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REGIONAL-SCALE SUITABILITY ANALYSIS FOR WIND ENERGY DEVELOPMENT IN LIGHT OF SELECTED CONDITIONS

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REGIONALNA ANALIZA PRZYDATNOŚCI TERENÓW DO ROZWOJU ENERGETYKI WIATROWEJ W ŚWIETLE WYBRANYCH UWARUNKOWAŃ

STRESZCZENIE: W ostatnich latach notowano rosnący wzrost zainteresowania krajowych i zagranicznych inwestorów lokalizacją obiektów energetyki wiatrowej w różnych rejonach Polski. Wśród nich, województwo podlaskie charakteryzuje się korzystnymi warunkami wietrzności i znaczną dostępnością terenów predysponowanych do rozwoju energetyki wiatrowej. Obszary predysponowane można uznać za użyteczne, niemniej jednak w kontekście pewnych uwarunkowań, niektóre z nich mogą odznaczać się wyższym stopniem przydatności do pełnienia założonej funkcji.
W pracy zaproponowano procedurę oceny stopnia przydatności terenów predysponowanych do rozwoju energetyki wiatrowej w skali regionalnej na podstawie wybranych uwarunkowań.

SŁOWA KLUCZOWE: GIS, energetyka wiatrowa, wielokryterialne wspomaganie decyzji

Introduction

A rising trend resulting from the presence of strong political and economic stimuli has been observed both in the global production, as well as the consumption of energy from renewable resources[1]. After the Polish accession to the European Union an increasing level of investment of domestic and foreign capital in the wind energy sector was noted[2]. Nevertheless, because of the collision risk, wind turbines cannot be placed in random locations[3], which generates the need for ongoing research on this problem.

One of the commonly used solutions in this area is the implementation of modern IT tools offered by the rapidly developing discipline of Geographic Information Science and Technology (GIS&T)[4]. Due to the interdisciplinary nature of the discussed problem, GIS technology is often combined with the methods of multi-criteria decision support. The popularity of this type of solution is evidenced by numerous Polish[5] and foreign publications[6] on the optimal location of wind power structures.

This paper proposes a methodological approach allowing for the assessment of the suitability of land predisposed to the development of wind energy in the light of a wide range of conditions. Results from the study were confronted with the existing locations of wind turbines.

1 B. Bożętka, *Pozyskiwanie energii wietrznej a zmiany krajobrazu. Konsekwencje dla funkcji rekreacyjnej*, „Krajobrazy rekreacyjne – kształtowanie, wykorzystanie, transformacja. Problemy Ekologii Krajobrazu" 2010 Vol. XXVII, p. 49.

2 M. Kistowski, *Propozycja metodyczna oceny środowiskowych uwarunkowań lokalizacji farm wiatrowych w skali regionalnej,* „Przegląd Geograficzny" 2012 No. 84(1), p. 5.

3 J. Swofford, M. Slattery, *Public attitudes of wind energy in Texas: Local communities in close proximity to wind farms and their effect on decision-making,* "Energy Policy" 2010 Vol. 38, pp. 2508–2519.

4 J. Kozak, *Jerzy Bański: Jaka geografia? – uwarunkowania i spojrzenie w przyszłość: głos w dyskusji,* „Przegląd Geograficzny" 2013 No. 85(3), p. 456.

5 W. Synowiec, M. Luc, *Wielokryterialna ocena przydatności terenu do rozwoju energetyki wiatrowej na przykładzie gminy Rymanów*, „Przegląd Geograficzny" 2013 No. 85(3), pp. 323–352; M. Szurek, J. Blachowski, A. Nowacka, *GIS-based method for wind farm location multi-criteria analysis*, "Mining Science" 2014 No. 21, pp. 65–81.

6 J.R. Janke, *Multicriteria GIS modeling of wind and solar farms in Colorado,* "Renewable Energy" 2010 Vol. 35, pp. 2228–2234.

Study area

The presented case study concerns Podlaskie province in north-eastern Poland. Previous analyses by the author[7] demonstrated that Podlaskie province is characterised by advantageous wind conditions and has a significant reservoir of areas predisposed to wind energy development. Based on a set of exclusion criteria, considering infrastructural, environmental, socio-cultural and hydrogeological aspects, ranges of areas predisposed to the development of wind energy, representing approximately 30% of the studied area, were identified. Considering the whole province, most of the available predisposed areas (more than 40% of the total area) were found in the districts of Suwałki, Wysokie Mazowieckie, Bielsk Podlaski and Kolno.

Areas predisposed to the location of wind energy structures may be considered useful, but in the light of additional factors some of them may offer more favourable conditions for this function. Further sections of this paper present a comprehensive analysis of the conditions that determine the features of land predisposed in the context of its suitability for future investment related to the use of wind energy.

Material and methods

The spatial character of the undertaken research problem and the need to take into account a number of different conditions are the reasons to use GIS spatial analysis integrated with multi-criteria decision support techniques.

The soft computing criteria (parameters or factors) considered in this study[8] may determine the suitability of land in Podlaskie province predisposed to the predefined function to a different extent, and thus their hierarchy has to be identified. The preference for individual criteria and subcriteria was investigated using one method of multiple criteria decision-making – the Analytic Hierarchy Process (AHP), for which theoretical foundations were developed by the American mathematician T.L. Saaty[9]. AHP is a popular tool for solving interdisciplinary research problems, as confirmed by

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7 Ł. Kolendo, *Przestrzenno-środowiskowe determinanty rozwoju energetyki wiatrowej w województwie podlaskim*, „Ekonomia i Środowisko" 2015 No. 3(54), pp. 42–55.

8 B. Hejmanowska, E. Hnat, *Wielokryterialna analiza lokalizacji zabudowy na przykładzie gminy Podegrodzie*, „Archiwum Fotogrametrii, Kartografii i Teledetekcji" 2009 Vol. 20, pp. 109–121.

9 T.L. Saaty, *How to make a decision: The Analytic Hierarchy Process*, "European Journal of Operational Research" 1990 No. 48, pp. 9–26.

numerous works devoted to both the theoretical and practical aspects of this method[10].

The next level in the hierarchical model (PII) includes the main criteria related to anemometric, geomorphological, environmental, social and infrastructural conditions. In the process of the decomposition of the investigated decision-making problem a total of 17 subcriteria for assessment (PIII) assigned to the main criteria of level II were identified. At level IV (PIV), additional ranges of variation were defined within individual subcriteria. Due to the nature of the principal objective, i.e. the global assessment of suitability, there was no need to create the last level (PV) of the structure, corresponding with decision-making variants (hypothetical locations of wind farms).

In the next step global and local preferences were determined through a series of paired comparisons of individual criteria and subcriteria at each predefined level of the hierarchical model. The comparisons were carried out using the 1–9 fundamental scale of absolute numbers developed by Saaty (where 1 means equal importance and 9 means extreme importance). The consistency of comparisons was assessed based on the value of the consistency ratio.

The necessary calculations related to the implementation of the AHP method for the analysed problem were carried out in suitably prepared MS Excel sheets.

The second part of the proposed procedure involved the use of spatial analysis conducted using open source GIS[11]. Relevant spatial data had to be gathered for that purpose, and they are presented in Table 1.

At first GIS technology was used to create a database including layers with a spatial representation of the 17 assessed subcriteria (PIII). The individual layers were mainly generated using a buffering operation. Different size buffer zones were adopted, depending on the nature of the analysed spatial layer and sizes proposed by other authors, and in other cases the size of equidistants was determined arbitrarily by the author.

10 M. Dytczak, *Wybrane metody rozwiązywania wielokryterialnych problemów decyzyjnych w budownictwie*, Opole 2010, pp. 63–65.

11 P. Netzel, *Analizy przestrzenne z wykorzystaniem GRASS*, „Rozprawy Naukowe Instytutu Geografii i Rozwoju Regionalnego Uniwersytetu Wrocławskiego" 2011 No. 15, p. 7.

Table 1. Spatial data used for analysis

Database name	Format	Source
Baza Danych Obiektów Ogólnogeograficznych (BDOO) (General Geographic Database)	*.gml	Centralny Ośrodek Dokumentacji Geodezyjnej i Kartograficznej w Warszawie (Central Documentation Centre of Geodesy and Cartography in Warsaw)
Państwowy Rejestr Granic (State Register of Borders)	*.shp	
Vector map of soil and agricultural land, scale 1:25 000	*.shp	Wojewódzki Ośrodek Dokumentacji Geodezyjnej i Kartograficznej w Białymstoku (Provincial Documentation Centre of Geodesy and Cartography in Białystok)
Legal forms of nature protection	*.shp	Regionalna Dyrekcja Ochrony Środowiska w Białymstoku (Regional Directorate for Environmental Protection in Białystok)
Important Bird Areas (IBA)	*.shp	www.birdlife.org
SRTM terrain model with a resolution of 1 second (approx. 30 m)	*.GeoTIFF	www.earthexplorer.usgs.gov

It was also assumed that the generated buffer zones should cover the entire study area (land predisposed to the development of wind energy in Podlaskie province). The proximity analysis included such elements as the network of protected areas, surface water bodies and forests, linear infrastructure (power lines, roads), as well as buildings and existing wind turbines.

Geomorphological factors taken into consideration included primary topographic attributes[12] shown in the maps of slopes and aspects, determined directly from the terrain model. Assessment also included wind zones[13] and conditions related to the value of agricultural production space determined based on the system of soil classification. All subcriteria adopted for assessment (PIII), and the corresponding ranges of variation (PIV) are shown in Tables 2 and 3.

The final suitability of land predisposed to fulfil the expected function was determined as the sum of global preferences at the lowest level (PIV) of the hierarchical structure, and results were presented for a basic plot size of 10x10 m. Then, 6 contractual suitability categories were identified based on the spatial distribution of the results. In the last phase of the proposed analytical process the obtained data on the suitability of areas were confronted with the existing distribution of wind power structures in Podlaskie province.

12 J. Urbański, *GIS w badaniach przyrodniczych*, Gdańsk 2008, p. 158.

13 H. Lorenc, *Atlas klimatu Polski,* Warszawa 2005.

A hierarchical structure of the research problem

Global weights (WG) and local weights (WL) at each level of the model were identified after the decomposition of the investigated decision-making problem into a model of hierarchical structure and subsequent stages of AHP (Tables 2 and 3).

Of all the five primary groups of criteria (PII) analysed in this study the highest rank was given to the conditions of the natural environment. The key importance of environmental factors is mainly dictated by their large number (10 of 17 examined subcriteria at level PIII of the structure). Among the subcriteria of level PIII the environmental factors with the greatest impact on the primary objective of the analysis included the distance from protected areas, especially important bird areas. One of the above environmental parameters under assessment is the agricultural production space, where poor soils and wasteland are the preferred locations for wind power structures.

Further analysis of data in Table 2 and 3 revealed that in addition to environmental factors, social and infrastructural parameters also have a high priority. With respect to social conditions for wind power development in the analysed area a key role is attributed to the distance between the hypothetical investments and built-up areas. In this group the lowest priority was given to the distance between the hypothetical wind power structures and the existing wind turbines, assuming that a lower priority should be given to areas where a cumulative effect could be achieved (concentration of the planned and existing wind power infrastructure).

As with other elements of infrastructure in the study area, greater importance in the context of achieving the primary objective was found for the distance between wind power infrastructure and power lines. The accessibility of power lines is closely correlated with the profitability of wind energy investments.

At the level of the main assessment criteria (PII) the lowest preferences with respect to level PI was given for anemometric and geomorphological conditions (with designated global weights of 0.0612 and 0.0670, respectively). However, anemometric conditions are one of the key elements determining the cost-effectiveness of this type of investment. Due to the lack of detailed anemometric data, only a general regionalization of the studied area into four wind zones was considered in the analysis. Because of the high degree of uncertainty of these data, anemometric conditions were given a lower rank compared to other groups of parameters at level II.

Table 2. Global weights (WG) and local weights (WL) for individual levels of the hierarchical structure in the light of anemometric, geomorphological and environmental conditions

PI	PII	WG	PIII	WL	WG	PIV	WL	WG
SUITABILITY ANALYSIS FOR WIND ENERGY DEVELOPMENT	Anemometric conditions	0,0612	wind zone	1,0000	0,0612	zone I	0,4673	0,0286
						zone II	0,2772	0,0170
						zone III	0,1601	0,0098
						zone IV	0,0954	0,0058
	Geomorphology	0,0670	slope [degrees]	0,5000	0,0335	0-7	0,5462	0,0183
						7-12	0,2323	0,0078
						12-15	0,1377	0,0046
						> 15	0,0838	0,0028
			aspect [degrees]	0,5000	0,0335	N, NW, flat	0,5396	0,0181
						N, NE, S, SW	0,2970	0,0100
							0,1634	0,0055
	Natural environment	0,4586	agricultural production space	0,1095	0,0502	class I-III	0,0551	0,0028
						class IV	0,1301	0,0065
						class V-VI	0,2640	0,0133
						wasteland	0,5508	0,0277
			distance from forest borders [m]	0,0775	0,0355	0-200	0,0652	0,0023
						200-1000	0,1128	0,0040
						1000-3000	0,2257	0,0080
						> 3000	0,5963	0,0212
			distance from the borders of a landscape park [m]	0,1165	0,0534	within borders	0,0416	0,0022
						0-500	0,1414	0,0076
						500-1000	0,3122	0,0167
						> 1000	0,5047	0,0270
			distance from the borders of a protected landscape area [m]	0,0411	0,0188	within borders	0,0954	0,0018
						0-500	0,1601	0,0030
						500-1000	0,2772	0,0052
						> 1000	0,4673	0,0088
			distance from the borders of a Natura 2000 site (SPA) [m]	0,1390	0,0638	0-500	0,0613	0,0039
						500-1000	0,0948	0,0060
						1000-5000	0,2589	0,0165
							0,5850	0,0373

SUITABILITY ANALYSIS FOR WIND ENERGY DEVELOPMENT	Natural environment	distance from the borders of a Natura 2000 site (SAC) [m]	0,0715	0,0328	0-500	0,1047	0,0034
					500-1000	0,2583	0,0085
					> 1000	0,6370	0,0209
		distance from the borders of IBA [m]	0,1443	0,0662	within borders	0,0783	0,0052
					0-500	0,1517	0,0100
					500-1000	0,2628	0,0174
					> 1000	0,5073	0,0336
		distance from the borders of a national park or nature reserve [m]	0,2013	0,0923	0-500	0,1047	0,0097
					500-1000	0,2583	0,0238
					> 1000	0,6370	0,0588
		distance from the borders of other protected areas* [m]	0,0538	0,0247	0-500	0,1634	0,0040
					500-1000	0,2970	0,0073
					> 1000	0,5396	0,0133
		distance from watercourses and surface water bodies [m]	0,0456	0,0209	0-500	0,1634	0,0034
					500-1000	0,2970	0,0062
					> 1000	0,5396	0,0113

* other protected areas include ecological sites, nature and landscape complexes and documentation sites

Use of Geographic Information Systems

The use of Geographic Information Systems was a key element in the solving of the analysed problem. Global preferences from level IV of the hierarchical structure identified through the implementation of AHP were used for the polarization of the study area in the context of the 17 analysed sub-criteria of assessment (PIII). Examples of spatial layers, created through the reclassification of raster images representing selected criteria for the assessment of the suitability of predisposed land in Podlaskie province are shown in Figure 1.

The final suitability of predisposed land can vary in theory from 0.0869, if a certain location (10x10 m plot) is given the lowest rating in light of the evaluation criteria, to 0.5410 if the situation is the opposite. In practice, such

Table 3. Global weights (WG) and local weights (WL) for individual levels of hierarchical structure in the light of social and infrastructural conditions

PI	PII	WG	PIII	WL	WG	PIV	WL	WG
SUITABILITY ANALYSIS FOR WIND ENERGY DEVELOPMENT	Social conditions	0,1896	distance from buildings [m]	0,8000	0,1517	500-1000	0,0524	0,0079
						1000-2000	0,1157	0,0176
						2000-3000	0,2586	0,0392
						> 3000	0,5733	0,0870
			distance from the existing wind turbines [m]	0,2000	0,0379	< 1000	0,1634	0,0062
						1000-5000	0,2970	0,0113
						> 5000	0,5396	0,0205
	Infrastructural conditions	0,2236	distance from power lines [m]	0,7500	0,1677	250-2000	0,4673	0,0784
						2000-5000	0,2772	0,0465
						5000-10000	0,1601	0,0268
						> 10000	0,0954	0,0160
			distance from roads [m]	0,2500	0,0559	< 500	0,0688	0,0038
						500-1000	0,5447	0,0304
						1000-2000	0,2286	0,0128
							0,1579	0,0088

extreme values of land suitability were not recorded. Końcowa przydatność terenów predysponowanych może teoretycznie wykazywać zmienność od 0,0869, w przypadku uzyskania w danej lokalizacji (pole 10×10 m) najniższych ocen w świetle stosowanych kryteriów oceny, do 0,5410 przy założeniu sytuacji odwrotnej. W rzeczywistości nie odnotowano wskazanych wcześniej skrajnych wartości przydatności terenu.

Statistical analysis of the final map of suitability defined as the sum of global preferences at the lowest level of the hierarchical structure indicated that the actual range of variation of the investigated feature was from 0.1611 to 0.5188. Considering the above, 6 contractual suitability zones were established: class I (> 0.46), class II (0.41-0.45), class III (0.36-0.40), class IV (0.31-0.35), class V (0.26-0.30), and class VI (< 0.25) (Figure 2).

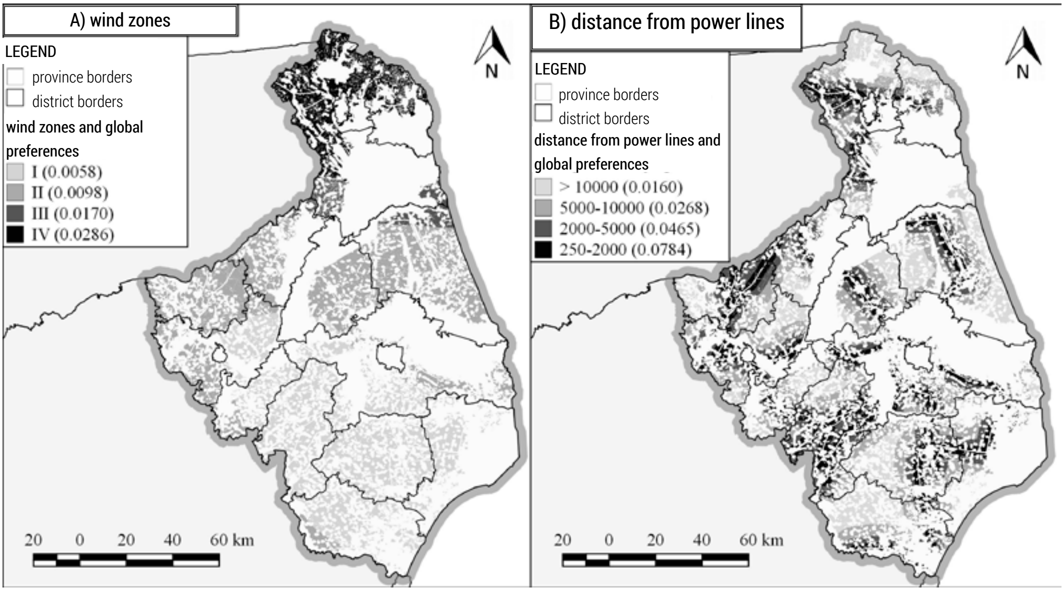

Figure 1. Wind zones (A) and global preferences and ranges of the distance from power lines (B) with corresponding global weights

Among the areas predisposed to the development of wind energy in Podlaskie province, the largest space is occupied by areas of suitability class IV (Table 4). They cover 51.71% of all the predisposed area and 15.42% of the total area of the province. The most suitable class I covers only 1.50% of predisposed land (0.45% of the total area of the province). In Podlaskie province areas of suitability class I-III cover about 2,400 km^2, which accounts for 11.86% of the total area of the province.

The analysis of data presented in Figure 2 shows a significant difference in the distribution of areas representing the identified classes of suitability in the districts of the province. The majority of areas classified in the course of the analysis as the most suitable for wind energy development (suitability class I-III) are located in districts where this type of investment has already been made[14] (Table 5). These include areas in Suwałki district (dominant position in the field of wind energy investments), and Wysokie Mazowieckie and Grajewo districts, where the total share of class I-III areas is from 12.22% to 34.76% of the total district area.

[14] Map of renewable energy sources based on licenses granted by the President of the Energy Regulatory Office and entries in the register held by the President of the Agency for Regional Development (ARR), www.ure.gov.pl [06/01/2016].

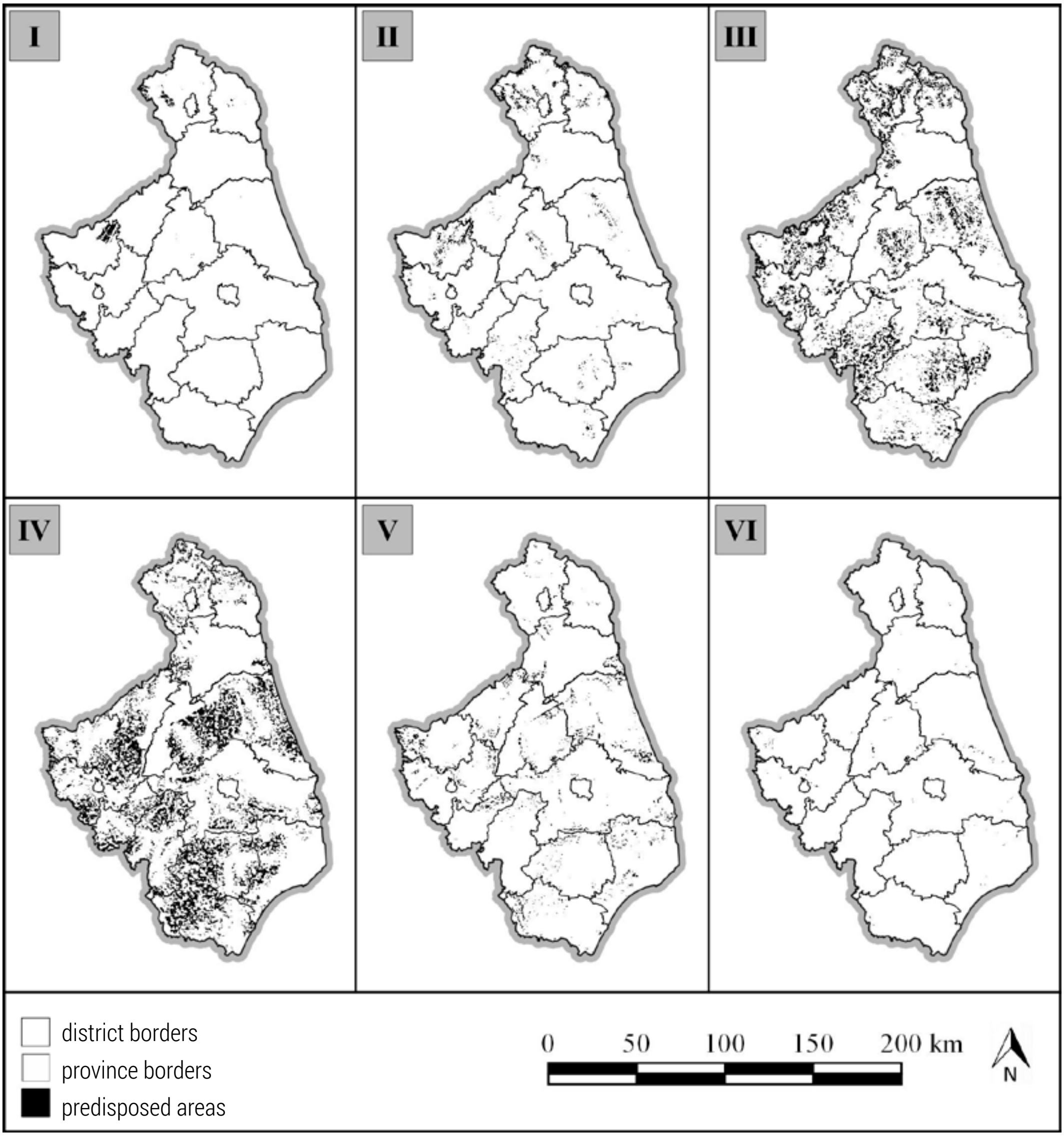

Figure 2. Distribution of areas predisposed to the development of wind energy in Podlaskie province, with indication of individual suitability classes

Different conditions can also be observed proving the existence of investment potential, but this is not reflected in the actual utilisation of this potential and construction of wind power structures. For example, in Kolno and Sejny districts, characterised by relatively large potential for the development of wind energy, no such investments have been made.

Table 4. Areas of individual classes of suitability and their share in the area of predisposed land and total area of the province

Class	Area [km^2]*	Share in predisposed land [%]	Share in total area of the province [%]
I	90,55	1,50	0,45
II	361,55	6,00	1,79
III	1942,72	32,25	9,62
IV	3114,32	51,71	15,42
V	477,40	7,93	2,36
VI	36,51	0,61	0,18
Total:		100,00	29,83

* area calculated as the product of the number of raster cells for a given suitability class and surface area of the basic plot used for calculation (10×10 m)

Location of wind energy structures in the context of study results

Current statistics from the Energy Regulatory Office[15] show that Podlaskie province is characterised by a significant use of wind power compared to the whole country. The 27 wind farms installed in Podlaskie province generate in total 181.41 MW. This information was used to verify the effectiveness of the proposed analytical procedure. It was assumed that investments made to date in the field of wind energy were implemented in line with legislation while maximizing return on investment. Therefore, the existing wind turbines should be located within the boundaries of predisposed areas having big advantages in terms of their suitability.

One–hectare plots[16] around the existing wind turbines higher than 30 m were analysed. The data on their location were acquired from the General Geographic Database (BDOO). There was good compatibility between the characteristics of each area: most of the existing wind farms are situated within the boundaries of predisposed and highly-suitable areas. Over 91% of the analysed wind power structures are located within the predisposed areas. The existing wind power structures are situated in areas of moderate level of suitability (0.38, suitability class III, 48.44% of wind turbines). 17.18% of all turbines are located in class IV areas, 29.69% of turbines in class II areas, and 4.69% – in the most suitable class I areas.

15 Ibidem.

16 M.J. Banak, *Lokalizacja elektrowni wiatrowych – uwarunkowania środowiskowe i prawne*, „Człowiek i Środowisko" 2010 No. 34(3–4), p. 120.

Table 5. Zestawienie procentowego udziału klas przydatności w powierzchni całkowitej poszczególnych powiatów oraz zainstalowanej mocy elektrowni wiatrowych

District	Power of wind farms [mw]	Share of the class in the total area of the district [%]					
		I	II	III	IV	V	VI
Sejny	0,00	0,22	4,07	11,17	6,44	0,47	0,04
Wysokie Mazowieckie	5,60	0,00	1,38	19,46	19,35	0,76	0,15
Łomża	2,00	0,00	0,60	10,34	24,02	2,99	0,29
Augustów	0,00	0,00	0,54	3,52	5,41	2,18	0,08
Białystok	0,60	0,00	0,08	5,53	8,59	1,57	0,08
Mońki	0,00	0,05	1,12	8,58	19,05	2,89	0,45
Suwałki city	0,00	0,00	0,89	9,08	3,59	0,07	0,00
Sokółka	4,10	0,00	1,28	10,23	22,16	4,09	0,36
Zambrów	0,00	0,00	0,16	5,33	17,09	3,78	0,01
Białystok city	0,00	0,00	0,01	0,42	0,01	0,00	0,00
Bielsk Podlaski	28,50	0,00	0,75	10,81	27,51	1,60	0,08
Łomża city	0,00	0,00	0,00	2,81	0,15	0,02	0,07
Grajewo	25,30	0,05	1,17	11,00	15,61	3,28	0,18
Suwałki	114,71	2,87	10,88	21,01	10,59	0,70	0,03
Hajnówka	0,60	0,00	0,41	4,41	9,28	2,47	0,22
Siemiatycze	0,00	0,01	0,55	4,78	23,10	2,58	0,11
Kolno	0,00	5,29	7,12	19,78	14,23	5,05	0,50

Conclusions

The methodological approach integrating GIS techniques and the multi-criteria decision support proposed in this study allowed for a comprehensive assessment of the suitability of land predisposed to the development of wind power infrastructure in Podlaskie province. The use of spatial data available for the whole of Poland indicates that this approach can be successfully implemented in relation to other regions.

In the context of the obtained results it should be noted that Podlaskie province is significantly polarized in spatial terms and suitability of particular areas for the development of wind energy infrastructure. There are examples where the identified potential has been utilised through the installation of wind farms, but there are also other areas potentially suitable for this type of investment.

Despite the significant benefits of this type of solution in the sector of RES, one should bear in mind the limitations of the proposed method, which are related, among other things, to the regional scale of the analysis. The geographical space covered by the study was large, and this determined the use of generalised data sets, as well as simplified analysis of certain phenomena and issues. This particularly concerns anemometric conditions in the study area, as well as the assumption that existing investments in the sector of wind energy were implemented in locations ensuring maximum economic profit while fully maintaining the legal requirements. Considering the advantages and some limitations of the proposed approach it should be emphasized that it can still be widely applied to analyse the discussed problem on a regional scale. This method can successfully support regional spatial planning procedures to optimise the directions of development of the renewable energy sector.

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