GIS-BASED METHOD FOR WIND FARM LOCATION MULTI-CRITERIA ANALYSIS

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Abstract: The paper presents a GIS-based method for selecting an optimum location of wind farm on the case study of the *Prusice* commune in Lower Silesia (SW Poland). The adopted multi-criteria approach utilises the Analytic Hierarchy Process (AHP) and Weighted Linear Combination (WLC) methods to determine weights of sitting criteria (factors and constraints), and to develop a composite suitability map from single-factor maps representing these criteria. The adopted sitting criteria have been identified based on literature review, and include: technical, spatial, social and environmental aspects of wind farm development, and also address specific geographical constrains of this part of Poland.

The most suitable and suitable areas have been presented on a wind farm suitability map for the commune. The area size of the largest suitable spots (14) varies from 10 to 64 ha.

The proposed method and the results of this work can be used to support sustainable spatial policy and spatial development on all levels of public administration related to renewable resources use.

Keywords: multicriteria analysis, wind farm location, AHP, WLC

Abbreviations:
AHP – Analytical Hierarchy Process
GIS – Geographic Information System
MCA – Multi-Criteria Analysis
MCE – Multi-Criteria Evaluation
OWA – Ordered Weighted Averaging
WLC – Weighted Linear Combination.

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1. INTRODUCTION

Electrical energy is essential for economic growth and well-being of human populations. The growing concern with pollution resulting from the use of fossil fuels increases the pressure to use renewable energy sources to produce electricity. One of such resources is the energy obtained from wind. Location of wind farms producing electricity requires careful and combined analysis of numerous criteria such as technical requirements, as well as environmental, social and spatial constraints.

This study focuses on adopting a geographically referenced method to assess land suitability for location of wind farms on the case study of the *Prusice* commune in Lower Silesia (SW Poland). With this aim a multi-criteria spatial data analysis method based on the Analytical Hierarchy Process (AHP) and the Weighted Linear Combination (WLC) in geographic information system (GIS) was used.

Spatial multi-criteria analysis (SMCA) can be described as a process that combines and transforms geographically referenced data into a resultant decision. The GIS data are usually organized as vector or raster format thematic datasets known as maps or layers. Data representing particular criteria are referred as single-factor maps.

Multi-criteria analysis (MCA) also referred as multi-criteria evaluation (MCE) methods allow analysis of complex, multi-dimensional trade-offs between choice alternatives for example locations or suitability analysis of an area (Meng et al., 2011). The basic principle of MCE is to analyse a finite number of choice possibilities with respect to multiple criteria and different objectives (Voogd, 1983). In recent years various multi-criteria evaluation (MCE) methods have been developed and implemented in commercial and free and open source GIS software. Malczewski (2004; 2006) provides a concise review of these methods, which include: deterministic, probabilistic and fuzzy based multi-attribute and multi-objective techniques. Among the multi-attribute methods such as the: Boolean operator overlay, Weighted Linear Combination (WLC), Ordered Weighted Averaging (OWA), Analytical Hierarchy Process (AHP), concordance analysis and ideal point method. The first two are the most widely employed for site selection studies or suitability analysis (Malczewski, 2004; Drobne and Lisec 2009). These methods have developed from the original map overlay concept by McHarg (Steinar 2006). However, overlay procedures that use Boolean operators can do little more than identify areas, which simultaneously satisfy the specified criteria. Therefore, additional procedures based on the MCE methods such as the ones listed above are required to evaluate the suitability of sites and produce rankings of locations in terms of their attractiveness (Carver, 1991).

Noteworthy applications of GIS-based wind farm selection spatial analyses include studies by (Baban and Parry, 2001; Hansen, 2005; Haaren and Fthenakis, 2011; Kasbadji Merzouk and Djamai, 2011). Baban and Parry (2001) proposed wind farm location criteria for UK based on a questionnaire of public and private sectors and GIS-based raster operations to produce a composite suitability map for a test area

based on 14 identified criteria represented by single factor maps. The study by Hansen (2005) aimed at developing a multi-criteria evaluation method for analyzing the trade-offs between choice alternatives with different environmental and socioeconomic impacts with fuzzy logic approach in GIS. Haaren and Fthenakis (2011) proposed a GIS-based multi-criteria methodology for cost-revenue optimization of wind farm site selection. This, three-stage, method has been applied to the State of New York. In the first step unsuitable sites were excluded based on land use and geological constraints, the second stage identified the best sites based on the expected net present value. The last stage assessed potential ecological impact of wind farm project. Kasbadji Merzouk and Djamai (2011) have used GIS for wind resource mapping.

The evaluation of wind farm location criteria in the Polish conditions has been described for the *Dolnoslaskie Voivodeship* in (WBU 2010; WBU 2012), as well as other regions (*voivodeships*). This study attempted to identify and assess: environmental, spatial, legal and technical conditions of wind farm locations in the *Dolnoslaskie* region including an analysis of local spatial development plans and studies of condition and directions of spatial development with respect to wind farm location plans. A comprehensive methodology for a regional scale assessment of environmental conditions in relation to the establishment of wind farms has been proposed by Kistowski (2012). It includes the following environmental criteria: lithology, climate, hydrographical, biotic-ecological and conservation of natural resources and values. The proposed anthropological criteria are: infrastructure, spatial functions of land, legal protection of historical monuments and cultural environment, as well as effects of long-term exposure to wind turbine influence. One of the few examples of multi-criteria analysis in the evaluation of wind farm locations in Poland has been done by Synowiec and Luc (2013). This study employed GIS tools to assess land suitability for sitting a wind farm project on the case study of the *Rymanów* commune is SE Poland. Based on a MCA analysis of anemometric, environmental, technical and spatial factors a suitability map for this area has been developed.

In our study, the Analytical Hierarchy Process (AHP) method has been employed to determine weights of factors conditioning location of wind farms. The method developed by Saaty (1977) is one of the multi-criteria methods for hierarchical analysis of decision problems. It enables decomposition of a complex decision problem into sub-problems and construction of a ranking for a finite set of variants. It is widely used to determine weights of factors used in multi-criteria evaluation. In the scope of this study the AHP method was employed to derive the weights associated with wind farm sitting criteria maps used in the WLC to produce an output composite suitability map. In the WLC continuous criteria are standardized to a common numeric range, and then combined by means of weighted average to produce an output map (Carver, 1991; Drobne and Lisec, 2009). Combination of these two methods allowed spatial referencing of the analysed problem. Both procedures are explained in the following sections.

The proposed approach is aimed at determining significant criteria of wind farms sitting and assessing land suitability for location of such projects. The method and the results of this study can be used to support sustainable spatial policy and spatial development on all levels of public administration related to wind resource uses. It can also be used as means of evaluating wind farm area designations in local planning documents as there are cases of wind farm construction in areas that do not always guarantee the optimization of environmental gains generated by these installations (WBU 2010; Kistowski, 2012).

2. STUDY AREA

The study area for the preliminary research is the *Prusice* commune located in the NE part of the *Dolnoslaskie Voivodeship* (SW Poland). The commune covers approximately 158 square km. The land use structure is dominated by agriculture with 70.7% of the total area, followed by forest and wooden areas (24.1%). Built-up areas cover 4.1% of the land. The population of this administrative unit is 9 441 people (GUS, 2013) and the population density is approx. 60 people per square km. The biggest localities are the town of *Prusice* and the *Skokowa* village with 2333 and 1112 inhabitants respectively. There are 25 smaller localities.

The commune lies in the *Barycz River Basin* (located beyond the commune's boundaries) and the river network consists of the *Sąsiecznica* river and its tributaries. There is a large number of lakes and ponds used for fish breeding and these cover approx. 240ha of the total area.

Two geographical regions, the *Trzebnickie Hills* and the *Żmigrodzka Valley* can be distinguished within the commune's borders. The first one consists of end moraines that are the result of the last Scandinavian glaciation. The elevation differences between the top of the moraines and the gullies separating them reach up to 60 m. The main part of the second unit is the *Prusice Plain* in the northern part of the commune. The heights in this part vary from 95 to 125 m a.s.l. The highest point in the analysed region reaches 216.5 m a.s.l.

The nature protection areas include a fragment of the B*arycz River Valley Landscape Park* (87ha) and 81 registered nature monuments, mainly oak and beech trees. There are two Nature 2000[†] areas partially within the commune's administrative limits. One in the north-east part near the *Osiek* and *Gąski* villages and the other close to its western border, near the *Ligota Strupińska* locality.

The prevailing wind direction is from the West and large forest areas tend to lower the wind speed.

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[†] Natura 2000 is an ecological network of protected areas in the territory of the European Union.

The main communication route is the national road 5 connecting the cities of *Wrocław* (to the south) and *Poznań* (to the north). There are also two regional roads, 342 connecting the commune with the nearby *Oborniki Śląskie* and 339 connecting the area with the city of *Wołów* to the east. The remaining roads are of local categories and connect the localities. A 110 kV power line passes through the commune from the *Oborniki Śląskie* direction (to the south) towards *Żmigród* (to the north).

General land use map of the *Prusice* commune is shown in Fig. 1. The present study of conditions and directions of development of the *Prusice* commune (2011) does not designate areas for wind farm locations.
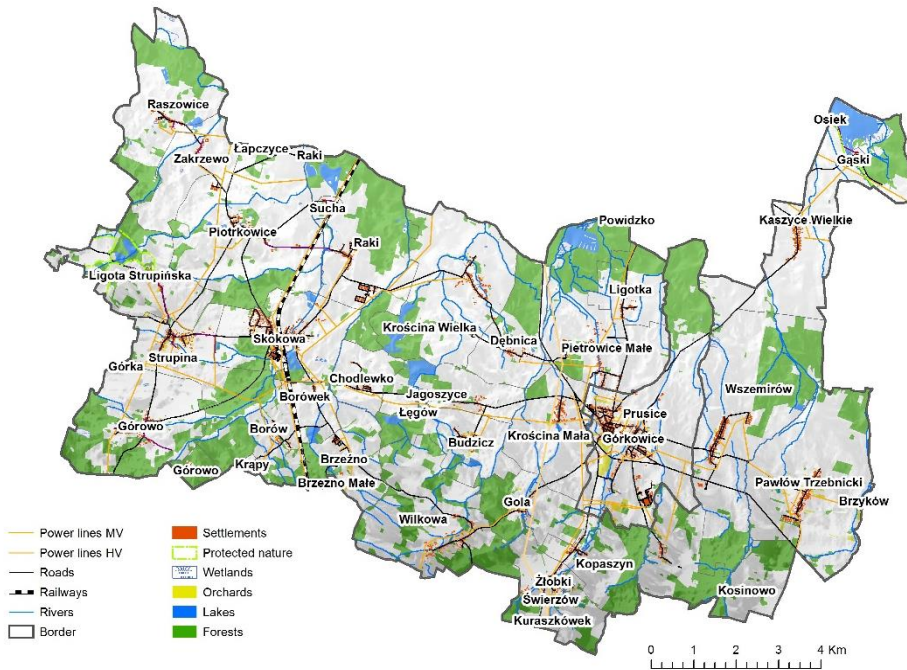

Fig. 1. Map of the *Prusice* commune

3. MATERIALS AND METHODS

3.1. WIND FARM SITTING CRITERIA

The criteria that determine location of wind farms can be classified into the following groups: environmental, spatial, social and technical. The environmental criteria include nature protection aspects, i.e.: location of nature protection areas, sensitive land such as forests, wetlands, surface waters. The technical criteria include commu-

nication and power grid accessibility, as well as anemometric factors. The social criteria concern human safety and well-being and the spatial ones relate to land use functions and designations.

These criteria may be divided into factors and constraints. Factors increase or decrease suitability of a given element and are assessed on a continuous scale e.g. slope derived from Digital Elevation Model (DEM) or wind speed. Constraints determine the qualification of a given element and are usually of logical character expressed as 1 – suitable, and 0 – restricted, e.g. existence of built up area restricts location of wind turbine.

In our study, the criteria used for the assessment of land suitability for location of a wind farm have been determined based on literature presented in part 1, and analysis of the legal acts including regulations concerning investments in nature protection areas (*Environmental Act*, *Nature Conservation Act*, *Act on the Provision of Information on the Environment and its Protection, Public Participation in Environmental Protection and Environmental Impact Assessments*), protection of forests (*Act on Forests*), protection of cultural heritage monuments (*Act on the protection of monuments and the guardianship of monuments*), protection of waters (*Water Act*), human health and safety standards and regulations concerning road (*Spatial Planning and Development Act*), railway and power grid technical standards.

Fig. 2. Part of the *Lipniki* wind farm in the *Kamiennik* commune (*Nyski* poviat)
(source: http://www.tauron-ekoenergia.pl/elektrownie/energia-z-wiatru/farma-wiatrowa-lipniki)

The criteria determined and used in further studies included:
- location of nature protection areas and their buffer zones
- built-up areas and their buffer zones
- location and distance from power lines
- location and distance from rivers and surface waters
- location and buffer zones from forests
- location, technical standards and distance from roads
- location, technical standards and distance from railways
- slope
- aspect
- location and distance from telecommunication lines.

The adopted threshold values of these criteria have been given in part 3.3. and are generally more strict than the values given in literature and regulations. Anemometric factors, e.g. wind speed, roughness of the terrain, as well as aesthetic factors have not been considered in this case. Fig. 2. shows example of two modern wind turbines constituting part of a larger wind farm.

3.2. DATA AND SOFTWARE

The main source of spatial data was the VMAP (Vector Map) Level 2 database from the Regional Office of Land Surveying and Cartography with vector datasets representing:
- major road networks
- railroad networks
- utility networks (pipelines and communication lines)
- hydrologic drainage systems
- populated places
- elevation contours.

In addition, the General Directorate for Environmental Protection and the Head Office of Land Surveying and Cartography Web Map Services[‡], as well as the study of conditions and directions of development of the *Prusice* commune (2011) have been used as spatial data sources.

Spatial data modelling with the Weighted Linear Combination (WLC) method in GIS has been done in the ArcGIS Advanced 10.2 software and the ArcGIS Spatial Analyst extension (ESRI, 2014).

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[‡] The OpenGIS® Web Map Service Interface Standard (WMS) provides a simple HTTP interface for requesting geo-registered map images from one or more distributed geospatial databases. A WMS request defines the geographic layer(s) and area of interest to be processed. The response to the request is one or more geo-registered map images (returned as JPEG, PNG, etc) that can be displayed in a browser application (OGC, 2014)

3.3. DATA PREPARATION

In the first step vector datasets representing individual criteria listed in part 3.1. have been prepared for the WLC analysis. This stage included the following tasks:

- generating new feature class from dataset representing nature protection areas that included 2000 m buffer zone around these areas
- generating new feature class from dataset representing built–up areas that included multiple buffer zones: 0–500 m, 501–1000 m and >1000 m around these areas
- generating new feature classes from datasets representing sensitive areas: forests, rivers, surface waters that included multiple buffer zones: 0–200 m, 201–350 m, 351–500 m, 500–650 m, 651–800 m and >800 m around these areas
- generating new feature classes from datasets representing infrastructure: railways and telecommunication lines that included multiple buffer zones: 0–200 m, 201–350 m, 351–500 m, 500–650 m, 651–800 m and >800 m around these areas
- generating new feature classes from datasets representing power lines that included multiple buffer zones: 0–250 m, 251–500 m, 351–500 m, 501–750 m, 751–1000 m, 1001–1250 m and >1250 m around these areas; in these cases the first buffer zone represented unsuitable areas for location of wind farms due to safety reasons and the remaining buffer zones represented diminishing suitability
- generating new feature classes from datasets representing roads that included multiple buffer zones: 0–50 m, 51–250 m, 251–500 m, 501–750 m, 751–1000 m, and >1000 m around these areas; in these cases the first buffer zone represented unsuitable areas for location of wind farms due to safety reasons and the remaining buffer zones represented diminishing suitability.

All of the above vector datasets have been converted to raster format with 10m pixel size and then reclassified to a common scale ranging from 0 to 5 based on the buffer distances. Where 0 represents constraint (restricted location), 1 the least suitable and 5 the most suitable areas. The complete classification has been presented in Table 1.

Slope and aspect raster maps were generated from DEM produced from contour line data in the VMAP Level 2 database. The slope single-factor map was reclassified into 5 classes: 0°–2.5°, 2.5°–5°, 5°–7.5°, 7.5°–10° and above 10°. The class representing flat areas (0° to 2.5°) has been judged as the most suitable and the steepest areas as the least suitable. Based on the Wroclaw meteorological station data (University of Wrocław, 2012) the aspect map has been determined where flat land and slopes facing west and north-west have been determined as the most suitable.

Tab. 1. Classification of single criteria raster maps

Criterion \ raster cell value	0	1	2	3	4	5
Nature protection zones	<2000 m	–	–	–	–	>2000 m
Distance from populated areas	< 500 m	–	–	501–1000 m	–	>1000 m
Distance from power lines	< 250 m	>1250 m	1001–1250 m	751–1000 m	501–750 m	251–500m
Distance from forests	< 200 m	201–350 m	351–500 m	501–650 m	651–800 m	>800 m
Distance from rivers and surface waters	< 200 m	201–350 m	351–500 m	501–650 m	651–800 m	>800 m
Slope	–	>10°	7.5°–10°	5°–7.5°	2.5°–5°	0° – 2.5°
Aspect	–	E, SE	–	N, NE, S, SW	–	W, NW, FLAT
Distance from railway lines	< 200 m	201–350 m	351–500 m	501–650 m	651–800 m	>800 m
Distance from tele-communication lines	< 200 m	201–350 m	351–500 m	501–650 m	651–800 m	>800 m
Distance from roads	< 50 m	>1000 m	751–1000 m	501–750 m	251–500 m	51–250 m

Single factor raster maps for the Weighted Linear Combination analysis in GIS have been presented in: Fig. 3 – nature protection criterion, Fig. 4 – populated areas criterion, Fig. 5 – sensitive areas (forests) criterion, Fig. 6 – slope criterion, Fig. 7 – distance to power lines criterion, Fig. 8 – aspect criterion and Fig. 9 – distance to roads criterion. The remaining ones can be found in (Szurek, 2014). The classifications of particular criteria have been symbolized with shades of blue, where light blue represents restricted or the least suitable areas and darker blue more suitable areas for location of wind farms.
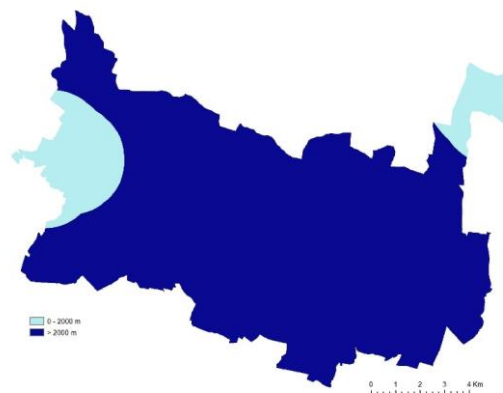

Fig. 3. Map representing nature protection areas and the buffer zones around them
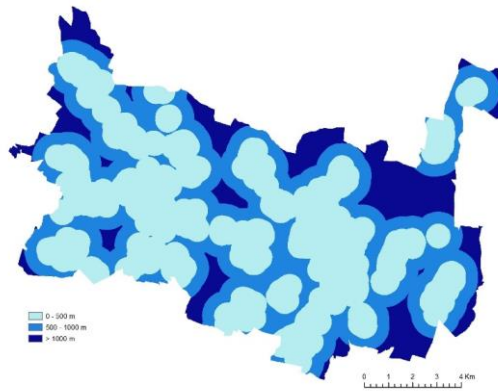
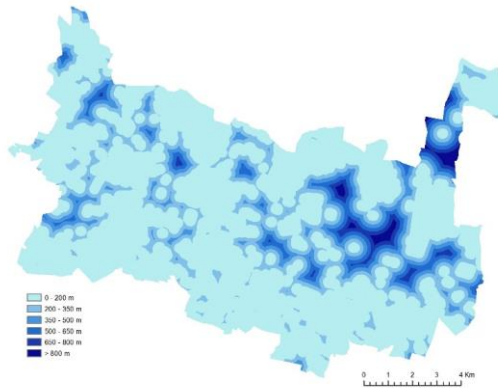Fig. 4. Map representing built-up areas and the buffer zones around them

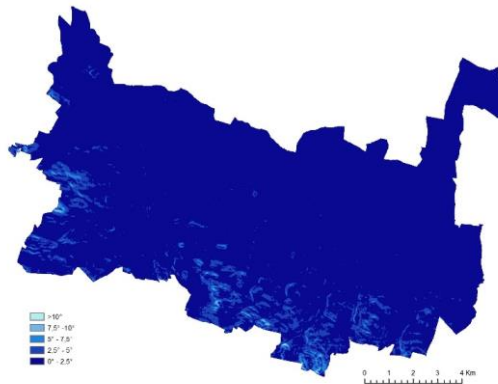Fig. 5. Map representing forests and the buffer zones around them
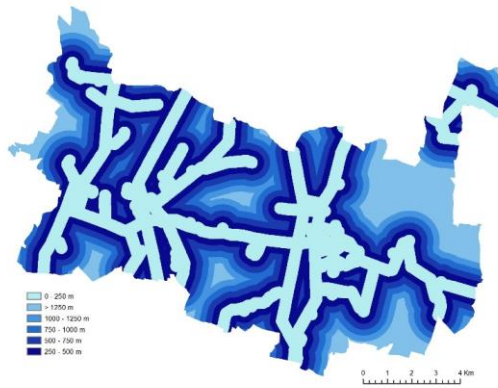

Fig. 6. Map representing slope

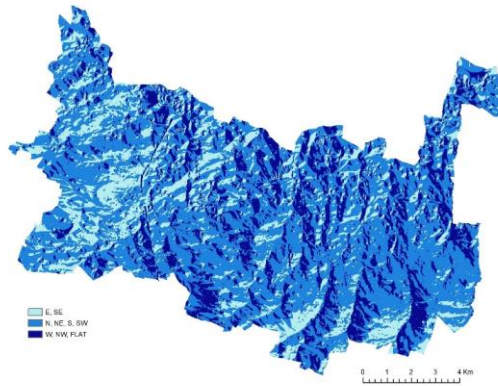Fig. 7. Map representing distance to power lines
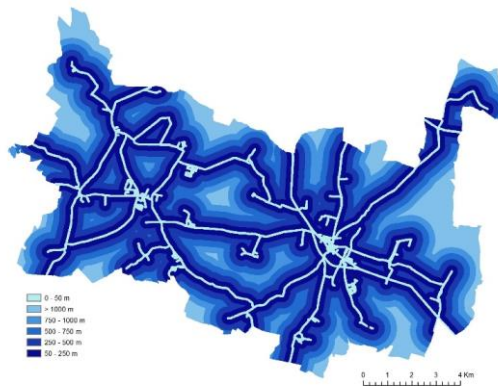

Fig. 8. Map representing aspect

Fig. 9. Map representing distance to roads

3.4. ASSESSMENT OF CRITERIA WEIGHTS WITH ANALYTICAL HIERARCHY PROCESS

Assessment of the suitability criteria relative weights has been done with the Analytical Hierarchy Process proposed by Saaty (1977). In this method the problem is analysed in a hierarchical structure, usually composed of several levels, i.e.: aim, criteria, sub-criteria and variants. The sub-criteria levels are optional. The method is used to obtain a comparison scale based on a comparison of the analysed criteria in pairs. The preferences are determined with relative grades expressed as numerical values, usually 1 to 9, where 1 indicates that the compared criteria are equivalent and 9 indicates that the first of the compared elements is strongly preferred with respect to the other element. On this basis preference matrices are constructed taking into account the following principles, a given element of the matrix is equivalent to itself, i.e. equal to 1 and the value of element a with respect to element b is the reciprocal of the value of element b with respect to element a (1) (Saaty 2008),

$$\mathbf{M} = \begin{bmatrix} a_{11}=1 & a_{12} & a_{1n} \\ a_{21} & 1 & a_{2n} \\ a_{n1} & a_{n2} & a_{nn}=1 \end{bmatrix} \tag{1}$$

The values of the normalised matrix are determined from equation (2) and priority vectors indicating weights of criteria from equation (3).

$$w_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{2}$$

$$w_{ij} = \sum_{j=1}^{n} w_j a_{ij} \tag{3}$$

where,

$$w_{ij} = \frac{\sum_{i=1}^{n} w_{ij}}{n} \tag{4}$$

The pairwise comparison values have been assigned based on the analysis of literature presented in part 1. The normalised matrix of the analysed criteria and the resulting weights of criteria are given in Table 2.

Tab. 2. The normalized pairwise comparison matrix and criteria weights

	1	2	3	4	5	6	7	8	9	10	11	weight
1	0.24	0.25	0.27	0.27	0.27	0.27	0.19	0.19	0.15	0.14	0.14	0.22
2	0.24	0.25	0.27	0.27	0.27	0.27	0.26	0.26	0.20	0.19	0.18	0.24
3	0.08	0.08	0.09	0.09	0.09	0.09	0.11	0.11	0.15	0.14	0.14	0.11
4	0.08	0.08	0.09	0.09	0.09	0.09	0.11	0.11	0.11	0.10	0.10	0.10
5	0.08	0.08	0.09	0.09	0.09	0.09	0.11	0.11	0.11	0.10	0.10	0.10
6	0.08	0.08	0.09	0.09	0.09	0.09	0.11	0.11	0.11	0.10	0.10	0.10
7	0.05	0.04	0.03	0.03	0.03	0.03	0.04	0.04	0.07	0.06	0.06	0.04
8	0.05	0.04	0.03	0.03	0.03	0.03	0.04	0.04	0.07	0.06	0.06	0.04
9	0.03	0.03	0.01	0.02	0.02	0.02	0.01	0.01	0.02	0.06	0.06	0.03
10	0.03	0.03	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.06	0.02
11	0.03	0.03	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.02

1 – nature protection zones
2 – distance from populated areas
3 – distance from power lines
4 – forest areas
5 – surface waters
6 – rivers

7 – slope
8 – aspect
9 – distance from railway lines
10 – distance from telecommunication lines
11 – distance from roads

3.5. LAND SUITABILITY ANALYSIS WITH WLC

The single factor raster maps described in part 3.3 and classified to a common scale, have been multiplied by the corresponding weights obtained in the result of AHP analysis to generate weighted map layers. The weighted overlay operation in ArcGIS software has been then performed to generate the overall composite suitability raster map shown in Fig. 10. In this method the suitability score is calculated from the following formula (5),

$$S = \sum_{i=1}^{n} w_i k_i$$

where: S – cell score of the final map,
w_i – weight of a criterium $i = 1, ..., n$
k – value of criterium $i = 1, ... n$
n – number of criteria.

In cases, where Boolean constraints also apply (i.e. restricted areas), the procedure can be modified by multiplying the suitability calculated from the factors by the product of the constraints (6),

$$S = \sum_{i=1}^{n} w_i k_i \prod c_j$$

where c_j is the criterion score of the constraint j.

4. RESULTS AND DISCUSSION

The output composite map from the WLC analysis is represented in the same value range as the input single factor maps, i.e. 1 to 5. The larger the values the more suitable the area for the location of wind farm. The constraints e.g. nature protection areas, have been marked as restricted in the WLC analysis and excluded from the weighting and map overlay processing.
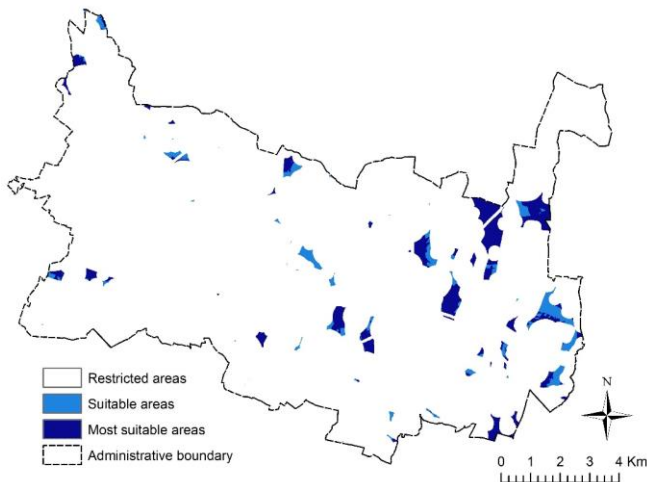

Fig. 10. Results of land suitability analysis for wind farm location

In the result of the WLC analysis the most suitable sites have been identified and presented on a suitability map (Fig. 10). It shows areas that have pixel value equal to 4 (most suitable) and 3 (suitable). The total area regarded as most suitable with respect to the analysed criteria is 4 758 300 square meters and 14 areas are larger than 100 000 square meters (10 ha) with the two largest 642 140 and 536 610 square meters. The largest and most uniform areas are located in the eastern part of the com-

mune. The total area regarded as suitable is 2 406 700 square meters. The area required for a single wind turbine is 2000 to 4000 square meters, whereas a wind farm consisting for example of 15 turbines can take up to 225 ha of land, e.g. "Zagórze" wind farm in NW Poland (Tauron, 2014). It must be mentioned that the identified sites are provisional and require further and more detailed investigations including field reconnaissance before final decision can be reached.

The proposed method, utilising a combination of AHP and WLC methods in GIS, provided a quantitative evaluation of criteria that determine land suitability for location of wind farms. The map obtained from the WLC presents continuous representation of land suitability for this purpose. The continuous character of the WLC single factor maps does not allow to estimate exactly the threshold values that would determine land suitability. This is known as trade-off or substitutability (Drobne and Lisec, 2009). Therefore, input maps have been classified to a common scale and constraints have been introduced using Boolean operators to account for restricted areas such as nature protection sites and excluded from further analysis. An alternative that can be used to account for the continuous character is to apply fuzzy membership measures in multicriteria evaluation, as suggested by (Jiang and Eastmann, 2000).

Application of pairwise comparison method (AHP) in assessment of criteria weights, which uses direct trade-off between each pair of compared factors, has the advantage of allowing an organized, and in many cases hierarchical, structure of criteria, which provides a better focus on specific criteria during the weight allocation process. The selection of attributes – criteria for comparison has to take into account their completeness. In this study it has been based on literature review but an another possibility is to perform a survey of group of experts representing different disciplines, such as spatial planning, environmental protection, electricity production, public administration, local communities, etc.

5. CONCLUSIONS

The aim of this study was to propose and test on a pilot area a GIS-based procedure for the assessment of suitable sites for wind farm locations taking into account the Polish conditions. The Analytic Hierarchy Process method was proposed for assessment of the weights of criteria determining suitability of wind farm location and the WLC method for identification of suitable sites in GIS. The following criteria groups have been used: environmental, social, spatial and technical. The particular factors and constraints have been identified based on literature of the subject and review of the Polish legal acts regulating such investments. One should note that as for now there are no regulations stating the minimum distance of wind turbines from populated areas. The proposed GIS-based geoprocessing model was applied to a pilot area in SW Poland – the *Prusice* commune and suitable areas were provisionally iden-

tified. The total area with the highest suitability score is 475 ha with an additional 241 ha regarded as suitable. The two largest suitable sites have 64.2 ha and 53.7 ha.

This procedure allows for inclusion of other criteria that have not been considered in this study. These may include: minimum size of area, which is specific for each wind farm project or wind speed and roughness of the terrain, which influence the performance of a wind farm. These, as well as other criteria can be added to the spatial data processing model if necessary. In addition landscape aesthetics can be analysed using 3D visualisation capabilities of GIS. The results, presented in the form of maps and reports, can play a significant role in the local community consultations process.

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