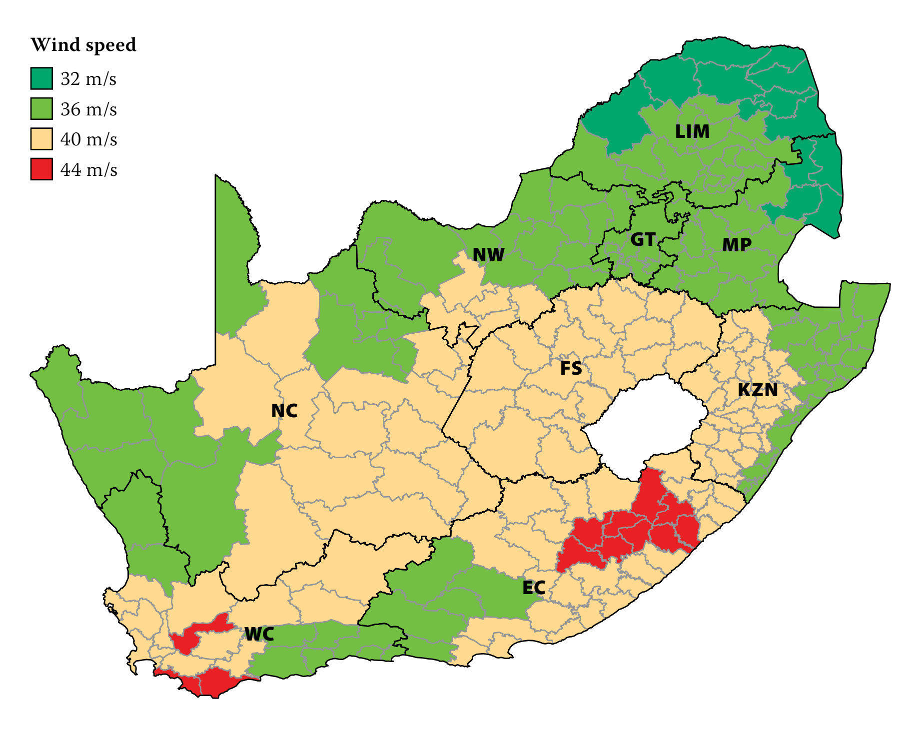

Figure 9: Proposed map of fundamental value of basic wind speed $v_{b,0}$ as the characteristic gust wind speed

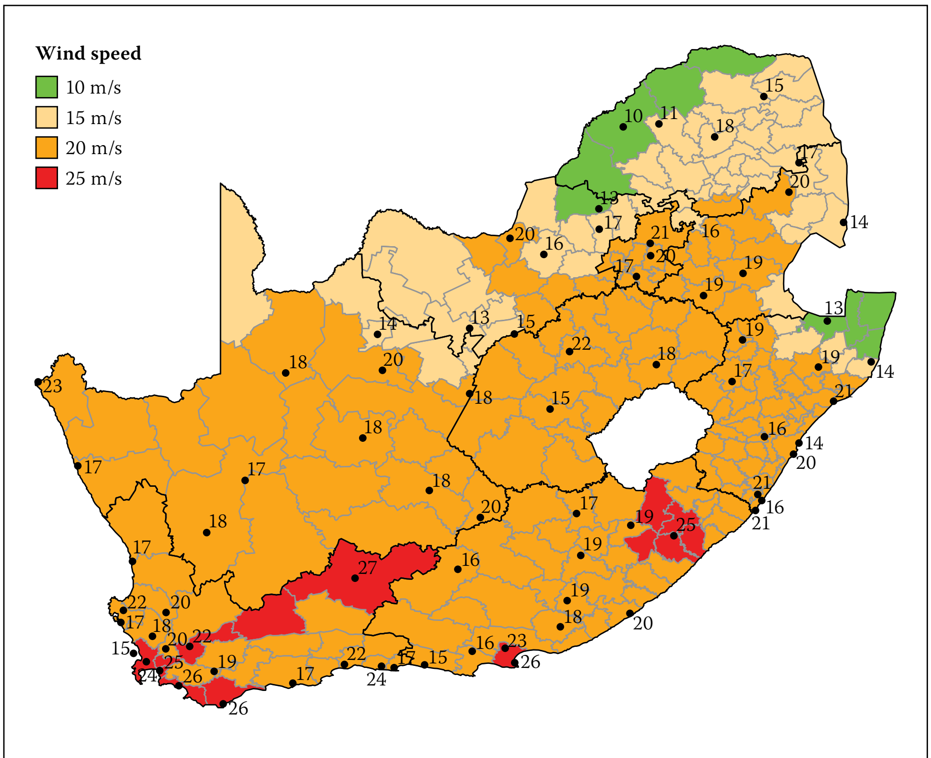

Figure 10: Map of basic hourly wind speed $v_{b,H}$ with intervals of 4 m/s

analysis v_k was 43 m/s, which can be considered to be accurate, bearing in mind the adequacy of the climate station from which the measurements were made, which is at the airport on the outskirts of the town. For the Eastern Cape several stations showed 1 in 50 year values of about 45 m/s, including Umtata. However, the true extent of the area to be assigned needs to be reconsidered when additional or updated information becomes available. Phase 2 of the Wind Atlas of South Africa (WASA) project will include the northern part of the Eastern Cape, and will hopefully provide improved insight into the prevailing strong wind climate to the south and southeast of the escarpment.

Hourly wind speed map

The advanced extreme value assessment of the hourly average annual maximum wind speed and mapping of the 1:50 year characteristic wind speed ($v_{k,H}$) reported by Kruger *et al* (2013a & b) serves as input for the compilation of an operational map on the basis of local district zoning, similar to that for gust wind. A wind speed interval of 4 m/s provides a balance between the underlying information on the spatial and temporal behaviour of $v_{k,H,}$ as well as the operational use of the map. Figure 10 provides a map for the basic hourly wind speed ($v_{b,H}$), covering the range of wind speed from 10 to 27 m/s by the set of four values {24; 20; 16; 12} m/s. This map shows a substantial improvement in resolution, compared to the map appended in SABS 0160:1989 and the simplification of the updated map given by Kruger *et al* (2013b). A comparison between the ratios of values allocated for gust and hourly values shows that, in the context of the South African mixed strong wind climate, it is impossible to apply a simple derivation from one time resolution to another. This "disconnect" between different time resolutions, where the ratios between the 1:50 year gust and 1:50 year wind speeds at longer time scales vary spatially, is indicative of the different causes of strong winds at different time scales. In the interior, where thunderstorms are prevalent, the ratio between the gust and hourly wind speed is much larger than along the coast (also see Kruger 2011).

CONCLUSIONS

The main features of the updated and revised map stipulating the basic wind speed $v_{b,0}$ shown in Figure 9, as derived from the 1:50 year or characteristic gust wind speed v_k shown in Figure 1, are as follows:

- The extensive increase in the number of annual extreme wind events across the country substantially increases the information in the form of probability models for the wind speed *V*, both spatially and temporally, including the resolution of the complex strong wind climate.
- The observation of a 2 to 3 s gust wind speed makes it possible to express $v_{b,0}$ directly as the gust wind, compared to the 'synthetic' map expressed as an effective 10 minute mean value used in SANS 10160-3:2010. Additional uncertainties resulting from the indirect model for a gust factor is thereby avoided.
- The spatial representation of $v_{b,0}$ on the basis of 240 local municipal districts provides a convenient grid of zones that is sufficiently compatible with the 74 $v_{k,AWS}$ datasets to cover the country, with limited interpolation needed to establish $v_{b,0}$ values for the balance of zones. Mapping could conveniently be separated into determining appropriate $v_{k,AWS}$ intervals for individual AWS positions and the

interpolation to obtain the countrywide basic wind speed $v_{b,0}$ map.

- The relatively even distribution of the AWS districts results not only in a reasonable spatial sampling of $v_{k,\mathrm{AWS}}$, but also results in most of the municipal regions with no AWS installations to be adjacent to at least one AWS zone (see Figure 5). Notable exceptions are the sparse distribution of AWS zones in the inland regions of KwaZulu-Natal and the Eastern Cape provinces, and the dense distribution across the complex topography of the southwestern parts of the Western Cape Province. Limited sampling of the large area across the central regions of the country, from the southern parts of the Northern Cape Province to the Free State Province, makes interpolation somewhat tentative.
- The haphazard shape of individual districts is smoothed out on a countrywide scale. This results in coherent regions for the lowest three $v_{b,0}$ values, with a limited number of small island regions for the 44 m/s zone. In addition to the reasonable shape of the zones, the administrative convenience of stipulating $v_{b,0}$ values adds to the utility of the map format. This is further substantiated by the possibility of providing the information in a tabular format.
- The significant reduction in $v_{b,0,}$ implied by the updated information (Kruger *et al* 2013b), is confirmed for the northern part of the country by Figure 9. However, for the central parts of the country there is no effective reduction in the value. This outcome results partly from the lower spatial resolution used for Figure 9, compared to Figure 1. To some extent this is due to the arguably somewhat conservative bias of interpolation for the sparse distribution of $v_{k,\mathrm{AWS}}$ for this region.
- A superficial comparison between the map for $v_{b,0}$, based on the gust wind speed shown in Figure 9 and the $v_{b,\mathrm{H}}$ hourly mean wind speed shown in Figure 10, indicates significant differences in the geographic distribution of wind speed intervals. This results from differences in the strong wind climate, ranging geographically to be described as synoptic, convective or mixed. The implied differences in the ratio of 3 s gust to hourly mean wind speeds across the country indicate that the Eurocode practice of applying a uniform procedure for a gust factor is not suitable for South Africa.
- The probability models on which the map for $v_{b,0}$ is based, serve as input to the reliability assessment of wind loading procedures, as expressed by the partial load factor for wind ($\gamma_{Q,W}$).

The spatial and wind speed discretisation of the basic map for the characteristic wind speed should facilitate the future updating based on:

i. additional information that will arise from the extension of the recording period of the AWS network,
ii. extension of the network by additional stations accumulating sufficient data for extreme value analysis, and
iii. the extension of the WASA project regions.

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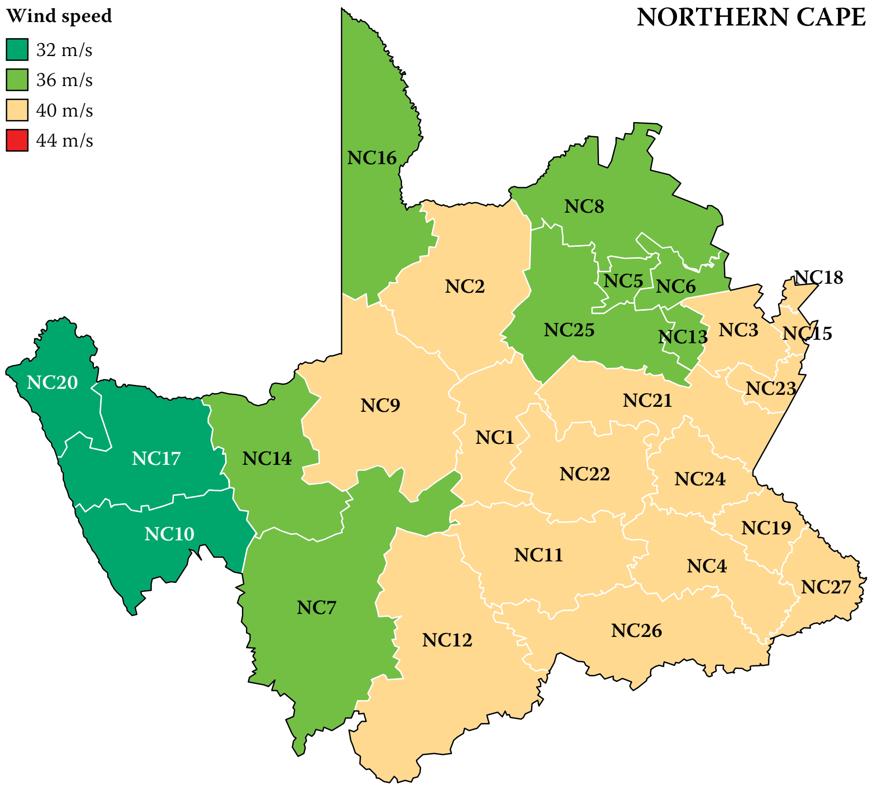
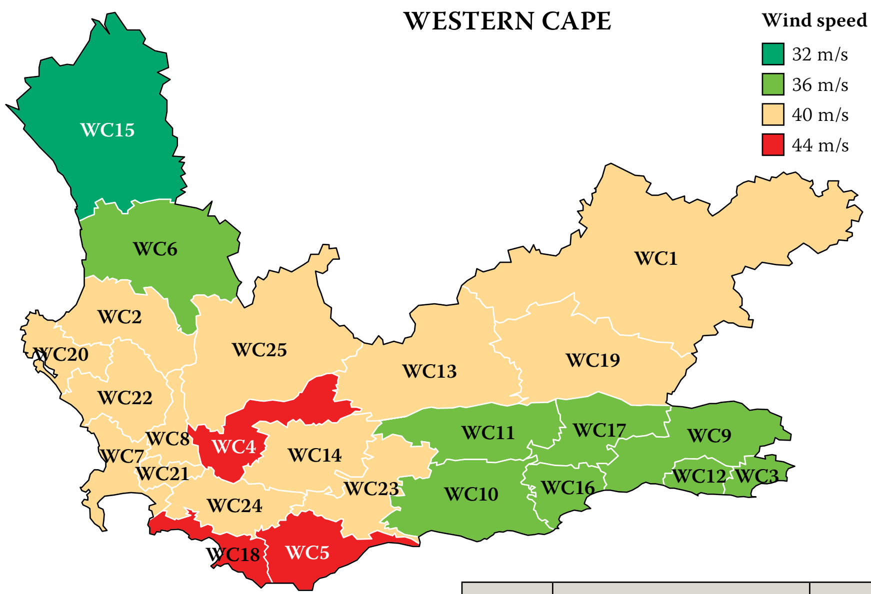
APPENDIX A

Gust design values assigned per local municipality, according to province and alphabetically arranged. District boundaries and the names of local municipalities are based on the demarcation information as at: http://www.demarcation.org.za/index.php/downloads/boundary-data (on 2016 11 01).



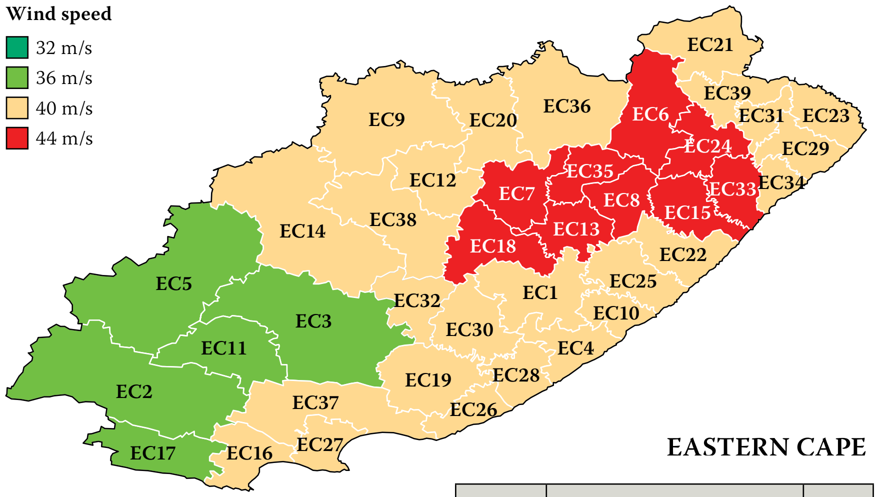
Code / Ref	Municipality	$v_{b,0}$
NC1	!Kheis	40
NC2	//Khara Hais	40
NC3	Dikgatlong	40
NC4	Emthanjeni	40
NC5	Gamagara	36
NC6	Ga-Segonyana	36
NC7	Hantam	36
NC8	Joe Morolong	36
NC9	Kai !Garib	40
NC10	Kamiesberg	32
NC11	Kareeberg	40
NC12	Karoo Hoogland	40
NC13	Kgatelopele	36
NC14	Khâi-Ma	36
NC15	Magareng	40
NC16	Mier	36
NC17	Nama Khoi	32
NC18	Phokwane	40
NC19	Renosterberg	40
NC20	Richtersveld	32
NC21	Siyancuma	40
NC22	Siyathemba	40
NC23	Sol Plaatjie	40
NC24	Thembelihle	40
NC25	Tsantsabane	36
NC26	Ubuntu	40
NC27	Umsobomvu	40



Code / Ref	Municipality	$v_{b,0}$
WC1	Beaufort West	40
WC2	Bergrivier	40
WC3	Bitou	36
WC4	Breede Valley	44
WC5	Cape Agulhas	44
WC6	Cederberg	36
WC7	City of Cape Town	40

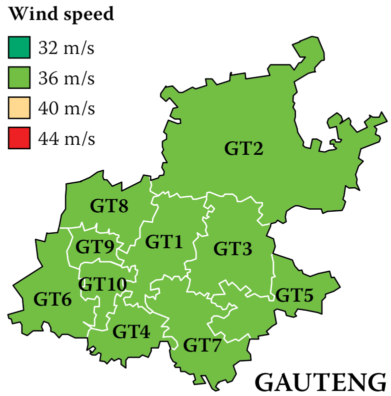
Code / Ref	Municipality	$v_{b,0}$
WC8	Drakenstein	40
WC9	George	36
WC10	Hessequa	36
WC11	Kannaland	36
WC12	Knysna	36
WC13	Laingsburg	40
WC14	Langeberg	40
WC15	Matzikama	32

Code / Ref	Municipality	$v_{b,0}$
WC16	Mossel Bay	36
WC17	Oudtshoorn	36
WC18	Overstrand	44
WC19	Prince Albert	40
WC20	Saldanha Bay	40
WC21	Stellenbosch	40
WC22	Swartland	40
WC23	Swellendam	40
WC24	Theewaterskloof	40
WC25	Witzenberg	40

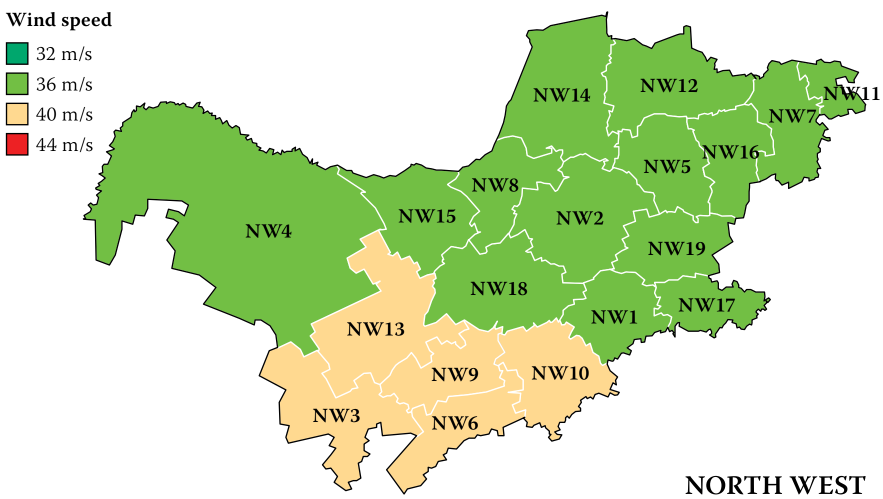


Code / Ref	Municipality	$v_{b,0}$
EC1	Amahlathi	40
EC2	Baviaans	36
EC3	Blue Crane Route	36
EC4	Buffalo City	40
EC5	Camdeboo	36
EC6	Elundini	44
EC7	Emalahleni	44
EC8	Engcobo	44
EC9	Gariep	40
EC10	Great Kei	40
EC11	Ikwezi	36
EC12	Inkwanca	40
EC13	Intsika Yethu	44
EC14	Inxuba Yethemba	40
EC15	King Sabata Dalindyebo	44
EC16	Kouga	40
EC17	Kou-Kamma	36
EC18	Lukanji	44
EC19	Makana	40

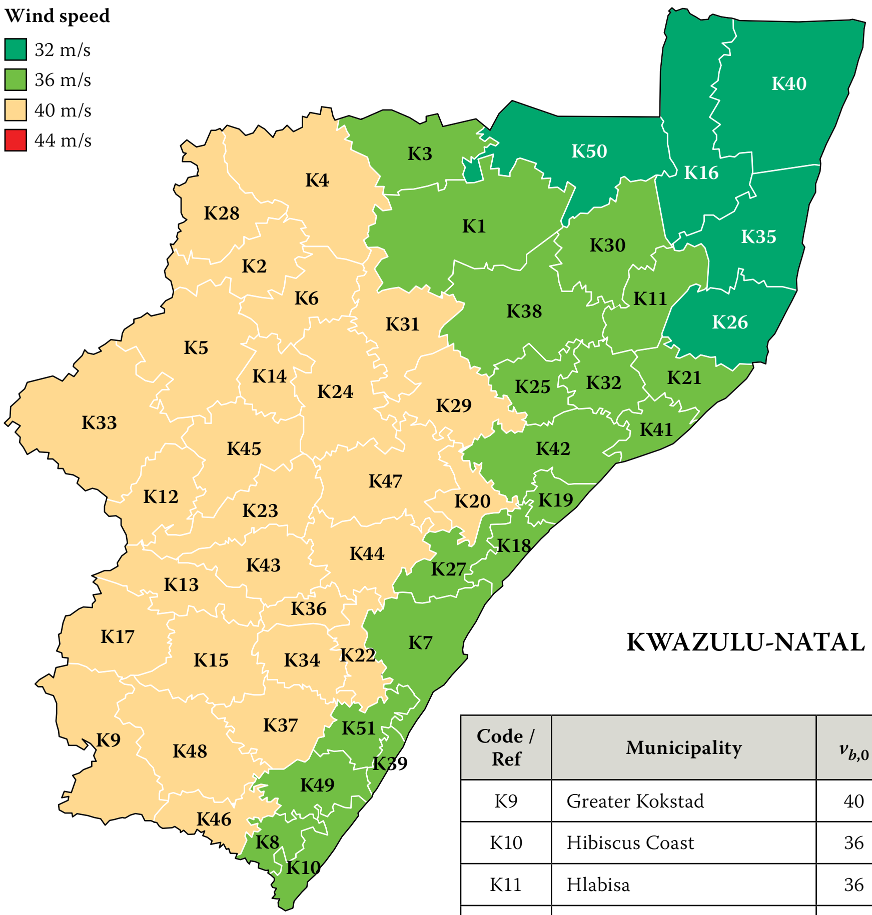
Code / Ref	Municipality	$v_{b,0}$
EC20	Maletswai	40
EC21	Matatiele	40
EC22	Mbhashe	40
EC23	Mbizana	40
EC24	Mhlontlo	44
EC25	Mnquma	40
EC26	Ndlambe	40
EC27	Nelson Mandela Bay	40
EC28	Ngqushwa	40
EC29	Ngquza Hill	40
EC30	Nkonkobe	40
EC31	Ntabankulu	40
EC32	Nxuba	40
EC33	Nyandeni	44
EC34	Port St Johns	40
EC35	Sakhisizwe	44
EC36	Senqu	40
EC37	Sundays River Valley	40
EC38	Tsolwana	40
EC39	Umzimvubu	40



Code / Ref	Municipality	$v_{b,0}$
GT1	City of Johannesburg	36
GT2	City of Tshwane	36
GT3	Ekurhuleni	36
GT4	Emfuleni	36
GT5	Lesedi	36
GT6	Merafong City	36
GT7	Midvaal	36
GT8	Mogale City	36
GT9	Randfontein	36
GT10	Westonaria	36



Code / Ref	Municipality	$v_{b,0}$
NW1	City of Matlosana	36
NW2	Ditsobotla	36
NW3	Greater Taung	40
NW4	Kagisano/Molopo	36
NW5	Kgetlengrivier	36
NW6	Lekwa-Teemane	40
NW7	Local Municipality of Madibeng	36
NW8	Mafikeng	36
NW9	Mamusa	40
NW10	Maquassi Hills	40
NW11	Moretele	36
NW12	Moses Kotane	36
NW13	Naledi	40
NW14	Ramotshere Moiloa	36
NW15	Ratlou	36
NW16	Rustenburg	36
NW17	Tlokwe City Council	36
NW18	Tswaing	36
NW19	Ventersdorp	36

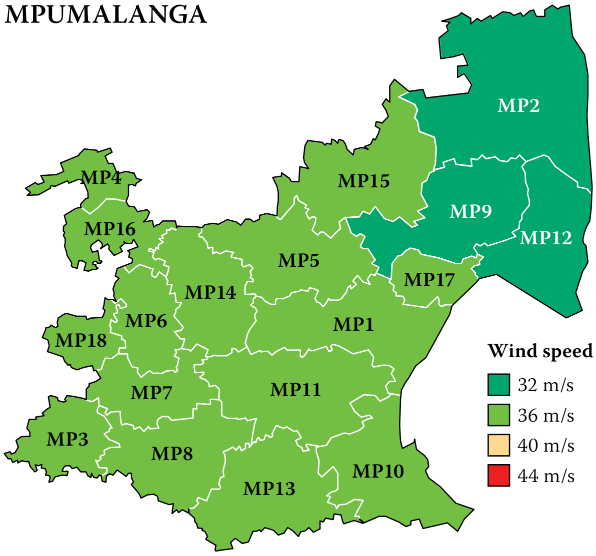


Code / Ref	Municipality	$v_{b,0}$
K1	Abaqulusi	36
K2	Dannhauser	40
K3	eDumbe	36
K4	Emadlangeni	40
K5	Emnambithi/Ladysmith	40
K6	Endumeni	40
K7	eThekwini	36
K8	Ezingoleni	36

Code / Ref	Municipality	$v_{b,0}$
K9	Greater Kokstad	40
K10	Hibiscus Coast	36
K11	Hlabisa	36
K12	Imbabazane	40
K13	Impendle	40
K14	Indaka	40
K15	Ingwe	40
K16	Jozini	32
K17	Kwa Sani	40
K18	KwaDukuza	36
K19	Mandeni	36
K20	Maphumulo	40
K21	Mfolozi	36

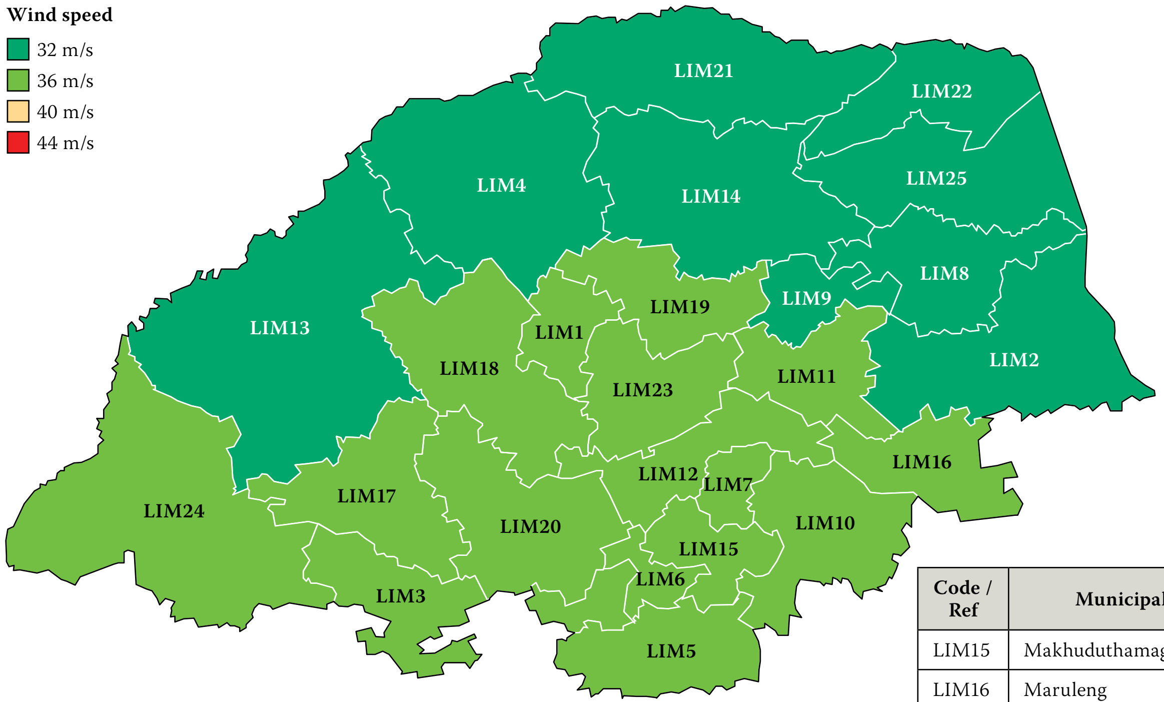
Code / Ref	Municipality	$v_{b,0}$
K22	Mkhambathini	40
K23	Mpofana	40
K24	Msinga	40
K25	Mthonjaneni	36
K26	Mtubatuba	32
K27	Ndwedwe	36
K28	Newcastle	40
K29	Nkandla	40
K30	Nongoma	36
K31	Nqutu	40
K32	Ntambanana	36
K33	Okhahlamba	40
K34	Richmond	40
K35	The Big 5 False Bay	32
K36	The Msunduzi	40
K37	Ubuhlebezwe	40
K38	Ulundi	36
K39	Umdoni	36
K40	Umhlabuyalingana	32
K41	uMhlathuze	36
K42	uMlalazi	36
K43	uMngeni	40
K44	uMshwathi	40
K45	Umtshezi	40
K46	uMuziwabantu	40
K47	Umvoti	40
K48	Umzimkhulu	40
K49	Umzumbe	36
K50	uPhongolo	32
K51	Vulamehlo	36

MPUMALANGA



Code / Ref	Municipality	$v_{b,0}$
MP1	Albert Luthuli	36
MP2	Bushbuckridge	32
MP3	Dipaleseng	36
MP4	Dr JS Moroka	36
MP5	Emakhazeni	36
MP6	Emalahleni	36
MP7	Govan Mbeki	36
MP8	Lekwa	36
MP9	Mbombela	32

Code / Ref	Municipality	$v_{b,0}$
MP10	Mkhondo	36
MP11	Msukaligwa	36
MP12	Nkomazi	32
MP13	Pixley Ka Seme	36
MP14	Steve Tshwete	36
MP15	Thaba Chweu	36
MP16	Thembisile	36
MP17	Umjindi	36
MP18	Victor Khanye	36

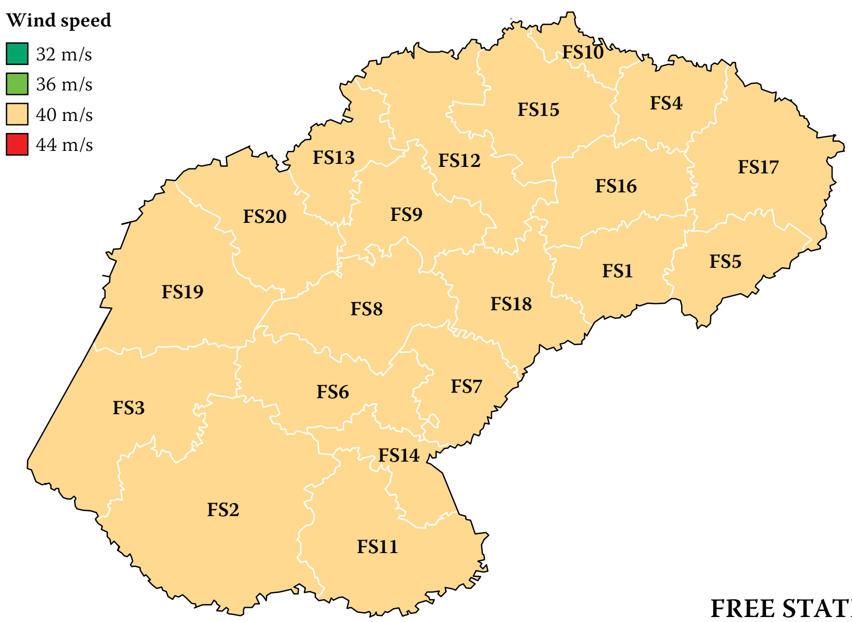


LIMPOPO

Code / Ref	Municipality	$v_{b,0}$
LIM1	Aganang	36
LIM2	Ba-Phalaborwa	32
LIM3	Bela-Bela	36
LIM4	Blouberg	32
LIM5	Elias Motsoaledi	36
LIM6	Ephraim Mogale	36
LIM7	Fetakgomo	36

Code / Ref	Municipality	$v_{b,0}$
LIM8	Greater Giyani	32
LIM9	Greater Letaba	32
LIM10	Greater Tubatse	36
LIM11	Greater Tzaneen	36
LIM12	Lepele-Nkumpi	36
LIM13	Lephalale	32
LIM14	Makhado	32

Code / Ref	Municipality	$v_{b,0}$
LIM15	Makhuduthamaga	36
LIM16	Maruleng	36
LIM17	Modimolle	36
LIM18	Mogalakwena	36
LIM19	Molemole	36
LIM20	Mookgopong	36
LIM21	Musina	32
LIM22	Mutale	32
LIM23	Polokwane	36
LIM24	Thabazimbi	36
LIM25	Thulamela	32



FREE STATE

Code / Ref	Municipality	$v_{b,0}$
FS1	Dihlabeng	40
FS2	Kopanong	40

Code / Ref	Municipality	$v_{b,0}$
FS3	Letsemeng	40
FS4	Mafube	40

Code / Ref	Municipality	$v_{b,0}$
FS5	Maluti a Phofung	40
FS6	Mangaung	40
FS7	Mantsopa	40
FS8	Masilonyana	40
FS9	Matjhabeng	40
FS10	Metsimaholo	40
FS11	Mohokare	40
FS12	Moqhaka	40
FS13	Nala	40
FS14	Naledi	40
FS15	Ngwathe	40
FS16	Nketoana	40
FS17	Phumelela	40
FS18	Setsoto	40
FS19	Tokologo	40
FS20	Tswelopele	40