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A NEWLY DEVELOPED MODEL FOR THE SPATIAL ALLOCATION OF WIND ENERGY UTILIZATION

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Összefoglalás – Kutatásunk célja a szélenergia hasznosításának területi allokációja. Ezt egy saját fejlesztésű klímaorientált modellel KMPAM (Komplex Multifaktoros Poligenetikus Adaptív Modell) kívánjuk megvalósítani. Ennek a modellnek a legfontosabb eleme a szélmező modellezés melyre a legtöbb energiát fordítottuk munkánk során, de más tényezőket is számításba vettünk. Ez a szélmező modellezés geostatisztikai, légkör fizikai és GIS számításokon, módszereken és egy Szekvenciális Gaussi Szimuláción (sGs) alapszik. A magyarországi szimulációkhoz a bemenő adatokat Radics (2004) WAsP 10 méter magasságra készített modellezési vizualizációjából vettük, melyet geokorrigáltunk. Feltáró variográfiát és az sGs-t használva elkészítettük a modellezett terültet – Magyarország – feletti szimulációs térképeinket, különböző magasságokra, melyek közül bemutatunk néhányat. A különböző magasságokra kapott szimulációs eredményeket összefoglaltuk illetve készítettünk egy vertikális szélprofilt leíró exponenciális regresszív függvényt is. A KMAPM komplex elemzései közül a 100m-es magasságra kapott eredményeket tartalmazza az utolsó térkép, mely alapján meghatározható több lehetséges helyszíne a szélenergia felhasználásnak.

Summary – Our research is on the spatial allocation of possible wind energy usage. We would like to carry this out with a self-developed model (Complex Multifactoral Polygenetic Adaptive Model = CMPAM), which basically is a climate-oriented system, but other kind of factors are also considered. The wind field modelling core is mainly based on sGs (sequential Gaussian simulation) hence geostatistics, but atmospheric physics and GIS are used as well. For the application developed for Hungary we used WAsP visualization from Radics (2004) at 10 m height as input data, the geocorrection of which was performed by us. Using optimized variography and sequential Gaussian simulation, our results were applied for Hungary in different heights. Simulation results received 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 received to the 100 m height were also included, on the basis of which several possible sites for the utilization of wind energy can be selected, under given conditions.

Key words: wind field modelling, complex modelling, Sequential Gaussian Simulation, expected value of wind speed, uncertainty of expected value of wind speed, wind profile

1. INTRODUCTION

Due to the ever increasing anthropogenic environmental pollution and the worldwide energy claim, the research and exploitation of environment-friendly renewable energy sources become more and more important. Developed countries, especially the European Union, support systems based on renewable energies, the exploitation of wind energy among them. Moreover, they inspire profit oriented ventures based on these. Besides economic incentives, the most extensive and most accurate scientific results are required in order to provide regional planning with the possibility of selecting geographical coordinates for optimal exploitation of renewable energy sources.

In this project a climate oriented model (Complex Multifactoral Polygenetic Adaptive Model = CMPAM) has been developed, which facilitates to select those regions where the exploitation of the available wind energy would yield profit. The model consists of several sub-modules, the most important one of them is the wind field modelling part (CMPAM/W) (W in the abbreviation denotes to Wind field modelling). 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 much more general way in the model.

2. WIND FIELD MODELLING

This wind field modelling comprises methods and calculations of atmospheric physics, geostatistics and GIS and its aim is to supply information on wind field for system planning and economic efficiency calculations, which can not or can hardly be provided by using other techniques. 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 (width of the probability interval) and (3) wind potential value.

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.

3. INPUT DATA FOR WIND FIELD MODELLING AND THE SAMPLING METHOD

Our basic input data come from *Radics's* (2004) 10 meters height wind field modelling visualization, 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). After performing polynomial geometric correction (transformation into geographic EOV projection) on this WAsP result, a so-called K – type randomized sampling algorithm was applied 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 coordinates of the sampling points. These newly gained sampling points constituted the basis of further calculations and simulations.

4. DATA PROCESSING AND MODELLING

Our newly developed wind field model was prepared using calculations and methods of atmospheric physics, geostatistics and GIS. The core of our simulation is a Sequential Gaussian Simulation (sGs) (*Deutsch et al.,* 1998). The variogram surface, which is the visualisation of the spatial anisotropy of the phenomenon examined, 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), were prepared on the basis of these semi-variograms. Each of these variogram models, comprising three structures (two spherical and a Gaussian ones), are nested models (*Pannatier,* 1996). They were used to the Sequential Gaussian Simulation for all of the modelled altitudes (10 m, 30 m, 60 m, 80 m, 100 m, 120 m, 140 m above ground level). The final results were received after the normal score back-transformation of the grid data.

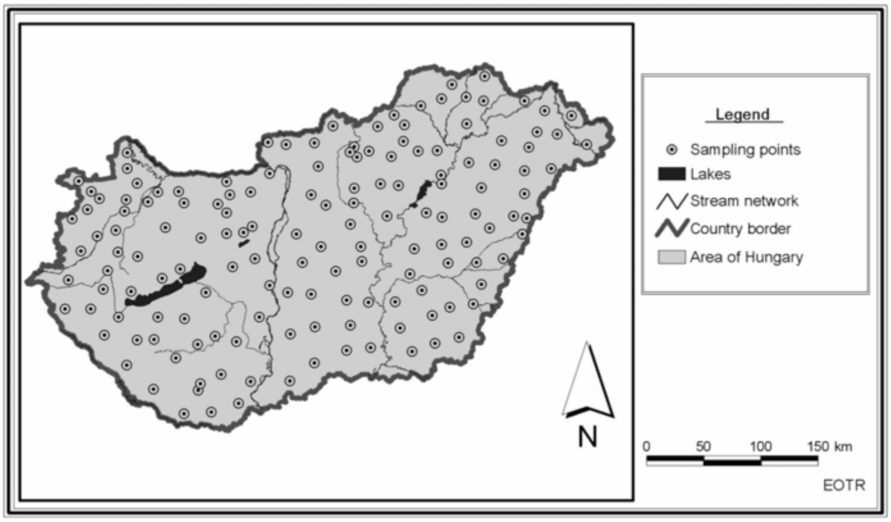

Fig. 1 Spatial distribution of sampling points for our simulation

Extrapolation of the vertical wind speed was performed using sampling points on the basis of the Hellmann exponent formula (*Molly*, 1990):

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha}, \qquad (1)$$

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.

5. DISCUSSION

When preparing the simulations, 100 different realizations with the same probability level were made for each simulation altitude. Results of the simulation, modelling and grid system of 1 km^2 resolution can not be evaluated, due to the special combination of small-scale heterogeneity and noise. But after increasing 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*). 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, and thus may be of good use (*Fig. 2*). Concerning the spatial pattern, similar results achieved by using significantly different methods have already been published (*Wantuchné*, 2005). So these can be regarded as the verification of each other.

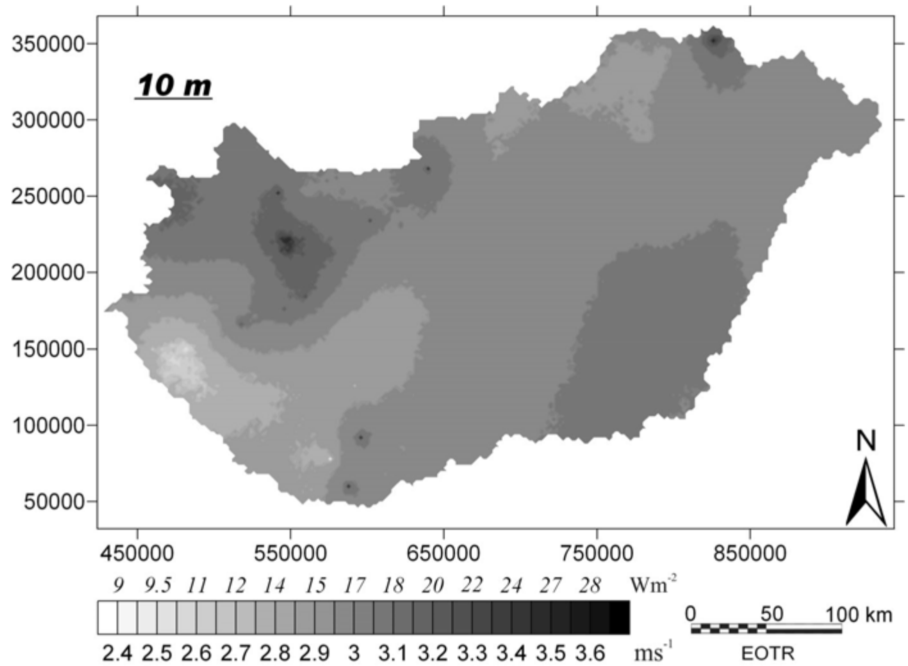

Fig. 2 Average values of the simulations realizations for wind speed and gross wind potential, 10 meter above ground level

Summarizing the results of wind field modelling for higher levels (from 10 meters to 140 meters above ground level), on large scale a spatial homogeneity appeared in the wind field structure, while on small scale heterogeneity 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 Inner Boundary Layer (IBL) is that the surface roughness is not as significant at higher altitudes as at low levels (*Baranka et al.,* 2001). That is, 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 (*Wieringa*, 1976, 1983; *Kircsi*, 2004).

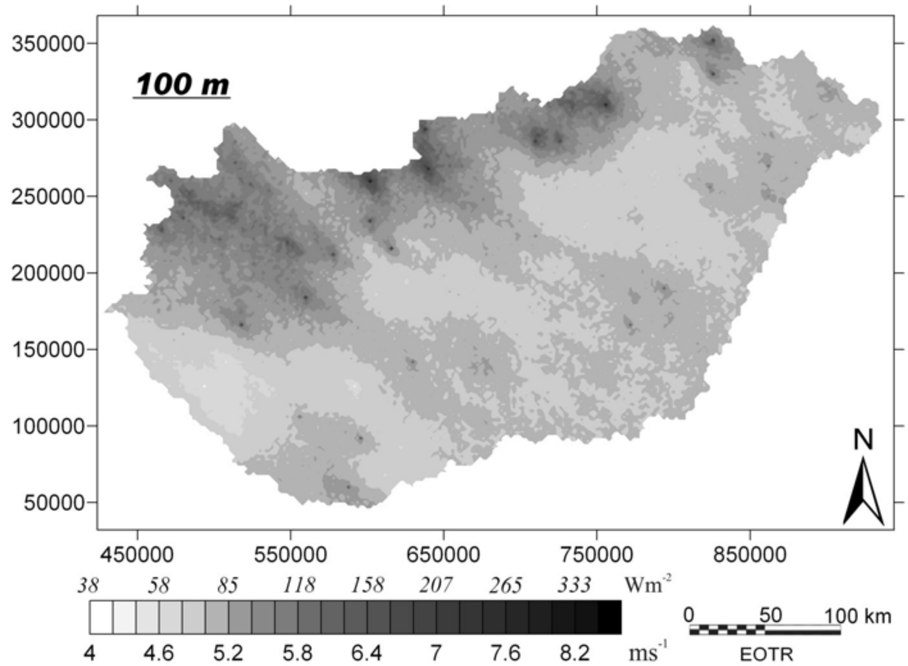

Fig. 3 Average values of the simulations realizations of wind speed and gross wind potential, 100 meter above ground level

In one-variable mathematical statistics it is evident to compute confidence interval 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 (*Geiger and Mucsi,* 2005). 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 map (*Figs. 4-5*)

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 into some equidistance scale between the minima and maxima of the uncertainty. Naturally these intervals can be expressed in a verbal scale, as well. This idea is demonstrated on *Fig. 4* and *5* with intervals and the corresponding verbal categories. It is very important to emphasize that uncertainty is not equal to error.

On the basis of our simulations a multiple regression function was established that describes the vertical wind profile for the modelled territory. This function was found to be 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 as follows:

$$y = 1{,}7437 \cdot x^{0{,}2353} \quad (R^2=0{,}9998) \qquad (2)$$

where *y* is the wind speed (ms^{-1}) and *x* is the height (m).

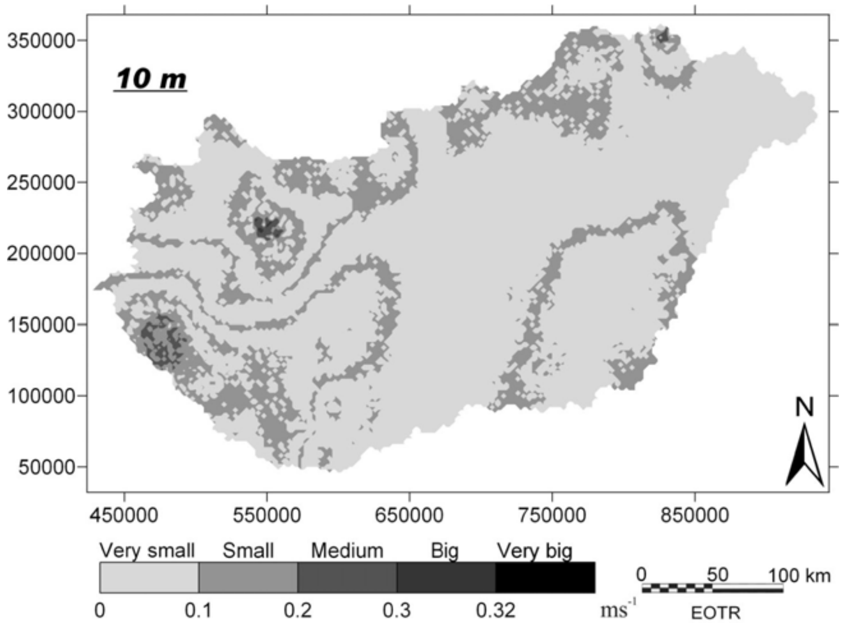

Fig. 4 Uncertainty of the expected values of wind speed, 10 m height above ground level

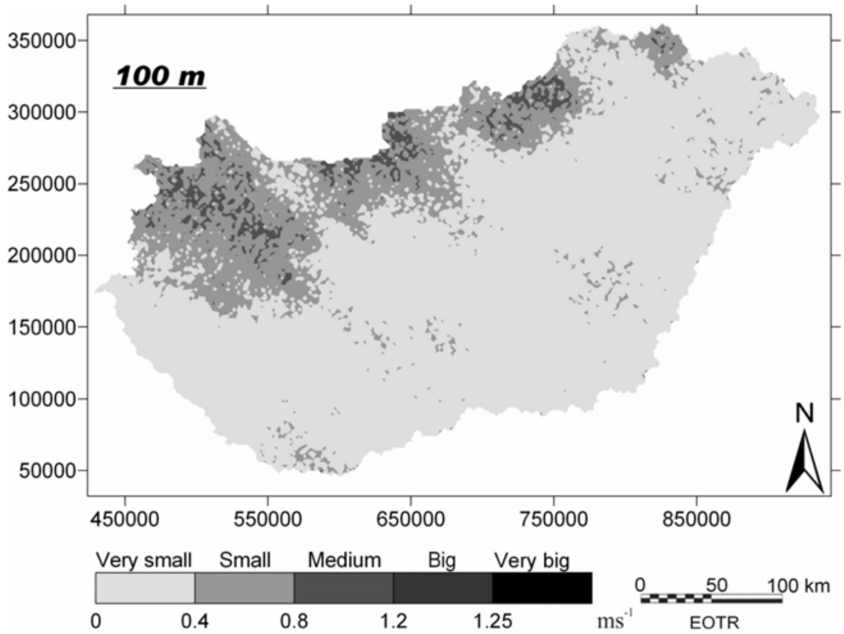

Fig. 5 Uncertainty of expected values of wind speed, 100 m height above ground level

The advantage of this function over other extrapolation functions (*Molly*, 1990; *Dobesch and Kury,* 1999) is that it was created from our wind field simulations on the characteristics of the modelled territory, so it is more suitable for vertical wind speed extrapolation for Hungary.

Results of the simulations are summarized in *Table 1* and *2*. *Table 2* consists of regional ratios (percentage) of each category in Hungary. According to these tables we can conclude that Hungary belongs to moderately windy regions. Other authors received similar results (*Tar et al.,* 2001; *Radics*, 2004). However, as our maps indicate, Hungary has economically utilizable wind energy. *Table 1* and *2* shows some mathematical statistical characteristics of the Hungarian wind climate. 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 power plant project. Hence, analysis of the spatial distribution of climatological 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*	*Modus*	*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*

Table 2 Regional statistics of results of simulations calculated to different levels

Ratios of regional distribution of simulation results 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

6. CMPAM IN PRACTICE

In the course of planning and developing CMPAM, not only the scientific but also the practical applicability of the model was of high priority.

Suppose that a firm would like to establish a wind power plant 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 impulse speed = 5.5 ms^{-1}. *Fig. 6* indicates a countrywide analysis of CMPAM for 100 m height, where three sub-modules of CMPAM were used. *The wind field modelling 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 power plant system are defined from the climatologic 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 6*. On this example it can be understood that a mere climatological 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 power station.

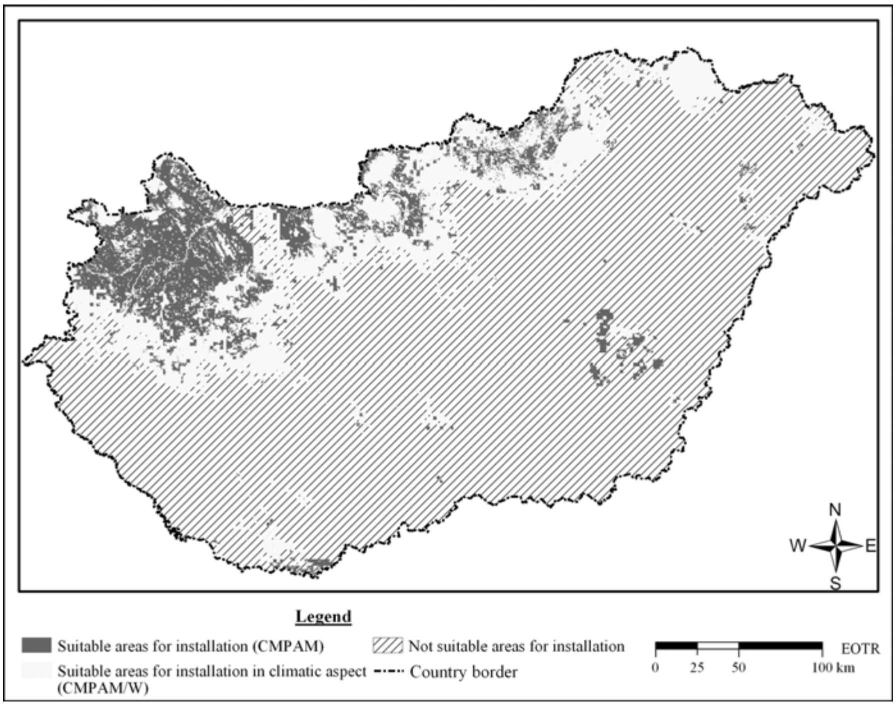

Fig. 6 Practical use of CMPAM in the planning of a speculative wind power plant project, in 100 m height

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