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Wind speed modeling using Weibull distribution: A case of Liptovský Mikuláš, Slovakia

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Abstract. In the present paper, the Weibull distribution is used to analyse the wind speed data of Liptovský Mikuláš-Ondrašová (49°05'52" N, 19°35'32" E), situated in northern Slovakia. Analysed wind speed data were collected over the 11-year period (2005-2015) and they were recorded three times a day. The results show that the seasonal values of the shape parameter k range from 1.474 to 1.607, with yearly value of 1.546 while the seasonal values of the scale parameter c range from 2.488 to 3.010 *m/s*, with yearly value of 2.726 *m/s*. We find out that according to the coefficient of determination and root mean square error, the Weibull distribution performs well in fitting the wind speed data..

1 Introduction

The Weibull distribution was introduced by the Swedish physicist Walodi Weibull who first used this distribution in 1939 to represent the distribution of breaking strength of materials. The reason of its popularity is its simplicity (in form and parameter estimation) and flexibility in fitting observed data. The Weibull distribution is widely used in many different areas such as material science, reliability engineering, medicine, energy, quality control and elsewhere [1, 2]. In addition, it is successfully used to model weather and climate data such as rainfall, flood and wind speed. The analysis of wind speed is quite crucial for design of wind farms, because when designing and operating wind turbines, the distribution of wind speed probability significantly affects the performance [3]. Wind speed forecasting in urban areas has many applications e.g. in construction of buildings, estimation of wind loads on buildings [4, 5]. Wind speed is the most important factor in the dispersion of air pollutants in urban environment [6].
Wind speed is a complicated random phenomenon. It changes over time, with altitude and varies depending on the location and surroundings. It is well known that wind speed depends on local climatic conditions, surface and landscape. Wind conditions in Slovakia are complicated due to the fragmentation of the earth's relief and the considerable variability of weather during the year. Therefore, it is appropriate to map the climatic

conditions, such as wind speed and direction, its intensity, temporal and geographical variability at the local level.
Statistical methods are a useful tool to predict wind speed. For this reason, probability distributions are used to model wind speed. Sometimes strong wind speed data are observed, but their occurrence is very rare while moderate and fresh winds are more common. The Weibull distribution is positively skewed for this reason therefore this distribution is suitable to model the wind speed data. In recent years, a large number of studies have been published and suitability of the Weibull distribution to model wind speed data has been discussed [7-25].
In the article, we focus on the analysis of wind speed in the town of Liptovský Mikuláš, which is the administrative and tourist centre of the Liptov region. The wind speed data of Liptovský Mikuláš-Ondrašová collected over 11-year period from January 2005 to December 2015 at 10 m height are analysed using the Weibull distribution. The monthly, seasonal and annual Weibull parameters k and c are determined for this location as a result of this study. The coefficient of determination and root mean square error are used to identify the quality of the fit of the Weibull distribution to the wind speed data. Detailed local knowledge is necessary to provide better understanding of current wind speed variability and how thewind speed might change in the future. The authors believe that this information will be helpful for understanding the wind speed behaviour in Liptovský Mikuláš.
The restof thispaper is structured as follows.Section 2 describes the study area, wind speed data and methods, including the Weibull distribution and performance criteria. Section 3 presents the statistical analysis, results and discussion. Finally, Section 4 summarizes major findings and conclusions.

2 Data and Methods

2.1 Description of location and wind speed data

The town of Liptovský Mikuláš (latitude 49º05'03" N, longitude 19º36'08" E, altitude 577 m) is situated in the northern Slovakia in the middle of the Liptovská kotlina basin, on the right bank of river Váh and next to the eastern bank of the water dam Liptovská Mara. Near Liptovský Mikuláš, there are Nízke Tatry and Vysoké Tatry mountains. Liptovský Mikuláš is an administrative, economic and touristic centre of the central Liptov [26].
The climate in Liptovský Mikuláš is cold and temperate. According to Köppen and Geiger, this climate is classified as Dfb (warm-summer humid continental climate). Over the course of the year, the temperature typically varies from -7°C to 23°C; the average annual temperature is 6.9°C. There is a significant rainfall throughout the year. The precipitation in Liptovský Mikuláš is about 842 mm per year. In Liptovský Mikuláš, the wind is usually stronger than in many other places [27].
Liptovská Ondrašová (latitude 49º05'52" N, longitude 19º35'32" E, altitude 569 m) is the administrative part of the Liptovský Mikuláš town. Name of the meteorological station (MS) is Liptovský Mikuláš-Ondrašová. It has been in operation since 1986. This MS is characterized by the automatic station class AWS2 (PVS) and is situated in Váh river basin, surrounded by the slightly to strongly undulating terrain. It is located inside the village-town. There is a large garden situated nearby. The overall character of the surroundings could be described as partially covered.
The standard direction and wind speed at Slovak Hydrometeorological Institute (SHMI) monitoring stations is 10 m above the ground surface (as it was mentioned also in [28]).

The Ultrasonic Anemometer 2D, type 4.3820.00.330 from Thies Clima, Germany is used to detect the horizontal components of wind velocity and wind direction in two dimensions.
Analysed wind speed data have been collected in m/s over the 11-year period from January 2005 to December 2015. The wind speed was recorded three times a day, namely at 7:00, 14:00 and 21:00. Before the statistical analysis of the wind speed data, a quality control check of all data was performed. Wind speed values less than 0.1 m/s were recorded as calm and they were not included into this analysis, similarly the erroneous data were eliminated from this analysis.

Fig. 1. Meteorological station Liptovský Mikuláš – Ondrašová (source: SHMI).

2.2. Weibull distribution

Let X be a random variable from the 2-parameter Weibull distribution with parameters $k > 0, c > 0$. Its probability density function (PDF) is for $x > 0$ given by

$$f(x) = \frac{k}{c^k} x^{k-1} exp\left(-\left(\frac{x}{c}\right)^k\right) \tag{1}$$

and cumulative distribution function (CDF) is given by

$$F(x) = 1 - exp\left(-\left(\frac{x}{c}\right)^k\right) \tag{2}$$

where x is the wind speed, k is the dimensionless shape parameter and c is the scale parameter in units of the wind speed (here in m/s). The scale parameter c is directly proportional to the mean wind speed and the value of shape parameter k indicates the wind stability. The low value for k means very variable wind, while constant wind is characterized by a higher k value [30]. For most wind sites in the world, the shape parameter k generally ranges from 1.5 to 2.5, rarely 3 [14, 29].
There are several methods for parameter estimation of the probability distribution. The most common are the method of moments, least square method, method of L-moments and maximum likelihood method, power density method [7, 8, 12, 29, 31-37]. In this paper, the estimation of the Weibull distribution parameters was performed by using the maximum likelihood method (MLM). This method is reported as widely used and preferred statistical estimation method because it possesses desirable asymptotic properties [8, 16, 38].

Let $x_1, x_2, \dots, x_n$ be a realization of a random sample of size n from the Weibull distribution. The MLM parameter estimates can be determined using the following nonlinear equations

$$\frac{1}{k} - \frac{\sum_{i=1}^{n} x_i^k \ln x_i}{\sum_{i=1}^{n} x_i^k} + \frac{1}{n}\sum_{i=1}^{n} \ln x_i = 0,$$

$$c = \left(\frac{1}{n}\sum_{i=1}^{n} x_i^k\right)^{1/k}. \quad (3)$$

Because the equations (3) are nonlinear, an iterative procedure is required to solve them. In this paper, the equations (3) have been solved using the standard iterative Newton method. The estimates of the parameters k and c are denoted $\hat{k}$ and $\hat{c}$, respectively. In order to determine the parameter estimates the statistical software STATISTICA and software MATLAB R2019b were used.

2.3 Performance criteria

In order to determine the performance of the Weibull distribution for modelling the wind speed data in Liptovský Mikuláš, the coefficient of determination (R^2) and the root mean square error (RMSE) were used [17, 39]. It should be noted that the lower value of RMSE and higher value of R^2 indicate that the distribution fits the wind speed data better.
The coefficient of determination can be calculated as follows

$$R^2 = \frac{\sum_{i=1}^{n}(\hat{F}(x_i) - \bar{F})^2}{\sum_{i=1}^{n}(\hat{F}(x_i) - \bar{F})^2 + \sum_{i=1}^{n}\left(F_n(x_i) - \hat{F}(x_i)\right)^2} \quad (4)$$

and the root mean square error can be calculated as follows

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}\left(F_n(x_i) - \hat{F}(x_i)\right)^2\right]^{\frac{1}{2}} \quad (5)$$

where $\hat{F}(x)$ is the estimated cumulative distribution function, $F_n(x) = \frac{1}{n}\sum_{i=1}^{n} I\left(x_{(i)} \le x\right)$ is the empirical distribution function, where $I\left(x_{(i)} \le x\right) = 1$ if $x_{(i)} \le x$ and 0 otherwise, $x_{(1)}, x_{(2)}, \dots, x_{(n)}$ are observations in ascending order, so that $x_{(1)} \le x_{(2)} \le \dots \le x_{(n)}$ and $\bar{F} = \frac{1}{n}\sum_{i=1}^{n} \hat{F}(x_i)$.

3 Statistical analysis and results

Some basic statistics such as mean, standard deviation (SD), coefficient of variation (CV), maximum (Max), coefficients of skewness and kurtosis for the seasonal, annual and monthly wind speed data are summarized in Tables 1 and 2.

Table 1. Descriptive statistics for the seasonal and annual wind speed data.

	Mean (*m/s*)	SD (*m/s*)	CV (%)	Max (*m/s*)	Skewness	Kurtosis
Spring	2.68	1.86	69.28%	12	1.57	2.84
Summer	2.21	1.56	70.97%	10	1.79	3.41
Autumn	2.31	1.59	68.70%	12	1.72	3.67
Winter	2.50	1.90	75.96%	14	1.91	4.71
Annual	2.43	1.74	71.72%	14	1.77	3.88

Table 2. Descriptive statistics for the monthly wind speed data.

	Mean (*m/s*)	SD (*m/s*)	CV (%)	Max (*m/s*)	Skewness	Kurtosis
January	2.20	1.94	88.20%	14	2.12	6.64
February	2.73	1.93	70.68%	13	1.39	2.24
March	2.82	1.90	67.37%	10	1.21	1.08
April	2.71	1.94	71.76%	12	1.76	3.76
May	2.49	1.69	67.96%	12	1.76	4.10
June	2.42	1.79	73.78%	10	1.67	2.58
July	2.17	1.56	71.93%	9	1.78	3.12
August	2.01	1.25	62.12%	8	1.58	2.87
September	2.24	1.47	65.61%	9	1.63	2.96
October	2.45	1.88	76.44%	12	1.85	3.79
November	2.25	1.41	62.56%	8	1.22	1.30
December	2.36	1.86	78.84%	12	2.05	5.08

The highest monthly mean wind speed was observed in March with value of 2.82 m/s, while in August there was observed the lowest mean wind speed with value of 2.01 m/s. The standard deviation ranged between 1.25 - 1.94 m/s. The coefficient of variation is useful for identifying months with higher variable wind speed. The coefficient of variation ranged from 62.12 % in August to 88.2% in January. According to [40], the value of CV>40% is classified as a very high variability and CV>70% indicates the extremely high variability of wind speed. Skewness and kurtosis measure the asymmetry and the peakness of the wind speed distribution, respectively. The coefficients of skewness ranged from 1.21 in March to 2.12 in January. The coefficients of skewness for all months are greater than 1 therefore the wind speed data can be regarded as highly right skewed. The coefficient of kurtosis ranged from 1.08 in March to 6.64 in January. That indicates a leptokurtic distribution.

It was observed that the mean and standard deviation of seasonal wind speed ranged between 2.21 - 2.68 m/s, and 1.56 - 1.90 m/s, respectively. The highest seasonal mean wind speed was observed in spring while in summer, there was observed the lowest mean wind speed. The coefficient of variation ranged from 68.70% to 75.96% that indicates a very high variability. The coefficient of skewness ranged from 1.57 to 1.91. That implies that wind speed is right skewed. The coefficient of kurtosis ranged from 2.84 to 4.71. The annual mean wind speed during the studied period 2005-2015 was 2.43 m/s with standard deviation of 1.74 m/s and coefficient of variation of 71.72%.

The maximum likelihood estimates of the Weibull distribution parameters and values of the statistical tests for the seasonal, annual and monthly wind speed data are presented in Tables 3 and 4.
It was observed that the seasonal value of shape parameter k ranged from 1.474 in winter to 1.607 in autumn, while the value of the seasonal parameter c ranged from 2.488 m/s in summer to 3.010 m/s in spring. The seasonal value of R^2 ranged from 0.7711 to 0.8736 and the value of RMSE ranged from 0.1058 to 0.1464. The annual shape parameter k is 1.546, while the annual scale parameter c is 2.726 m/s. The annual value of R^2 is 0.8232 and the annual value of RMSE is 0.1269.

Table 3. Seasonal and annual estimates of the parameters and statistical tests.

	Parameter estimates		Statistical tests	
	$\hat{k}$	$\hat{c}$	R^2	$RMSE$
Spring	1.580	3.010	0.8736	0.1058
Summer	1.571	2.488	0.7711	0.1464
Autumn	1.607	2.602	0.8124	0.1319
Winter	1.474	2.790	0.8168	0.1295
Annual	1.546	2.726	0.8232	0.1269

The fitted Weibull PDFs for the seasonal wind speed data are presented in Figure 3. Graphical comparison between the observed wind speed data and Weibull distribution shows that Weibull distribution fits well the wind speed data for all seasons.
The fitted Weibull PDF for the annual wind speed data is presented in Figure 2. As it can be seen from the Figure 2, the Weibull distribution fits the annual wind speed data satisfactorily.
Analysis showed that the monthly shape parameter k ranged from 1.442 in December to 1.761 in August and the monthly scale parameter c ranged from 2.276 m/s in August to 3.175 m/s in March. The monthly values of R^2 are greater than 0.7526 and the values of RMSE are less than 0.1536. It indicates that the Weibull distribution describes the data satisfactorily.

Table 4. Monthly estimates of the parameters and statistical tests.

	Parameter estimates		Statistical tests	
	$\hat{k}$	$\hat{c}$	R^2	$RMSE$
January	1.466	2.717	0.7899	0.1364
February	1.539	3.056	0.8817	0.1054
March	1.601	3.175	0.9019	0.0950
April	1.541	3.038	0.8651	0.1079
May	1.620	2.807	0.8444	0.1171
June	1.510	2.716	0.8104	0.1316
July	1.556	2.439	0.7526	0.1536
August	1.761	2.276	0.7632	0.1532
September	1.674	2.536	0.8088	0.1330
October	1.471	2.742	0.8022	0.1338
November	1.733	2.547	0.8354	0.1279
December	1.442	2.632	0.7653	0.1484

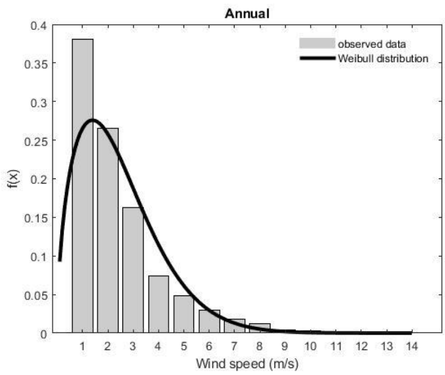

Fig. 2. Histogram and fitted Weibull PDF for the annual wind speed data.

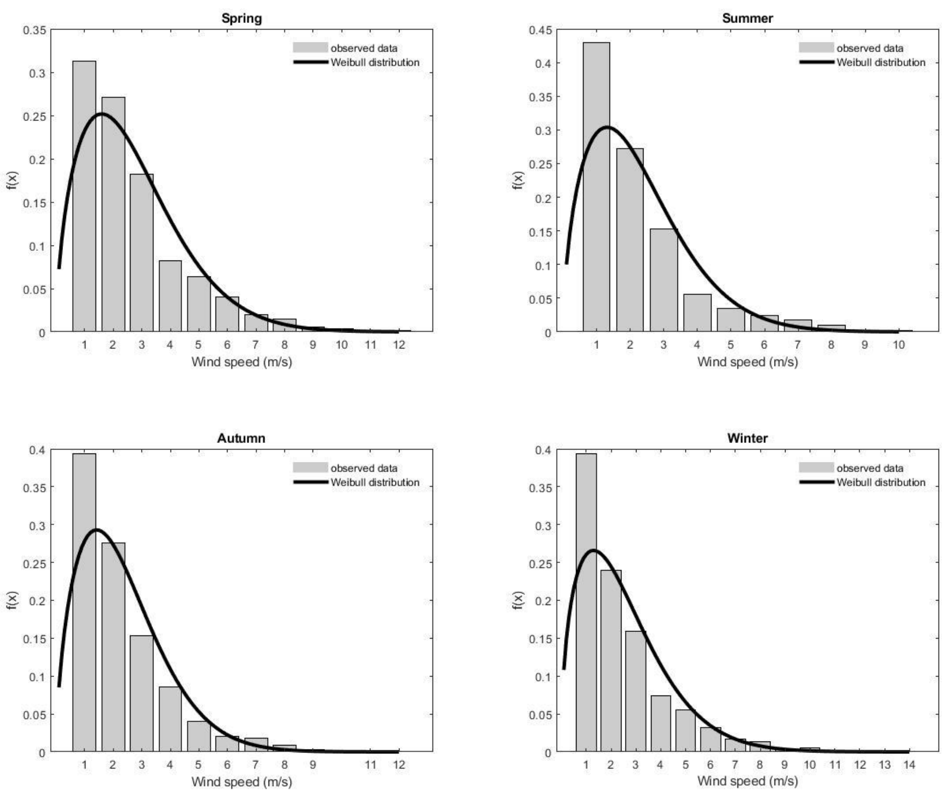

Fig. 3. Histograms and fitted Weibull PDFs for the seasonal wind speed data.

4 Conclusions

The monthly, seasonal and annual wind speed data obtained from the meteorological station Liptovský Mikuláš-Ondrašová, Slovakia, were statistically analysed in this paper using the

2-parameter Weibull distribution. The wind speed data were collected over the 11-year period (2005 - 2015). The maximum likelihood method was used to determine the Weibull parameters. Coefficient of determination and root mean square error were used as the performance indicators in this study.
The results can be summarized as follows:

- the annual shape parameter k is 1.546, the seasonal shape parameter k ranges from 1.474 to 1.607 and the monthly shape parameter k ranges from 1.442 to 1.761,
- the annual scale parameter c is 2.726 m/s, the seasonal scale parameter c ranges from 2.488 m/s to 3.010 m/s, the monthly scale parameter c ranges from 2.276 m/s to 3.175 m/s,
- the shape parameter k is less than 2. This implies that Liptovský Mikuláš is a location with variable winds,
- the value of R^2 is greater than 0.7526 and the value of $RMSE$ is less than 0.1536 in all studied cases, therefore the 2-parameter Weibull distribution is suitable for description of the wind speed data in Liptovský Mikuláš.

The results show that 2-parameter Weibull distribution describes annual, seasonal and monthly wind speed data in this location satisfactorily and therefore it can be employed in the future wind speed prediction.

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