Spatial Complex Model for Wind Farm Site Assessment

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Abstract: Our research is on the spatial allocation of possible wind energy usage. We would like to carry this out with a newly developed model (CMPAM = Complex Multifactoral Polygenetic Adaptive Model), which basically is a climate-oriented system, but other kind of factors are also considered. With this model those areas and terrains can be located where construction of wind farms would be reasonable. The wind field modeling core of CMPAM is mainly based on sequential Gaussian simulation (sGs) otherwise known as geostatistics. But concepts from atmospheric physics and Geographical Information Systems (GIS) are used as well. For application for Hungary WAsP generated 10 m wind speed data was used as input data. The geocorrection (geometric correction) of this data was performed by us. Using optimized variography and sGs, our results were applied for Hungary in different heights. Simulation results for different heights are summarized furthermore, an exponential regressive function describing the vertical wind profile was also established. From the complex analyses of CMPAM, results derived to the 100 m height are also included and explained in a map in this paper. This produces a basis for certain several possible sites for the utilization of wind energy, under given conditions.

1. INTRODUCTION

Due to ever increasing anthropogenically caused environmental pollution and the worldwide energy claim, the research and exploitation of environment-friendly renewable energy sources like wind, solar, geothermal, and biomass becomes more and more important. Developed countries support systems based on renewable energies, specifically wind energy. During the last decade wind energy utilization has developed dynamically with big steps. Over just the past seven years, annual worldwide growth of installed wind capacity has grown to near 30%. This means over 94,000 MW is installed currently [1]. Moreover many countries inspire profit oriented ventures based on renewable energies. Besides economic incentives, the most extensive and most accurate scientific results are required in order to provide regional planning with the possibility of selecting ideal location for wind energy exploitation.

In this project a climate oriented model Complex Multifactoral Polygenetic Adaptive Model (CMPAM) has been developed to select those regions where the exploitation of the available wind energy would yield profit under the given factors. This model helps the wind site assessment for wind farms. The model consists of several sub-modules, the most important of them being the wind field modeling part (CMPAM/W) (W in the abbreviation denotes wind field modeling). Our research focuses mainly on this sub-module. The other sub-modules (e.g. those of landscape ecology, administration and physical geography) are declared in a more general way in the model.

There are various studies on wind resource mapping all over the world. Some similarities can be noticed among them but it can be also stated that for wind site assessment there are different programs, models and methods [2-3]. In general these solutions may arise from fluid dynamics or complex models or simulations or interpolations [4]. The CMPAM is a new complex model that has new features in comparison to other models and systems for wind site assessment or wind resource analysis.

2. MATERIALS AND METHODOLOGY

2.1. Features of Wind Field Modeling Sub-Module (CMPAM/W)

This wind field modeling is comprised of methods and calculations from atmospheric physics, geostatistics and GIS and its aim is to supply information for a wind field for system planning and economic efficiency calculations. Resolution of the CMPAM/W grid system is 4 km^2 and supplies the following information for each grid: (1) expected value of the wind speed, (2) uncertainty of the wind speed (in the form of width of the probability interval) and (3) wind power density.

All of this information is ensured mainly by geostatistics, since this field of science, contrary to mathematical statistics, uses regionalized variables with structural and erratic features and works with dependent sampling methods. On the other hand, mathematical statistics uses probability variables and works with independent sampling. Geostatistics deals with the spatial structure of the data; it is able to measure variability and heterogeneity in this structure and to use these in estimating the values of grid points.

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2.2. Input Data for Wind Field Modeling and the Sampling Method

Our basic input data come from 10 meters height wind field modeling data [5], which was compiled by the Wind Atlas Analysis and Application Program (WAsP) using wind speed data of 29 Hungarian meteorological stations for a 6-year period (1997 – 2002). Comparative case studies were carried out to analyze the applicability of the WAsP model on different terrain conditions [6]. WAsP was used in other studies and researches with success [7-10]. However the study of applicability to Hungarian wind conditions was based on data of meteorological stations in some cases other measurement methods and measuring devices (for instance SODAR) can serve better database [11].

This data aquition method was needed because the research project could not get enough observed data. After performing polynomial geometric correction (transformation into geographic EOV projection) on this WAsP result, random points were gathered in order to get sampling points (150) for further processing (Fig. **1**). These new sampling points received the appropriate wind speed data by GIS processes. Then two GIS functions were used to determine the proper geographic X and Y coordinates of the sampling points. These newly gained sampling points constituted the basis of further calculations and simulations.

2.3. Data Processing and Modeling

Our newly developed wind field model was prepared using calculations and methods of atmospheric physics, geostatistics and GIS. Geostatistics uses variogram ($2\gamma(x,y)$ – *theoretical variogram (1)*) that is describing the degree of spatial dependence of a spatial random field or stochastic process ($Z(x)$). It is defined as the expected squared increment of the values between locations *x* and *y*.

$$2\gamma(x,y) = E\left(\ \left|Z(x)-Z(y)\right|^2\right) \tag{1}$$

The core of our simulation for every examined altitude is a sequential Gaussian simulation (sGs) [12] where empirical variograms *(2)* are used:

$$\gamma(h) = \frac{1}{2N(h)} \cdot \sum_{i=1}^{N(h)} \left[Z(x_i) - Z(x_{i+h})\right]^2 \tag{2}$$

where $N_{(h)}$ donates the set of pairs of observation (*i; j*) placed at an approximate distance of *h*. Here "approximate distance h" is not exactly defined and typically implemented by a certain tolerance.

$Z_{(x)}$ is the initial point of *h* separator vector that divides the data point pairs and $Z_{(x+h)}$ is endpoint of *h* separator vector. The empirical variogram is used in geostatistics as a first estimate of the (theoretical) variogram and needed for spatial interpolation [13].

The variogram surface, which is the visualization of the spatial anisotropy of the examined phenomenon, was made of the z-score transformation of wind speed data coming from random sampling. Furthermore, segments of the variogram surface in different directions, namely the semi-variograms (which are measures of spatial continuity) were also prepared from our newly gained data. Variogram models, required for further simulations (sGs) [14], were prepared on the basis of these semi-variograms. Each of these variogram models comprises three structures (two spherical and a Gaussian ones) therefore they are nested models [15]. They were used in the sequential Gaussian simulation for all of the modeled altitudes (10 m, 30 m, 60 m, 80 m, 100 m, 120 m, 140 m above ground). The final results were received after the normal score back-transformation of the grid data.

Extrapolation of the vertical wind speed was performed using sampling points on the basis of the Hellmann exponent formula (modified version of power law) [16]:
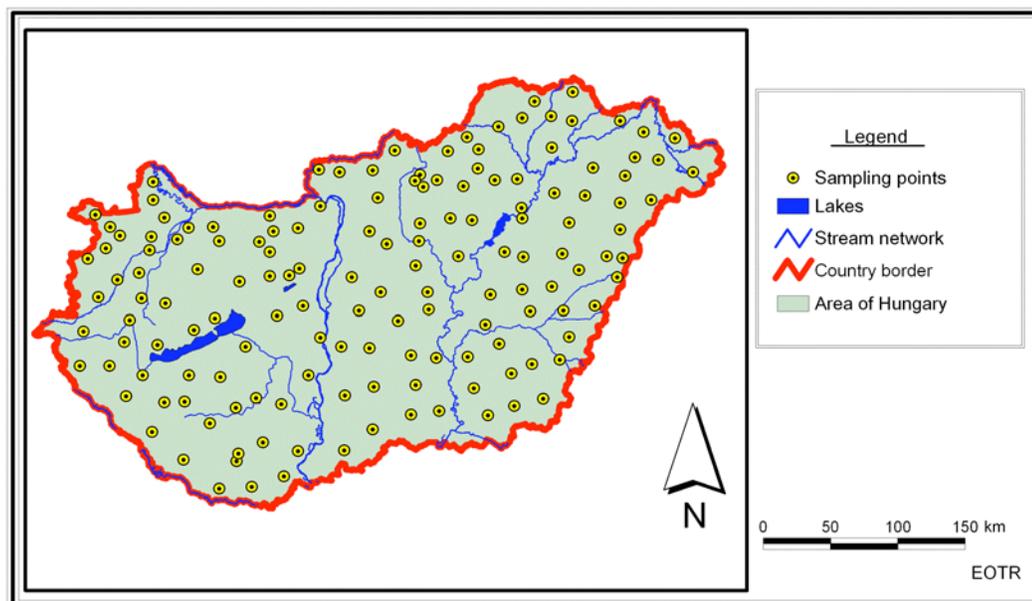

Fig. (1). Spatial distribution of sampling points for our simulation.

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha}, \qquad (3)$$

where $\alpha = 1/\ln(10/z_0)$; α characterizes the roughness of the surface, and z_0 is the aerodynamic roughness height. The value of α was determined by GIS methods on the basis of CORINE data [17, 18]. Surface roughness was determined by the help of CORINE, WAsP wind atlas surface roughness classification index and weighed by area by the help of GIS. The results of the simulations were processed with other sub-modules by the help of GIS geoprocessing techniques and algorithms. One of the final outcomes is represented at the end of this paper (CMPAM in practice paragraph).

3. RESULTS

When preparing the simulations, 100 different realizations with the same probability level were made for each simulation altitude. Results of the simulation, modeling, and grid system of 1 km^2 resolution can not be evaluated due to the special combination of small-scale heterogeneity and noise of sGs. But after changing the grid resolution to 4 km^2, acceptable results could be achieved. The spatial variability was preserved in a better way on this scale. When performing the sGs simulations, the results of each altitude for all of their 100 realizations can be analyzed and displayed on maps. However, the mean of these 100 realizations represents a good approximation of the expected value of the wind speed (Figs. **2**, **3**).
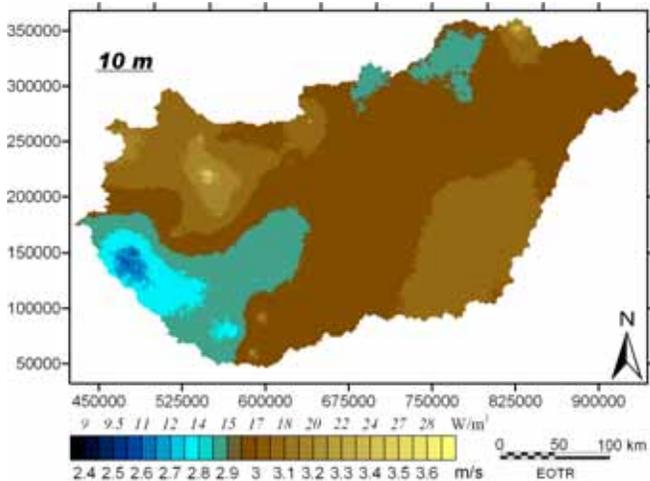

Fig. (2). Average values of the simulations realizations for wind speed and gross wind potential, 10 m above ground level.

According to the results, in the height of 10 m above ground level, the Transdanubian Mountain Range shows high wind potential, including the Bakony Mountain, Marcal Basin and the plain in Northwestern Hungary. On the other hand, some parts of the Great Hungarian Plain (mouths of the Rivers Maros and Körös as well as Nagy-Sárrét and Kis-Sárrét) have higher than average wind potential, thus may be these regions are good for larger scale of utilization of wind (Fig. **2**). Concerning the spatial pattern, similar results were achieved and have already been published by using significantly different methods [19]. So these can be regarded as the verification of each other to some extend.
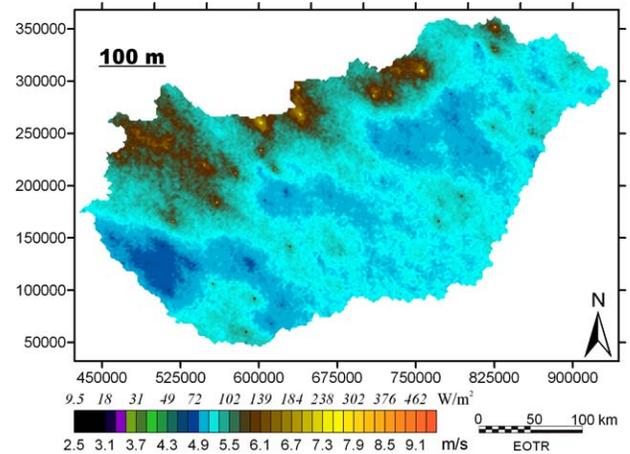

Fig. (3). Average values of the simulations realizations of wind speed and gross wind potential, 100 m above ground level.

Summarizing the results of wind field modeling for higher levels (from 10 meters to 140 meters above ground level), on large map scale spatial heterogeneity appeared in the wind field structure, while on small map scale spatial homogeneity of the expected values of wind speed are indicated. This is a very interesting dual feature of the wind field (Fig. **3**). The possible reason of the large scale homogeneity of the wind field in the Internal Boundary Layer (IBL) is that effect of the surface roughness is not as significant at higher altitudes as at low levels. This is one of the main reasons why the wind field becomes more and more homogenous at higher altitudes. According to our simulation outcomes it can be stated that at the altitude of 60 meters above ground level or higher, the surface objects do not have significant influence on the wind field [20-22]. Nevertheless the current resolution (4 km^2) is not sufficient to detect smaller local impacts such as individual buildings or building groups therefore the previous statement seems to be true only on this resolution that is good for meso-scale examination and helps to locate those areas where micro-scale modeling should be run.

If result of sGs and one of the most sophisticated interpolation technique the Kriging (simple Kriging) is compared with each other it can be concluded that sGs is capable of capturing the typical wind flow pattern in some respect (Fig. **5**) whilst Kriging smoothes the entire wind field (Fig. **4**) that is not appropriate for correct wind resource mapping due to the attributes of wind flow over terrain.
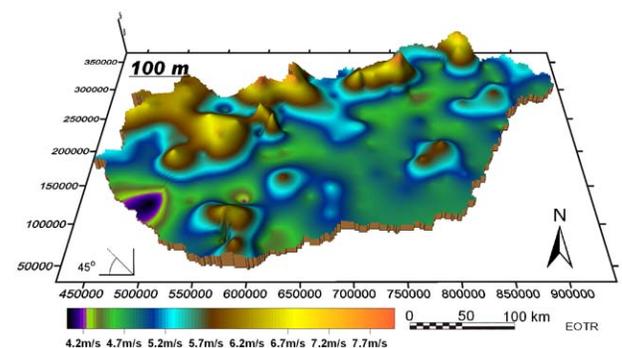

Fig. (4). Wind field at 100 m height calculated by SK interpolation (Simple Kriging).
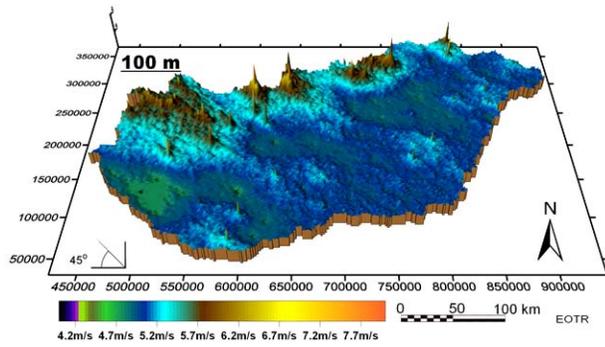
Fig. (5). Wind field at 100 m height calculated by sGs.

In one-variable mathematical statistics confidence interval is often calculated when estimating the expected value. At the first step of the geostatistical analysis, standard normal transformation of the input data was performed. Consequently, surfaces belonging to the lower and upper limit of the confidence intervals can be determined [23]. The tighter this confidence interval, the more stable the estimation of the expected values is. Consequently, the width of the probability (confidence) interval can be interpreted as the uncertainty in assessment of the expected value at every grid. Thus this can be interpreted as an uncertainty surface or map (Figs. **6**, **7**).
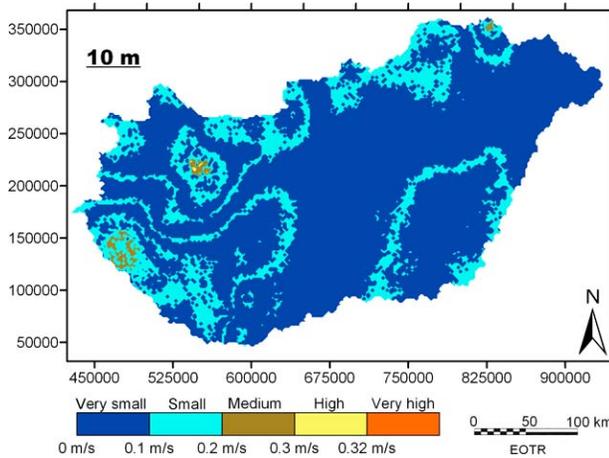

Fig. (6). Uncertainty of the expected values of wind speed, 10 m height above ground level.

Hence, the uncertainty maps are spatial extensions of the confidence intervals of the expected values, belonging to each simulation grid.

All of the uncertainty values according to the above definition have been classified with the same way between the minima and maxima of the uncertainty. Uncertainty intervals were divided by four and the residual values went to the fifth interval therefore each verbal category represents 20% of the classified uncertainty interval. Furthermore numeric values belonging to thresholds of each verbal category can be also seen. Thus this is the representation of cumulative distributive function of uncertainty. This idea is demonstrated on Figs. (**6**, **7**) with intervals and the corresponding verbal categories.

On the basis of our simulations a multiple regression function was established that describes the vertical wind

profile for the modeled territory. This function might be more suitable for vertical extrapolation of wind speed from 10 m to 140 m height above ground level, but this function seems to be applicable for higher altitudes, as well. This function is:

$$u = 1.7437 \cdot z^{0.2353} \qquad R^2 = 0.9998 \qquad (4)$$

where u is the wind speed (ms^{-1}) and z is the height (m).
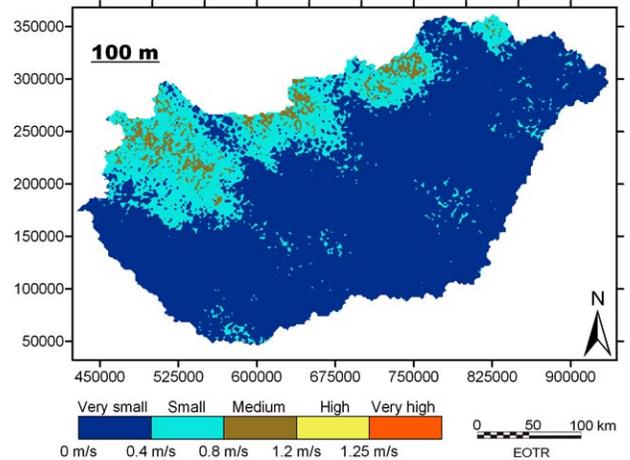

Fig. (7). Uncertainty of expected values of wind speed, 100 m height above ground level.

The advantage of this function over other general extrapolation functions [15, 24] is that it was created from our wind field simulations on the characteristics of the modeled territory, so it is more suitable for vertical wind speed extrapolation for Hungary than general equations [15; 24] that can be found in scientific literature. However this wind extrapolation function (Eq. 4) has limitation since this is mass consistent approach that assumes just neutral boundary layer condition. Unfortunately SODAR data from the examined time period was not possible to acquire to test this new formula.

Results of the simulations are summarized in Tables **1-4**. On Table **1** minimum, maximum, mean, mode, and variance of the various examined altitudes can be found.

Table **2** consists of regional ratios (percentage) of each height category in Hungary. Wind potential value is that amount of energy that could be produced maximum from wind speed [25, 26] hence other wind potential decreasing factors for instance Betz-limit [27] are not considered. According to these tables we can conclude that Hungary belongs to moderately windy regions. The lowest average wind speed at 10 m altitude is 3 ms^{-1} and the highest average wind speed, that is 5.61 ms^{-1}, is at 140 m height. Other authors received similar results [5, 28]. However, as our maps indicate, Hungary has economically utilizable wind energy.

Tables **1** and **2** shows some mathematical statistical characteristics of the Hungarian wind climate. Table **2** indicates the territorial statistics at different altitude. It shows how many of the simulated grid points belong to each category. For example 73.38% of grid points that were computed by simulation belong to 2.4-3.0 ms^{-1} wind speed category at 10 m height. Nevertheless, researches dealing

with the spatial distribution of wind speed have great importance, since mathematical statistical parameters do not inform us about the spatial structure of wind speed, therefore they are not sufficient for the planning of a possible wind farm project. Hence, analysis of the spatial distribution of climatic and energetic components of wind parameters is of vital importance.

Table 1.   Statistics of the Results of the Simulations Calculated to Different Levels

Height (m)	Wind Speed (ms^{-1})				
	Min	*Max*	*Mean*	*Mode*	*Variance*
10	2.4	3.6	3.00	3	0.005437
30	3.08	5.43	3.88	3.86	0.009207
60	3.72	6.92	4.56	4.52	0.023178
80	3.87	7.66	4.88	4.839	0.03931
100	4.12	8.28	5.14	5.09	0.04609
120	4.27	8.83	5.37	5.31	0.071292
140	4.4	9.31	5.61	5.5	0.174398
mean between 10 -140	*3.7*	*7.14*	*4.63*	*4.59*	*0.052702*

Summary of wind field spatial uncertainties, which were calculated by the simulations, are indicated in the Table **3**. In this table the different uncertainty categories belonging to each altitude can be seen as well as ratio of number of grids. This table is based on the numbers and values of uncertainty girds over the modeled territory (Hungary) at different heights. For instance the second column and third row means that at 10 m height in case of very low uncertainty category, which means 0 – 0.1 *ms^{-1}* at this altitude, there are 43527 gird points that belong to this uncertainty category and 43527 gird points mean 99% of all of the simulated grid points at that specific height. It can be concluded that the most frequent uncertainty category is the *Very small*

category at all examined altitudes. However it is probable that above 140 m height the most frequent uncertainty category would slip to the *small* category from lowest category. The possible explanation of this phenomenon is that the higher altitude we examine or model the more uncertainty can be assumed in the data from 10 m altitude. Consequently wind speed data from 10 m height is essential but not always sufficient for high wind profile estimation or wind field simulation.

In order to estimate numbers of uncertainty grids from the modeled results in lowest and low categories two functions were determined on the basis of run of uncertainty grid curves. Only the lowest and low categories were considered. With these functions number of uncertainty girds can be estimated for higher altitude than 140 m as a result numbers of grids of the most frequent uncertainty categories can be calculated. The function of very low uncertainty (5) indicates a decreasing trend while the function of low uncertainty (6) shows an increasing trend by the altitude rise:

$$Y_{very\ low} = -2805.2 \cdot x + 46317 \ R^2 = 0.7238 \qquad (5)$$

$$Y_{low} = 2430.7 \cdot x - 1672.6 \ R^2 = 0.7525 \qquad (6)$$

where numbers of uncertainty grids are represented by *Y* and altitudes (in meter) are represented by *x*.

Increase of number of girds of medium uncertainty category is negligible at all heights thus it is very probable that in the lower layer of IBL [29] this category will not have significant role above the modeled territory (Hungary).

3.1. CMPAM in Practice

During the development of CMPAM, not only the scientific but also the practical applicability of the model was of high priority as well.

Suppose that a company would like to establish a wind farm system in Hungary. They would like to know which sites would be the best ones for wind turbines having the following parameters: height = 100 m and cut in speed = 5.5

Table 2.   Regional Statistics of Results (Gird Points) of Simulations Calculated to Different Levels

Ratios of Regional Distribution of Simulation Results (Grid Points) in Hungary (%)								
Wind Speed (ms^{-1})	*Wind Potential (Wm^{-2})*	Height (m)						
		10	*30*	*60*	*80*	*100*	*120*	*140*
2.4 – 3.0	8 – 17	**73.38**	~0	0	0	0	0	0
3.1 – 3.5	17 – 26	26.6	10	~0	0	0	0	0
3.6 – 4.0	26 – 39	~0	**77**	1.4	~0	0	0	0
4.1 – 4.5	39 – 56	0	12.7	44.4	1.7	~0	~0	0
4.6 – 5.0	56 – 77	0	~0	**51**	**78**	37.6	2	~0
5.1 – 5.5	77 – 102	0	0	3	19.1	**51.25**	**75**	**54.5**
5.6 – 6.0	102 – 132	0	0	~0	1.5	9.8	16.35	28
6.1 – 6.5	132 – 168	0	0	0	~0	1.3	5.4	10
6.6 – 7.0	168 – 210	0	0	0	0	~0	1.1	6.5
7.1 – 7.5	210 – 258	0	0	0	0	0	~0	~0
7.6 – 8.0	258 – 314	0	0	0	0	0	0	0

Table 3.   **Values and Numbers of Uncertainty Grids in All of the Modeled Altitudes as Well as Occurrence of Uncertainty Categories in Ratio of All Grids**

Altitudes	Categories				
	Very Small	*Small*	*Medium*	*High*	*Very High*
10 m	*(0 – 0.1)*	*(0.1 – 0.2)*	*(0.2 – 0.3)*	*(0.3 – 0.32)*	*(0.32 <)*
	43527 → (99%)	**476 → (1%)**	**104 → (~0%)**	**1 → (~0%)**	**1 → (~0%)**
30 m	*(0 – 0.2)*	*(0.2 – 0.4)*	*(0.4 – 0.6)*	*(0.6 – 0.65)*	*(0.65 <)*
	38311→ (87%)	**5000 → (11%)**	**790 → (2%)**	**7 → (~0%)**	**1 → (~0%)**
60 m	*(0 – 0.35)*	*(0.35 – 0.7)*	*(0.7 – 1)*	*(1 – 1.06)*	*(1.06 <)*
	38502 → (87%)	**5458 → (12%)**	**147 → (~0%)**	**1 → (~0%)**	**1 → (~0%)**
80 m	*(0 – 0.35)*	*(0.35 – 0.7)*	*(0.7 – 1.05)*	*(1 – 1.15)*	*(1.15 <)*
	33840 → (77%)	**9257 → (22%)**	**736 → (~0%)**	**5 → (~0%)**	**1 → (~0%)**
100 m	*(0 – 0.4)*	*(0.4 – 1.2)*	*(1.2 – 1.25)*	*(1 – 1.25)*	*(1.25 <)*
	36534 → (83%)	**6777 → (15%)**	**796 → (2%)**	**1 → (~0%)**	**1 → (~0%)**
120 m	*(0 – 0.45)*	*(0.45 – 0.9)*	*(0.9 – 1.35)*	*(1.35 – 1.45)*	*(1.45 <)*
	34252 → (78%)	**9173 → (21%)**	**680 → (2%)**	**3 → (~0%)**	**1 → (~0%)**
140 m	*(0 – 0.35)*	*(0.35 – 0.7)*	*(0.7 – 1.05)*	*(1.05 – 1.06)*	*(1.06 <)*
	20707 → (47%)	**19941 → (45%)**	**3459 → (8%)**	**1 → (~0%)**	**1 → (~0%)**

ms^{-1}. Fig. (**8**) indicates a countrywide analysis of CMPAM for 100 m height, where three sub-modules of CMPAM were used. *The wind field modeling sub-module* (CMPAM/W) was run with the condition that the expected value of the wind speed is at least 5.5 ms^{-1}. In this way, regions appropriate to settle a wind farm are defined from the wind climatic, meteorological aspect. The next one is *the administration sub-module*, comprising administration regions of towns, villages and farms. The third one is *the landscape ecology sub-module*, consisting of the regions of Natura 2000 and bird conservation regions (according to the edict no. 275/2004 X. 08, completing the Conservation Law no. 1996/53), as well as regions of wells, springs, wetlands, rivers and their 50 m zones, furthermore lakes and their 100 m ranges and last but not least specially protected natural conservation regions and national parks. The last two sub-modules represent those regions, which are not suitable to perform such projects. Practical utilization and importance of CMPAM is well demonstrated by Fig (**8**). Through CMPAM various important factors can be considered at the same time. On this example it can be understood that a mere wind climatic analysis is not sufficient, since the regions with the best the climatic conditions will not necessarily be the ones suitable for the establishment of a wind farms.

4. DISCUSSION AND CONCLUSION

A new complex model for wind energy utilization has been developed. The model core (CMPAM/W) consist of geostatistics, GIS, and atmosphere physics in this special system furthermore other sort of factors can be considered as well by the help of other sub-modules. As a result this modeling system can handle different essential factors at the same time though sub-modules of CMPAM.

Due to the special model core of CMPAM, uncertainty can be defined both numeric and verbal way for the users in addition new wind field maps were also made on Hungary for various altitudes 10 m, 30 m, 60 m, 80 m, 100 m, 120 m, 140 m). Basic statistics of wind field of examined altitudes are indicated in this paper. Regarding to the wind field over Hungary it can be assessed that above 60 meters altitude from ground level or higher, the surface objects do not have significant influence on the wind field in the current resolution.

According to the outcomes of CMPAM/W, Hungary belongs to the moderate windy regions. Although some part of the country (from 100 m altitude) especially the north-western region of Hungary seems to be appropriate for larger capacity wind farms however there are other locations of the country where building of wind farms would be reasonable.

On the basis of the modeled territory some important functions have been determined that can be used for further examinations and calculations on Hungary instead of simple and sometimes very general equations.

Capabilities of the entire modeling system (CMPAM) are demonstrated at the end of this paper. In our opinion, mere wind climatic or meteorological analysis are not sufficient, since the regions with the best wind climatic conditions will not necessarily be the ones suitable for the establishment of a wind farms. Hence complex analysis systems are highly needed in order to provide the best available information for the investors and system planners of wind energy and technology projects. The more information they have the more motivation they have to invest capital into renewable energies. Consequently investments into renewable energy projects like wind farms can be promoted and assisted by the help of these complex analyses in addition environmental
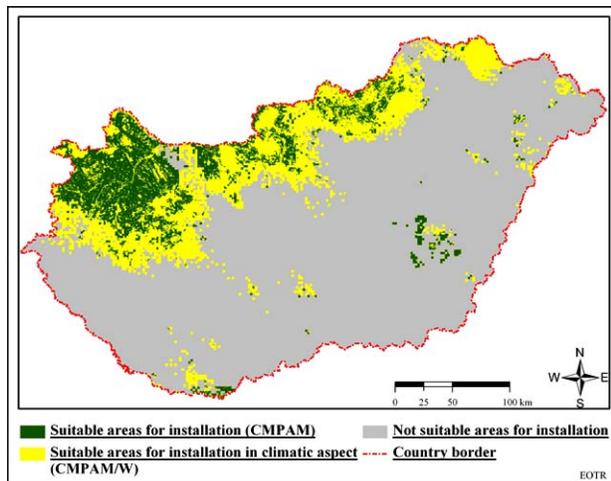
Fig. (8). Practical use of CMPAM in planning of a speculative wind farm project, in 100 m height.

protection can be sub served at the same time as well. In the following example advantage and applicability of CMPAM is described. During wind farm construction, lot of factors need to be considered at different levels. For instance different permissions need to be acquired, as well as transmission lines, roads, environment, local population, wind resource, sounding, visibility, have to be considered as well besides many other factors. It is very complex process. All of these factors can have spatial extend therefore can be processed through GIS thus can be implemented into CMPAM. In terms of wind resource the uncertainty coming from spatial system of wind field can be determined and considered. In some modeling programs wind speed values can be computed easily but spatial uncertainty is not always calculated therefore high wind speed values over some regions can delude wind project developers. If they know about the uncertainty they can reconsider their plans. Hence this information is beneficial to calculate possible energy production rate with uncertainty and calculate profitability too.

In the future this model will be run and developed further on West Texas Mesonet (WTM) data base. With data from WTM the modeling procedure can be more precise and further development can be done as well. Moreover new wind climate modeling result can be received for Texas Panhandle area with this model where WTM is located. Texas panhandle area has complex terrain therefore it will be perfect for development of surface terrain influenced wind flow development for CMPAM/W.

ACKNOWLEDGEMENTS

ABBREVIATIONS

CMPAM	=	Complex Multifactorial Polygenetic Adaptive Model
CMPAM/W	=	Complex Multifactoral Polygenetic Adaptive Model, wind field sub-module
CORINE	=	Coordination of information on the environment. It is a European program initiated in 1985, aimed at gathering information relating to the environment (air, water, soil, land cover, coastal erosion, biotopes, etc.).
EOTR	=	Unified country map system for Hungary
GIS	=	Geographical Information System
sGs	=	Sequential Gaussian simulation
SK	=	Simple Kriging
SODAR	=	Sonic Detection And Ranging
WAsP	=	Wind Atlas Analysis and Application Program

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