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# FIELD VALIDATION OF THE ΔRIX PERFORMANCE INDICATOR FOR FLOW IN COMPLEX TERRAIN

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**Abstract**
Reanalyses of a case study using field measurements taken over 3½ years over rugged terrain in northern Portugal have been carried out using contemporary calculation procedures and topographical input data. The significance of the site ruggedness index (RIX) and the associated performance indicator (ΔRIX) are confirmed and the consequences of applying WAsP outside its operating envelope are quantified. A log-linear relation between WAsP prediction errors and the performance indicator ΔRIX is found to describe the field measurements and modelling results well. The largest coefficient of determination is obtained with a calculation radius of about 3.5 km and a critical slope of about 0.40-0.45 used in the RIX calculations. A simple procedure is further proposed to improve wind speed and power production predictions in terrain outside the operational envelope of the WAsP flow model. Results from the case study in northern Portugal, employing five meteorological stations with ruggedness indices between 10 and 33%, indicate an average improvement of WAsP power production predictions of 69%. Cross-predictions between sites with ΔRIX values larger than 5% are improved by more than 90% on average. The procedure has further been applied to a 23-MW wind farm sited in similar terrain and in similar climatological conditions. Here, the prediction of the net annual energy production was improved by about 70%. The correction procedure is empirical and requires the determination of a site-specific fitting constant.

**Keywords:** Resources, complex terrain, ruggedness index, RIX, models (mathematical), siting.

## Introduction

The ruggedness index concept has been used extensively over the last 10 years in wind resource assessment and siting studies in complex terrain, especially in terrain which is outside the operational envelope of linearised flow models such as WAsP. The index was proposed as a coarse measure of the extent of flow separation and, thereby, the extent to which the terrain violates the requirements of WAsP. The associated performance indicator ΔRIX has been shown to provide the sign and approximate magnitude of the prediction error for situations where one or both of the sites are situated in terrain well outside this operational envelope. Calculation of the ruggedness indices is often performed using the default configuration specified in the WAsP program; however, no standard procedure or analysis method seems to have been widely accepted for the analysis of the associated prediction errors [9]. Being empirical in nature, the ruggedness index calculation and interpretation depend on a number of calculation parameters and also on the topographical input data used.

The purpose of the present investigation is therefore fourfold. First of all, we investigate to what extent the *site ruggedness index* and *orographic performance indicator* concepts are still supported when using contemporary calculation procedures and topographic data. Secondly, we attempt to determine the optimum configuration values used for the calculation of these two quantities. Thirdly, we will try to find a simple operational relation between WAsP prediction errors and the performance indicator ΔRIX. Finally, we'll attempt to use such a relation in order to improve WAsP predictions in complex terrain that is outside the operational envelope of the WAsP model.

**The site ruggedness index, RIX**

The ruggedness index (RIX) of a given site is defined as the fractional extent of the surrounding terrain which is steeper than a certain critical slope [1, 2]. The index was proposed as a coarse measure of the extent of flow separation and, thereby, the extent to which the terrain violates the requirement of WAsP, that the surrounding terrain should be sufficiently gentle and smooth to ensure mostly attached flows [1, 2]. The operational envelope of WAsP thus corresponds to a RIX value of ~ 0%.

The RIX value for one site is calculated for each of a number of radii originating at the site, by dividing each radius ($R$) into line segments defined by the crossing of the radius with the height contour lines. The sum of the line segments representing slopes greater than a critical slope ($\theta_c$) divided by the total sum of the segments (i.e. the radius $R$) is then the RIX value of the radius in question. The overall RIX value for the site, the *site ruggedness index*, is then simply the mean of the sector-wise RIX values. Figure 1 shows a graphical representation of the ruggedness index concept.

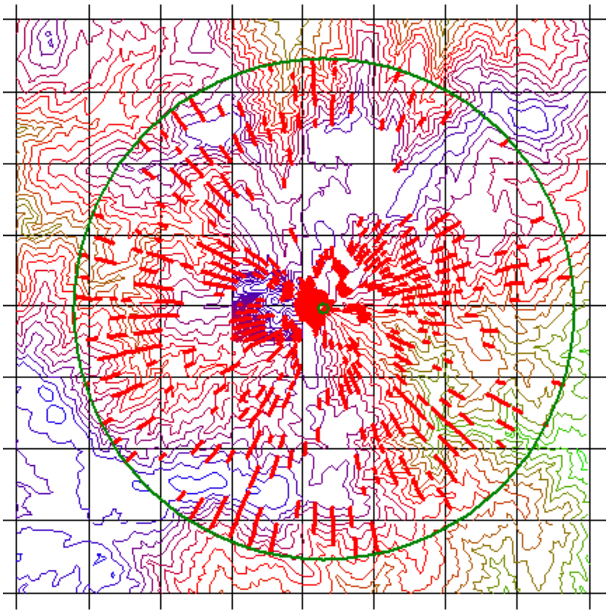

Figure 1. The terrain surrounding a met. station site as seen in the WAsP Map Editor. Terrain steeper than a certain critical angle, $\theta_c$, is indicated by the thick red (radial) lines.

For a given site, the exact value of the site ruggedness index depends on three parameters: the calculation radius $R$, the critical slope $\theta_c$ and the number of radii $N$. Furthermore, the value may also depend slightly on the height contour interval. Bowen and Mortensen [1, 2] used a calculation radius of 3.5 km, largely determined by the size of the digital height contour maps at hand, but further considering that the terrain within this distance exert the strongest influence on the WAsP flow model results. The critical slope $\theta_c$ was taken as 0.3, assuming that the critical slope – marking the onset of flow separation – has a fixed, conservative value for all hills [2, 4]. The number of radii used was set to 12, corresponding to the centre radius in each of 12 wind direction sectors.

Site ruggedness index calculations have now been implemented in the WAsP program for all predictor and predicted sites [5]. The default (but configurable) values used for the RIX calculations are: calculation radius $R$ = 3.5 km, critical slope $\theta_c$ = 0.3 and number of radii $N$ = 72. The RIX calculation radii thus correspond exactly to the radii used in the polar grid of the WAsP flow model [5].

The *orographic performance indicator* $\Delta$RIX is defined as the difference in the (percentage) fractions between the predicted and reference sites [1, 2], i.e. $\Delta\text{RIX} = \text{RIX}_{\text{WTG}} - \text{RIX}_{\text{MET}}$. If the reference and predicted sites are equally rugged ($\Delta$RIX ~ 0%) the prediction errors are relatively small. If the reference site is rugged and the predicted site less rugged or flat ($\Delta\text{RIX} < 0$) the overall prediction is underestimated with a significant negative error. Conversely, if the reference site is flat or less rugged than a rugged predicted site ($\Delta\text{RIX} > 0$), the overall prediction is overestimated with a significant positive error [1, 2, 3].

**Case study in northern Portugal – revisited**

The present study uses long-term, high-quality wind measurements from five meteorological stations in the rugged mountains of northern Portugal, see Figure 2. The meteorological data and measurement sites were described in detail by Bowen and Mortensen [1, 2].

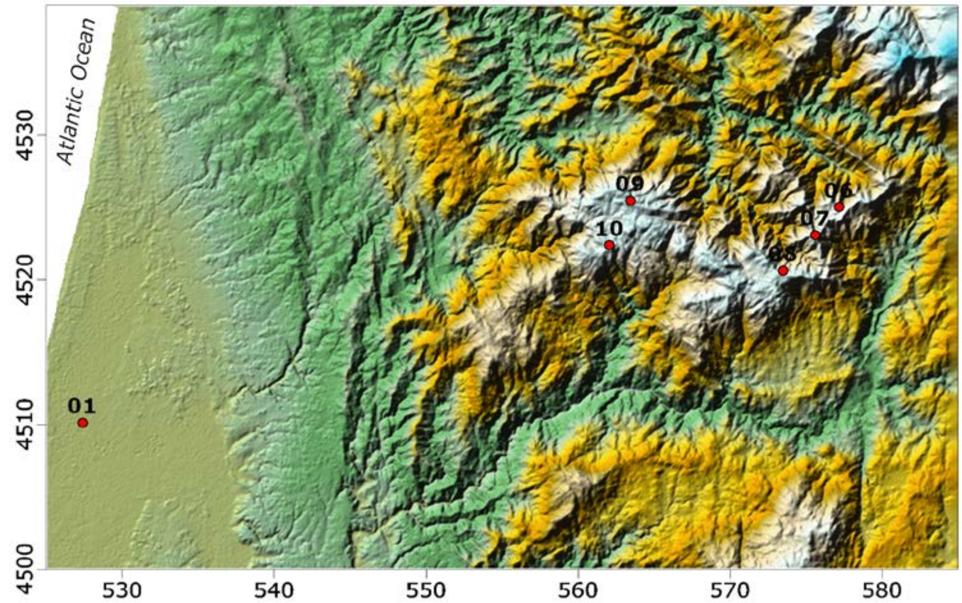


Figure 2. Overview map showing the field site locations 01, 06, 07, 08, 09 and 10 used for the case study. Coordinates are UTM in kilometres (zone 29, WGS 84). The height scale is exaggerated by a factor of four. Station 01 is not used for the analyses presented below.

The elevations of the five mountain sites range between 933 and 1082 m above sea level and the site ruggedness indices range from about 10 to 33%. Sites 06, 07, 08 are within 6 km of each other on a ridge some 50 km to the east of the Atlantic Ocean, while sites 09 and 10 are situated on an adjacent ridge about 15 km to their west. Evidently, the terrain surrounding the five sites is outside the operational envelope of the WAsP flow model.

Average cross-correlation coefficients at zero time lags for various site pairs were calculated from the wind speeds measured throughout the 3½ years of records [1]. The resulting coefficients are not high (61-86%) for any site pair and are lowest (35-45%) for pairs involving the coastal-plain site 01. Station 01 is therefore not used for the analyses presented below.

The relation between WAsP prediction errors and ruggedness indices is investigated below following the general approach of Bowen and Mortensen, but using contemporary calculation procedures and topographical data. The analysis of WAsP prediction errors is based on pair-wise intercomparisons of cross-predictions between two stations or sites: a reference (predictor) site and the predicted site, where all sites may take either role. The latest version of WAsP (8.2) is used for the flow modelling and calculation of the ruggedness indices. The exact same wind data are used for the analyses as was used by Bowen and Mortensen, but the regional and predicted mean values of wind speed, power density and power production are here calculated from the so-called emergent wind speed distribution [5] rather than from the omni-directional Weibull *A*- and *k*-parameters [2]. The ruggedness indices are calculated as described above. Based on recent GPS readings, the coordinates of one site has been changed slightly compared to some earlier studies.

Elevation maps were derived from the 3 arc-sec. elevation data set obtained during the Shuttle Radar Topography Mission (SRTM). The elevation grids were checked for spikes and wells, and height contours were constructed using the Surfer program package (with Kriging interpolation). These maps were compared to elevation maps obtained by digitisation of ordinary paper maps, in order to verify the applicability of SRTM maps for the wind flow modelling and to add relevant spot heights. An example of a height contour map derived from SRTM data is shown in Figure 3.

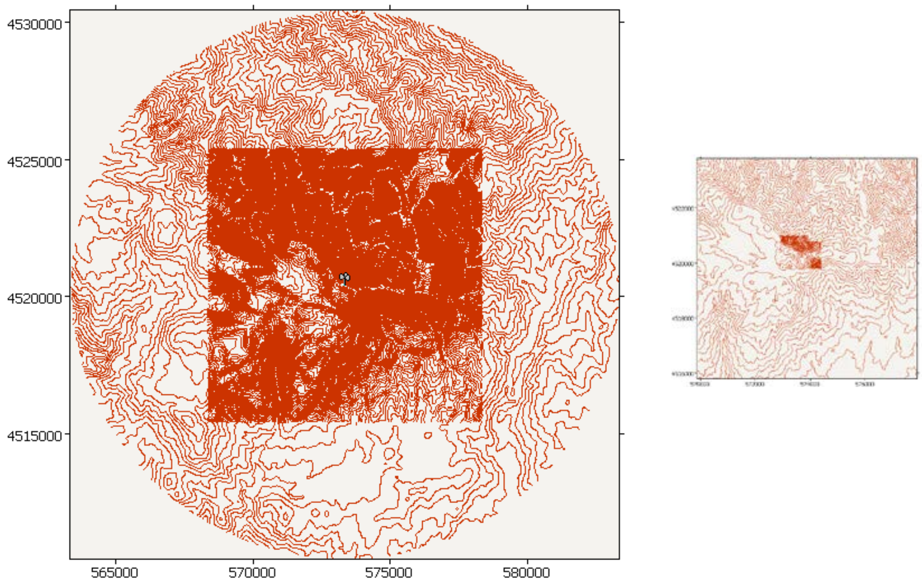


Figure 3. The left-hand contour map (20×20 km$^2$) was derived from SRTM 3 arc-sec. elevation data and is the elevation map used for the analyses below. For comparison, the right-hand map (8×8 km$^2$) shows the map originally used by Bowen and Mortensen [1]; this was obtained by digitization of the height contours of a standard topographical map.

**WAsP prediction errors and site ruggedness**

Figure 4 shows the WAsP wind speed prediction error as a function of the difference in extent of steep slopes (RIX values in %) between pairs of sites. With five sites, the figure contains 25 cross-predictions, including the self-prediction at each site. The wind speed errors and orographic performance indicators ΔRIX are given here in per cent for easy comparison to previous results [1, 3]. The wind speed prediction error is calculated as $(U_p/U_m - 1)\times100$.

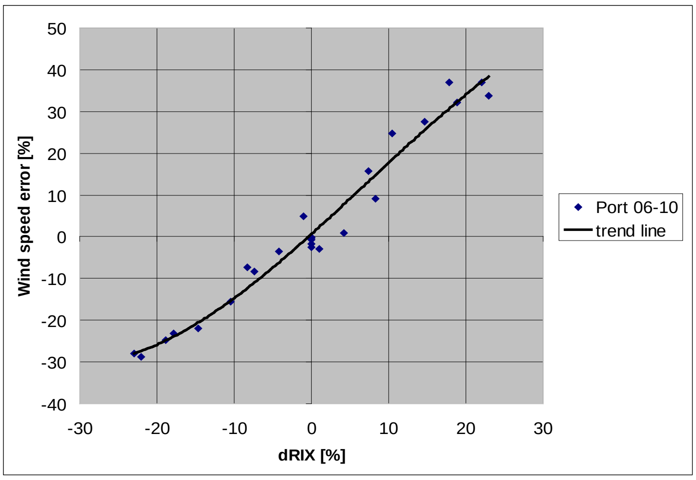


Figure 4. WAsP wind speed prediction error [%] as a function of the difference in ruggedness indices, ΔRIX, between the predicted site and the predictor site [%].

A trend line has been fitted to the points in Figure 4; however, due to the asymmetry in plot it is not obvious which form of trend line to use and the shape of the trend line seems to be different for positive and negative prediction errors. In order to avoid this asymmetry we substitute $\ln(U_p/U_m)$ for $(U_p/U_m - 1)$. In Figure 5 the prediction errors are therefore analysed by plotting the logarithm of the ratio between the predicted and measured wind speeds versus the orographic performance indicator ΔRIX. This relation seems to be close to linear and the best-fit line crosses the axes at (0, 0). The slope of the line ($\alpha$) and the coefficient of determination ($R^2$ = 0.975) are given in the figure as well.

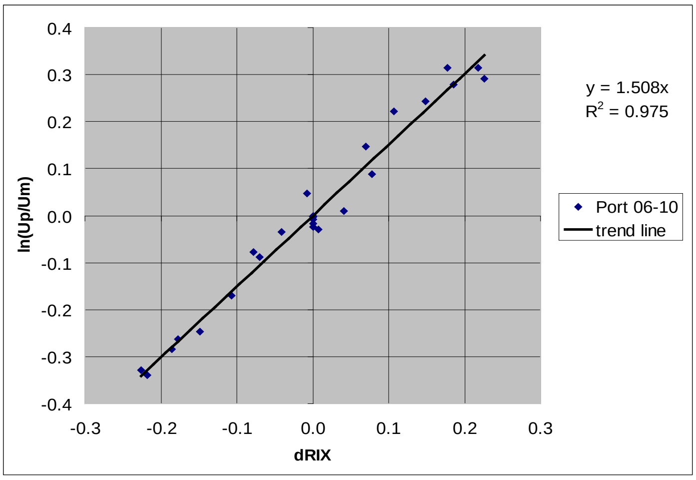


Figure 5. WAsP wind speed prediction error as a function of the difference in ruggedness indices, ΔRIX, between the predicted site and the predictor site in a log-linear plot. Note, that the ΔRIX values are given as fractions here.

**Optimum configuration of the ruggedness index calculation**

The ruggedness indices used for calculation of the ΔRIX values in Figure 4 and Figure 5 were determined using the default configuration in WAsP: calculation radius $R$ = 3.5 km, critical slope $\theta_c$ = 0.3 and number of radii $N$ = 72. Assuming that the relation between $\ln(U_p/U_m)$ and ΔRIX is linear, the coefficient of determination (Figure 5) can be used to determine which values of calculation radius and critical slope provide the least scatter of the data points, i.e. the largest $R^2$. The number of radii is kept fixed here at 72, corresponding to the set-up of the WAsP flow model. Table 1 shows the results of varying the calculation radius between 3 and 5 km and the critical slope between 0.30 and 0.45.

Table 1. Coefficient of determination, $R^2$, for different values of calculation radius and critical angle used in the calculation of the ruggedness index, RIX.

| **Radius $R$ [m]** | **Critical slope $\theta_c$** | | | |
|---|---|---|---|---|
| | **0.30** | **0.35** | **0.40** | **0.45** |
| **3000** | 0.960 | 0.967 | 0.978 | 0.973 |
| **3500** | 0.972 | 0.974 | 0.984 | 0.986 |
| **4000** | 0.971 | 0.978 | 0.982 | 0.979 |
| **5000** | 0.969 | 0.977 | 0.979 | 0.973 |

The coefficient of determination $R^2$ changes by a few per cent only when varying the radius and slope within the limits used in Table 1, indicating that the exact choice of values may not be critical. A (local) maximum is found corresponding to a radius of about 3.5 km and a critical slope of about 0.40-0.45.

**Self-prediction and the vertical wind profile**

Figure 5 shows that the self-prediction at any of the five meteorological stations is associated with quite small errors; this is also the general experience for other sites in complex terrain. The figure also suggests that the vertical profile of mean wind speed should be predicted quite well since all the 'sites' (anemometer levels) in this case have identical RIX values. Less experience is available to support this, but Figure 6 shows an example where this is indeed true. This site is quite similar to the Portuguese sites, with a ruggedness index of 16%.

Since the self-prediction and the prediction of the vertical wind profile seem to be quite accurate regardless of the site ruggedness index, the relation between WAsP prediction errors and the orographic performance indicator (Figure 5) can be readily determined for other heights above ground level than the measuring height(s) – e.g. at the hub height of a given wind turbine.

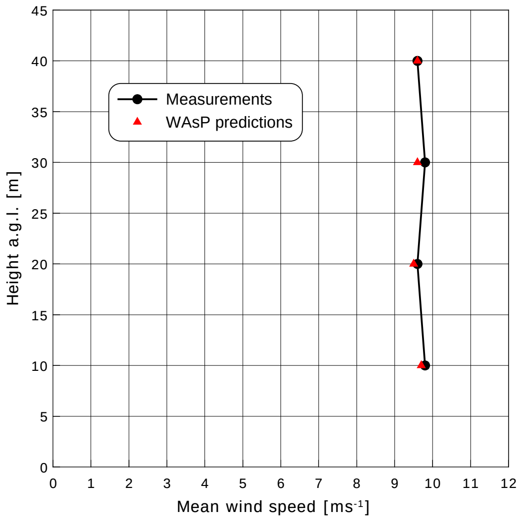


Figure 6. Measured and predicted vertical profiles of mean wind speed at a hill-top site with a RIX value of 16%. The 40-m anemometer is used as the predictor in the WAsP modelling.

**Improving WAsP predictions in (too) complex terrain**

If we assume that the logarithm of the wind speed ratio $U_p/U_m$ is linearly related to the difference between the RIX values at the two sites and the linear fit is characterised by its slope only, the following equation can readily be derived

$$U_m = \frac{1}{\exp(\alpha \Delta \mathrm{RIX})} U_p$$

where $\alpha$ is the slope of the regression line. Given a predicted wind speed $U_p$ at a certain height above ground level, this equation then provides the correction factor that could be applied to $U_p$ in order to obtain the 'measured' (true) wind speed $U_m$ at the same site and height.

Similar analyses have been carried out with respect to the prediction errors in power production, by inserting a wind turbine at each of the five met. station sites; the results of this analysis is shown in Figure 7. Here, a radius of 3.5 km and a critical slope of 0.4 have been used, corresponding to the best-fit linear relation.

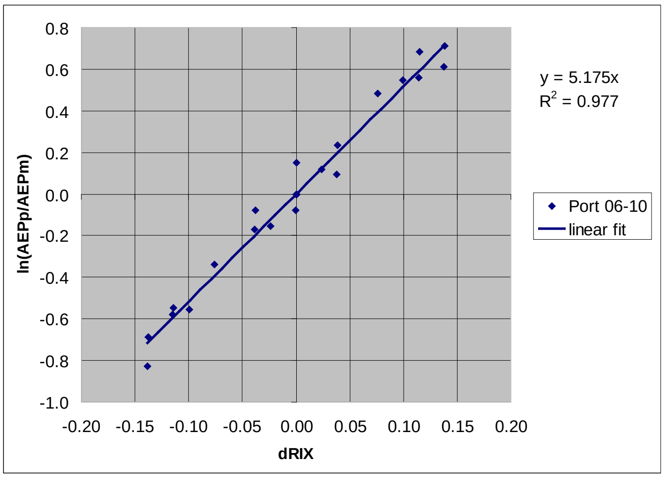


Figure 7. WAsP power production prediction error as a function of the difference in ruggedness indices, ΔRIX, between the predicted sites and the predictor sites in a log-linear plot.

The relation between the logarithm of the ratio of the predicted to the 'measured' power productions versus the performance indicator ΔRIX seems also to be well described by a linear fit; this provides an alternative way of correcting the predicted power productions. In order to illustrate the potential of applying such a correction procedure to the WAsP predictions at the five Portuguese sites, we have calculated and plotted the predicted versus the 'measured' power productions in Figure 8.

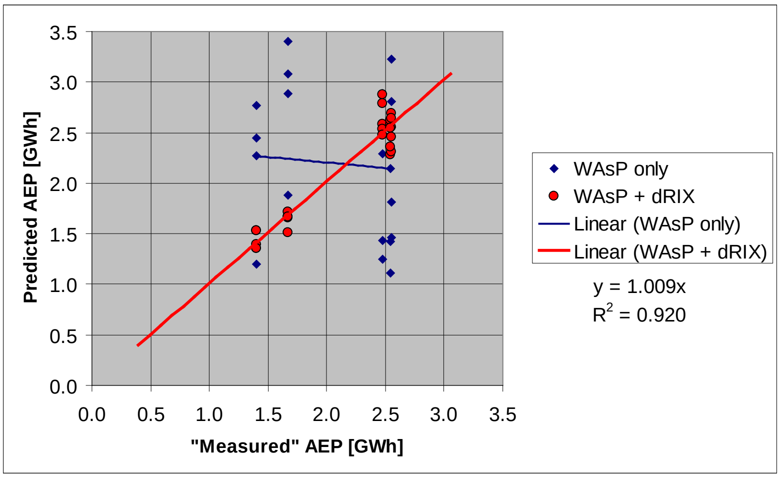


Figure 8. Comparison of predicted and measured power productions for a 1-MW wind turbine with a hub height of 50 m and a rotor diameter of 54 m. Blue symbols correspond to standard WAsP predictions; red symbols correspond to ΔRIX-corrected values.

The 'measured' power production is estimated by using the regional wind climate derived from the met. station at the site; the predicted production is estimated by using regional wind climate data from the other sites. Blue symbols correspond to standard WAsP predictions; as expected, the prediction errors are significant since we are outside the operational envelope of the WAsP flow model. Red symbols correspond to predictions which have been corrected using the information shown in Figure 7 and following the procedure outlined above.

The average improvement of the WAsP power production predictions in Figure 8 is 69% (where 100% improvement corresponds to no error in the prediction). Cross-predictions between site pairs with a ΔRIX value larger than 5% are improved by more than 90% on average.

It should be borne in mind, that the relation between prediction error and ΔRIX is purely empirical, based on the data obtained at the five met. stations. The correction procedure illustrated in Figure 8 uses the same data and therefore cannot be used for verification purposes; the graphic only serves to illustrate the potential of the procedure. To what extent the procedure is valid for other sites in the same region cannot be estimated from the data at hand; proper verification would require many more data sets from different sites in the region. However, one might speculate that the conclusions and procedure are at least valid for *similar* sites in the same region, where *similar* is taken to mean similar topographical settings, similar climatological conditions and similar topographical input data to the WAsP models [7, 8].

**A wind farm case study**

The procedures described above have been applied at a different wind farm site in complex terrain. Here, a 23-MW wind farm consisting of 38 wind turbines has been installed, see Figure 9. Wind speed and direction data are available from two reference masts; measured power productions and other statistics are further available for the wind farm. The net annual energy production of the wind farm can thus be calculated from the time-series of wind and production data by applying a wind farm power curve (dump file) derived from WAsP modelling.

The ruggedness indices for the two met. masts are in the range of 4-5% and the ruggedness indices of the 38 turbine sites range from about 4 to 14%, see Figure 9. A standard WAsP calculation overestimates the measured power production by about 13%. The reason for this overestimation is assumed to be mainly related to variation of the ruggedness index over the wind farm site [6]. The reference masts are located in the western part of the wind farm where the ruggedness indices are in the range of 4 to 9%; in the eastern part of the wind farm the ruggedness indices are larger and reach almost 14%.

Since the two reference masts are situated very close to each other, and close to some of the wind turbines in the wind farm, it has not been possible to establish the local relation (fitting constant $\alpha$) between WAsP prediction error and ΔRIX. The wind farm site is, however, quite similar to the Portuguese sites analysed above, and so we will assume that results found for the Portuguese sites are at least approximately valid and can be applied to the wind farm turbine sites.

Improving the WAsP modelling results for calculation of the wind farm power production consists of the following steps:

1. Find the relevant ΔRIX values for all sites in the wind farm.
2. Calculate the wind speed correction factor for each site from the equation above.
3. Insert the correction factor as a percentage in the WAsP Turbine Site window (User corrections tab) for each site and each sector.
4. Recalculate the wind farm and extract the corrected wind farm power curve (dump file).
5. Apply the wind farm power curve with the time-series of wind speed and direction.

After correction, the wind farm power production is overestimated by about <u>3%</u> only, i.e. the prediction of the actual annual energy production is improved by 70%. This is satisfactory, considering the uncertainties involved. In addition to the assumption of similarity with the five met. station sites in northern Portugal, further uncertainties are introduced by the fact that the wind farm site is also partly forested which is not taken properly into account in the WAsP modelling. Some of the turbines are situated in forest clearings; allowing for a smaller effective hub height for these turbines would bring the corrected WAsP prediction even closer to the actual production.

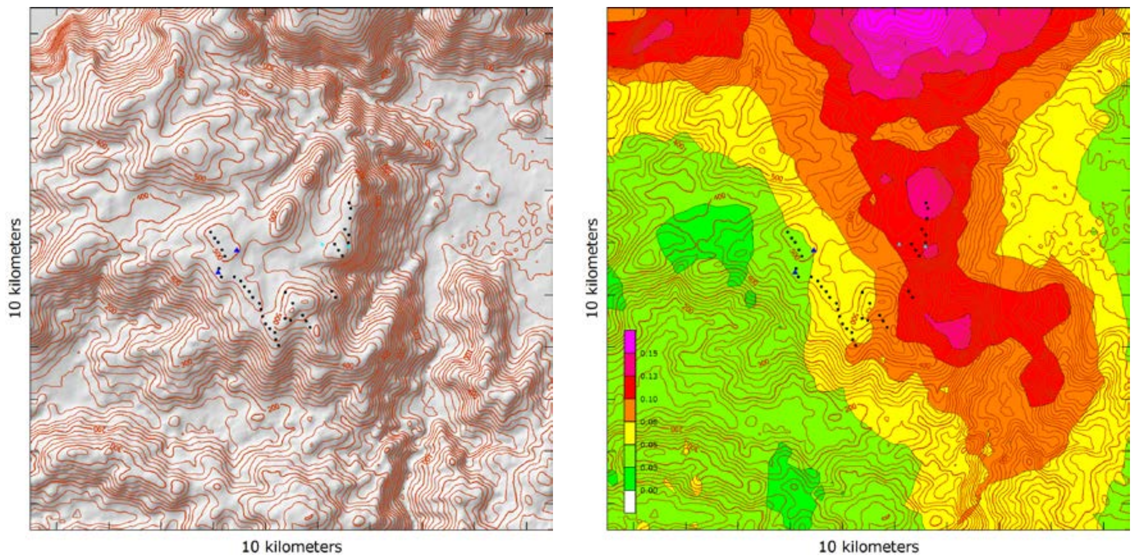


Figure 9. Wind farm in complex terrain. The turbine sites are shown in an elevation map (20-m contours) in the left-hand graphic; where the size of the dots is proportional to the rotor diameter. The reference met. stations are shown with dark blue triangles. The right-hand graphic is a map of the ruggedness index variation over the site.

**Discussion and conclusions**

In general, it is not recommendable to apply the WAsP model (or any other model) outside its operational envelope. The limitations of the flow model in WAsP are well known and it is straightforward to verify whether the terrain in general is too steep for the flow model to provide reliable results: the ruggedness index (RIX) of the modelling site(s) must be 0 (zero) or a few per cent at most.

The purpose of the present study, however, is to investigate and possibly quantify the WAsP prediction errors in complex terrain where the slopes are so steep as to violate the assumptions underlying the flow model and where flow separation is likely to occur. Reanalysis of the data sets originally used to identify and define the ruggedness index RIX and the orographic performance indicator ΔRIX is carried out using contemporary calculation procedures and topographical data. The two concepts are supported by the reanalysis and the magnitude of the WAsP prediction error in terrain characterised by RIX values greater than 0 is confirmed to depend strongly on the orographic performance indicator. The relationship between the prediction error and ΔRIX seems to be well described by a straight line in a log-linear representation.

The functional relationship between the WAsP prediction error and ΔRIX allows for a determination of the parameters that provide the largest coefficient of determination. It is found that a calculation radius of about 3.5 km and a critical slope of about 0.40-0.45 provide the best fit; this critical slope is somewhat larger than the default value used in the WAsP software (0.3). Ruggedness index calculations weighted with the wind rose frequencies of occurrence did not improve the linear fit.

A simple procedure for correcting WAsP predictions in complex terrain where the site ruggedness index values are typically larger than 0 is proposed. This procedure requires that the slope of the linear relation between prediction error and ΔRIX can be determined and further assumes that this relation is valid for similar sites in the same area. Preliminary results indicate that significant improvements of the WAsP wind speed and power production predictions in terrain well outside the operational envelope of the WAsP flow model may be obtained.

**Acknowledgements**
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