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Developing and applying a GIS-assisted approach to locating wind farms in the UK

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Abstract

An increase in public awareness regarding the negative impact of traditional power-generating methods, especially coal and oil-fired power stations, on the environment has created a demand for developing and using environmentally friendly renewable energy. Wind power is a popular and safe form of renewable energy. It can be economically viable, does not produce any physical pollution and can contribute radically to the reduction in air pollution. In the UK, the demand for wind energy is mounting. However, achieving the goal set by the EU will require a substantial expansion. Planning and environmental restrictions and conflicts would inevitably accompany this growth. A questionnaire targeting relevant public and private sectors in the UK has revealed the lack of coherent national criteria for locating wind farms. Using information from the questionnaire and the available published literature, simple Geographical Information System (GIS)-assisted wind farm location criteria were developed for the UK. A GIS (IDRISI) was employed to apply these criteria using two different methods to combine information layers for a site in Lancashire. The first considered all the layers as being equally important and gave them equal weight. The second grouped the layers and graded them according to perceived importance. The outputs were composed of classes from 0 to 10, where 0 represents ideal locations and 10 represents unsuitable locations. Using the second method has resulted in a slight increase in the geographical extent for the most suitable sites. These maps can be used to assist in the decision-making process when locating wind farm sites.

Keywords: Wind farm; Siting criteria; GIS; UK

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1. Introduction

There has been an increasing awareness of environmental degradation caused by anthropogenic activities such as greenhouse gases and acid rain [1]. As the negative impact of traditional power-generating methods, principally coal and oil-fired power stations, on the environment is visibly significant, the demand for more environmentally friendly renewable energy is also growing [2]. Consequently, these demands have been supported by recent changes in international and national laws and policies. Internationally, the Rio Summit in 1992 was the first international collaborative effort to examine the consequences of environmental impacts due to past and present anthropogenic activities. The latest to promote the use of renewable energy sources was the Conference of the Parties, Third Session, Kyoto, 1–10 December 1997. In the EU, several similar programmes were set up, including the Altener Programme and the Declaration of Madrid. These programmes aim to treble renewable energy sources, reducing carbon dioxide emission levels and promoting collaborative efforts to substitute the equivalent of 15% energy demand in the EU with renewable energy sources [3]. In the UK, the non-fossil fuel electricity production has been assisted by a toll paid by electricity generators from fossil fuels according to the Non-Fossil Fuel Obligation (NFFO) in the Electricity Act of 1989.

In recent years, these factors have stimulated the development of various renewable energy technologies. Wind power is one such form of renewable energy that is expected to encounter widespread commercial success. This is mainly because wind energy can be economically viable and does not produce any physical pollution. In fact, using wind to replace just 1% of the EU's fossil energy production would avoid an annual emission of 15 million tons of carbon dioxide [4], therefore contributing significantly to the much-needed reduction in air pollution.

In the UK, the demand for wind energy is mounting [5]. Since 1990 there has been a total of 205 wind projects awarded under the Renewable Obligations Act. By 1997 wind capacity was over six times the capacity of 1992, while electricity generated by wind power has increased by a factor of 20. This has been attributed to improvements in technology and the better siting of wind farms. Electricity generation by wind was estimated to be over 60 thousand tonnes of oil equivalent [6]. At present there is a total of 795 operational turbines on over 40 farms which produce approximately 325 MW of energy. This, in effect, is enough electricity to provide the energy needs of around 250,000 households. In accordance with the policies, and in particular the Altener Programme, the goal of wind energy production is to provide 8000 MW of installed capacity, providing 20 TWh of electricity a year throughout the EU, i.e. 25% of all new renewables [7]. To achieve this objective, the UK will have to produce approximately three times what it does now and therefore requires more wind farms. This continued growth would inevitably be accompanied by planning and environmental restrictions and conflicts [8], which will mainly stem from the process of selecting suitable locations to site wind farms. These farms, in addition to being economically viable, should have an insignificant impact on the local environment in terms of visual and noise intrusion, electromagnetic interference and possibly wildlife collisions [9]. Successfully managed growth will therefore require taking all the relevant factors into consideration and using an objective method for locating wind farms. The Geographical Information System (GIS) has the capability to handle and simulate the necessary physical, economic and environmental constraints [10–14]. Consequently, the GIS can play a significant role as a decision support tool regarding optimum wind farm locations.

This paper aims to gain an understanding of the factors necessary to determine site suitability for wind farms in the UK, to develop simplified GIS-assisted wind farm locating criteria in the UK, and to use these criteria and evaluate their performance.

2. Data collection

2.1. Questionnaire

A postal questionnaire, targeting public and private sectors, was used to identify criteria, polices and factors used by various organisations in the UK when attempting to identify suitable areas for locating wind farms. The questionnaire was sent out to 100 local council bodies throughout the UK. In addition, 12 wind companies were chosen from the British Wind Energy Association web pages (www.bwea.org). The subjects were chosen so as to provide a broad geographical spread, ensuring that all parts of the UK were included in the investigation. Of the 112 questionnaires sent, 64 were returned; 60 of the 100 sent to local council bodies and 4 of the 12 sent to the private sector. The questionnaire aimed to gather data from the following areas:

1. *The criteria used to locate new areas suitable for wind farms.*

Thirty-one organisations have had a document to locate wind farms. The criteria used for the assessment include: physical, economic, environmental impact, resource, visual and planning considerations.

2. *What factors or constraints are considered when trying to find an area suitable for locating a wind farm?*

The local authorities provided a list of the factors that they require to be taken into consideration for planning permission to be granted and these are: proximity to residential areas, noise/nuisance, shadow flicker, greenbelt, topography, ecology, agricultural land classification, conservation areas, and distance from electricity gridlines. The private consultancies listed the following factors: wind speed, prevailing wind, terrain, adjacent terrain, vegetation, proximity to residential areas, noise and appearance.

3. *Which central government regulation policies are used for locating wind farms?*

The responses to this query were imprecise, with most organisations providing an answer such as "Whatever policies are at present operational". However, specific policy and laws mentioned were Planning Policy Guidance Note 22 (PPG 22), Planning Policy Guidance Note 23 (PPG 23) [15] and planning and pollution control [16] as being a background against which consistency and scientific standards can be maintained.

4. *Specific questions relating to optimum wind speed and direction, terrain type, distances from settlements and roads, noise and aesthetics.*

Wind speed and minimum distance from settlements were the prime locational factors. Wind speed ranged from 7 to 15 m/s, optimum terrain was described as round, hilly or flat, ideal adjacent terrain was described as smooth/no change or incline, maximum grade slope was 10%, and minimum distances from urban centres ranged from 500 to 5000 m.

3. Methodology

3.1. Developing the wind farm location criteria (WFLC)

Specific siting criteria were developed based on the literature and the outcome from the questionnaire to comply with the guidelines used nationally and internationally. The wind farm location criteria (WFLC) consists of a number of constraint factors including: topography, wind speed and direction, land use/cover, population, access, hydrology, ecology and resources. The constraint factors, and the criteria to which they correspond, have been highlighted as being physical, planning, economic, environmental or resource considerations (Table 1).

3.2. Criteria justification

In physical terms, the wind farms will need to be located on suitably elevated sites, avoiding summits, and facing the prevailing wind conditions in the UK. Furthermore, the average wind speed on the sites should be able to produce economically viable energy. The questionnaires indicated that the threshold for the wind speed is set at about 5 km/h, hence constraints 1, 2, 3 and 4 apply. Vegetation in close proximity could affect wind speed and direction of flow. Therefore, the farms should be sited at least 500 m away from the closest large stand of trees and constraint 5 accounts for this. From a planning viewpoint, the social implications brought about by such a project, i.e. noise pollution, safety and aesthetics, dictate that wind farms need to be outside urban areas. They would also be contrary to health and safety laws. Therefore, they should be located some 2 km away from urban centres as indicated in constraint 6. The shadow flicker effect and noise pollution dictates that a wind farm should be located at least 500 m away from single dwellings, hence constraint 7. Constraint 8 accounts for access and the minimisation of development

Table 1
Wind farm location constraints criteria

Criteria	Constraints factor	Consideration
The wind farm location must:		
1. avoid summits of large hills	Topography	Physical
2. have slope angles less than 10%	Topography	
3. have a westerly orientation	Wind direction	
4. have a wind speed greater than 5 m/s	Wind speed	
5. not be located within 500 m of woodland	Land use/cover	
6. not be located within 2000 m of large settlements	Population	Planning
7. not be located within 500 m of single dwellings	Population	
8. not be located further than 10 000 m from roads	Access	Economic
9. not be located further than 10 000 m from National Grid	Economy	
10. not be located within 400 m of water bodies	Hydrology	Environmental
11. not be located within 1000 m of areas of ecological value/special scientific interest	Ecology	
12. not be located on or within 1000 m of historic sites	Historic/cultural resource	Resource
13. not be located within 1000 m of National Trust property		
14. avoid taking grade 1 and grade 2 agricultural land		

costs; a site should be located as close as possible to a main road. However, it must also be located at a safe distance from the road in order to reduce visual intrusion. The cost factor will also determine a maximum distance of 10 km from the national grid; this has been accounted for in constraint 9. In environmental terms, water bodies and land of ecological/special scientific interest value has been protected by constraints 10 and 11. In order to preserve the cultural heritage, constraints 12 and 13 were included to protect areas and sites of historic importance. As sites of historic value are normally small by nature, a safe distance was also included to prevent the encroachment of any development in their vicinity, the intention being the preservation of the sites' character and the prevention of an "imbalance" of land use. Another important constraint is resources and agricultural value was protected by including constraint 14.

4. Study area

The study area was 40 km by 40 km, and was bounded by the UK National Grid Coordinates SD610000, SD640000, SD910000 and SD940000. This area is found primarily in England within the boundary of Lancashire but also diverges slightly over the border into Yorkshire. Primary settlements in the area include the northern fringe of Manchester Metropolitan Council, Bolton, and Rochdale to the south, Nelson towards the north and Blackburn towards the west (Fig. 1). This area was chosen to implement the criteria for having a mean annual wind speed above 5m/s, contain-

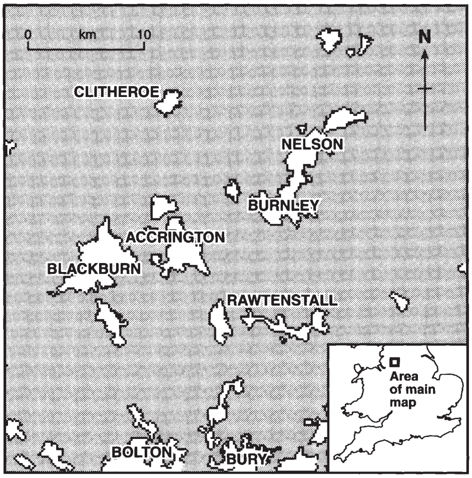

Fig. 1. Location map showing urban areas.

ing hilly areas, being close to a large number of settlements, containing National Trust property, high quality agricultural land, rivers and water bodies and woodlands.

5. Using the GIS to implement the WFLC

The necessary data to create map layers corresponding to each constraint criterion were obtained. These maps were then imported into the GIS for storing, followed by the allocation of weights to each layer and different scores to each attribute within the layers using reclassification and buffer generation methods. Finally, the constraints map is composed by using the overlay function to combine all the layers. This map will show the most and the least suitable areas for locating a wind farm, based on the developed WFLC.

5.1. Data types, preparation and analysis

The main source of data was Bartmap. This programme stores information digitised from the Bartholomew 1:253,440 motorist maps in coordinates on the UK National Grid. Bartmap was used to create layers for constraints 1–13 for the WFLC, but these were modified before importing into the GIS (IDRISI) as vector files. However, the data for the agricultural land classification came from conventional paper maps prepared by the agricultural development and advisory service of the Ministry of Agriculture, Fisheries and Food, with the assistance of the Soil Survey of England and Wales. The investigation had to ensure that all of the constraints were taken into consideration. To achieve this, a map layer was created for each constraint so that it could be accounted for in the analysis. The data used to create each layer, the constraint factor it corresponds to and their respective sources are listed in Table 1. Attribute scores were assigned with respect to their sensitivity and stored in tabular format (Table 2). The scores ranged from 0 to 10, where a score of 0 indicated no constraint and a score of 10 indicated total constraint.

In order to create the suitability map, all map layers had first to be converted from vector- to grid-based data models. Once the conversions had been completed for each file, the scores from the attribute table were assigned to the image files. Buffer zones were created and the distance scores then added, thereby creating layers for each of the constraint criteria. The layer for potential sites based on aspect (Fig. 2) was created by using the SURFACE and ASPECT modules on the elevation map. The RECLASS module was then used to categorise the outcome into potential sites, i.e. flat areas or areas with a south-westerly or a north-westerly aspect, and zones of exclusion. For purposes of demonstration, the map resulting for roads (Fig. 3) is also presented.

5.2. Map weightings and index overlay

Given the constraints for siting a wind farm, the accuracy in finding the most and the least suitable locations is dependent on how the information from all the con-

Table 2
Attribute scores for the maps used in the wind farm site selection

Class	Score	Class	Score	Class	Score
Topography		*Urban areas*		*National Trust property*	
Slope angle >10%	10	0–2000 m	10	0–1000 m	10
Slope angle <10%	0	>2000 m	0	>1000 m	0
Water bodies		*Woodland*		*Ecology*	
0–400 m	10	0–500 m	10	Important	10
>400 m	0	>500 m	0	Not important	0
Historical sites		*Railways*			
0–1000 m	10	0–100 m	10		
>1000 m	0	>100 m	0		
Agricultural land		*Roads*			
Grade 1	10	0–100 m	10		
Grade 2	5	101–999 m	1		
Non-agricultural	0	1000–1999 m	2		
		2000–2999 m	3		
		3000–3999 m	4		
		4000–4999 m	5		
		5000–5999 m	6		
		6000–6999 m	7		
		7000–7999 m	8		
		8000–8999 m	9		

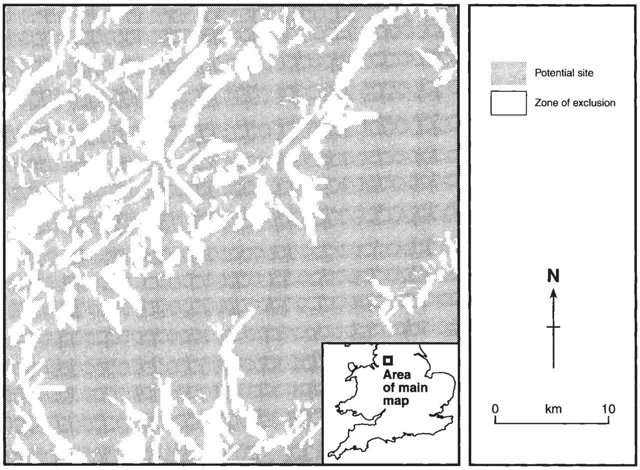

Fig. 2. Exclusionary zones and potential sites based on aspect.

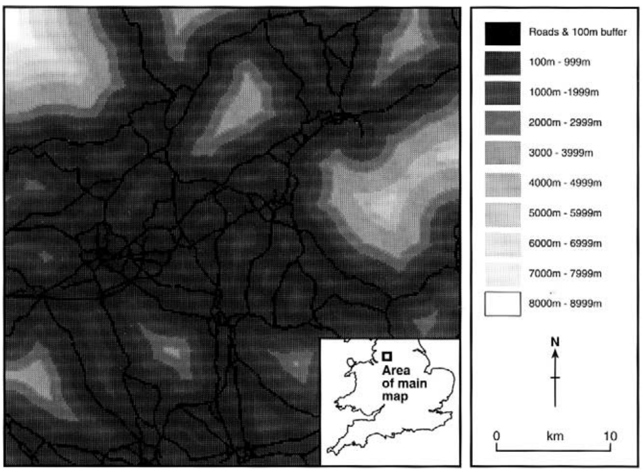

Fig. 3. Roads and buffer zones.

straint layers is combined to produce a single index of evaluation [17]. This can be realised in two different ways. First, by assuming that all the layers are of equal importance and therefore carry the same weight. This is achieved by summing the attribute scores, by map layer weights, on a cell by cell basis. In IDRISI this is attained using the ADD function of the OVERLAY module. In order for the output map to be meaningful and consistent, map weights had to add up to 100% and the attribute scores had to be chosen using a scheme that was the same for each map. Following this procedure, each of the 14 constraint maps was considered to be of equal importance, so they were weighted equally at 7.14%, and then combined using the "ADD" OVERLAY operation. On the outcome map, the constraint score of a

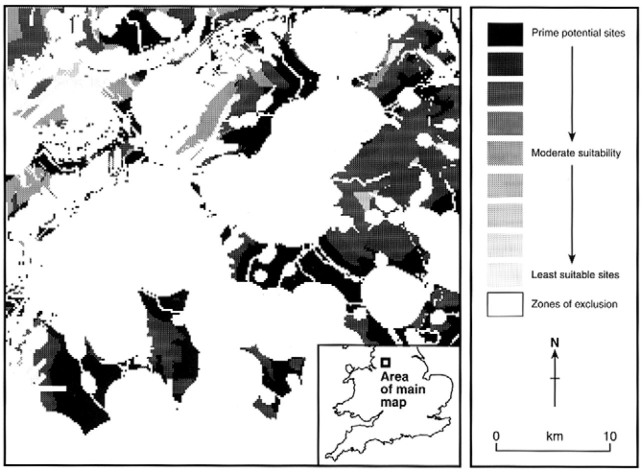

Fig. 4. Wind farm site suitability based on method 1.

cell was equal to the total of the corresponding cell scores from each of the constraint maps that were combined to produce it. However, as all classes of 10 and over were unsuitable for siting a landfill, the map was reclassified to rank all values greater than 10 equal to 10. This simplified the suitability map to just 10 classes (Fig. 4), ranging from the prime locations (0), through the moderate (5), to the areas that are totally excluded (10), making it easier to understand and interpret. Second, weights were allocated to constraint layers based on their perceived importance. In this study the factors were classified into first-, second-, third- and fourth-grade factors based on this principle (Table 3). The weights for each layer were allocated based on a pairwise comparison for the relative importance of the two layers by rating rows relative to columns and entering the ratings into a matrix. The procedure then requires that the principle eigenvector of the pairwise matrix is computed to produce a best-fit set of weights [12]. This approach was used to develop a pairwise matrix for all the layers (Table 3). The WEIGHT module, which computes a best-fit set of weights for a reciprocal pairwise in IDRISI, was used to calculate the principle eigenvector

Table 3
Groups of factors according to their significance

First-grade factors	Second-grade factors	Third-grade factors	Fourth-grade factors
Slope	Agricultural land	Historic sites	Paths
Roads	Railways	National Trust property	
Urban centres	Rivers		
	Woodland		
	Water bodies		
	Ecological sites		

Table 4
Weights allocated and derived for criteria factors

	First-grade factors	Second-grade factors	Third-grade factors	Fourth-grade factors
First-grade factors	1			
Second-grade factors	3	1		
Third-grade factors	5	3	1	
Fourth-grade factors	1/7	1/5	1/3	1

The derived weights were: first-grade factor=0.5650, second-grade factor=0.2622; third-grade factor=0.1175, fourth-grade factor=0.0553.

directly (Table 4). This information was used to produce suitability based on weighted layers (Fig. 5).

5.3. Results and analysis

The suitability map (Fig. 4) shows the varying ranges of suitability for locating a wind farm throughout the study area, according to the constraints given in Table 1 and the attribute scores given in Table 2. The suitability scale ranges from "ideal" (class 0) to "unacceptable" (class 11), where scores of 0 and 10 were attained respectively. The spatial patterns on the map strongly reflect the influence of the roads buffer (Fig. 3) and urban areas buffer (Fig. 1). The influence of urban areas is clearly evident in the south of the study area where the largest number of urban areas is concentrated. The combination of the two has also created a "distance decay" effect,

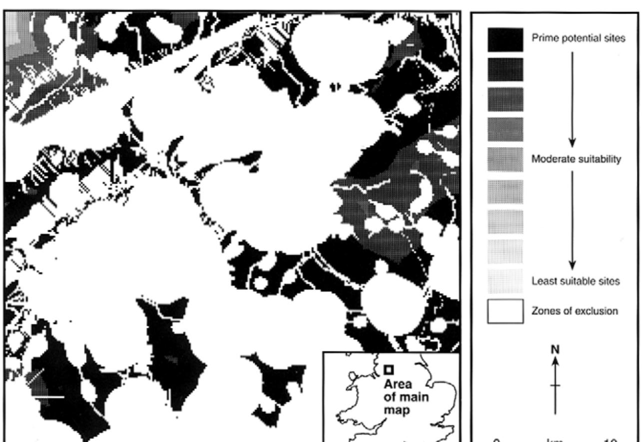

Fig. 5. Wind farm site suitability based on method 2.

where the most unsuitable areas are those found closest to a road and an urban area. The range of suitability then increases with distance until the critical distance is reached, when areas can be regarded as prime potential sites. In terms of area, as would be expected, the most suitable areas represent the smallest group, occupying only 3.79% of the total study area while the least suitable sites covers some 73.34% of the area. The suitability map using weighted layers (Fig. 5) shows a very similar pattern. However, the analysis in terms of areas occupied by each suitability class shows that these have changed slightly in favour of the most suitable sites. The most suitable areas are occupying 8.32% of the total study area while the least suitable sites cover 70.26% of the area.

6. Discussion

Basic wind farm location criteria have been developed for the UK, using information from criteria, policies and factors used by relevant public and private sector bodies, as well as the literature. The criteria were implemented in an area around Lancashire, using distance operations and index overlay modules within a grid-based GIS (IDRISI). This involved the mathematical combination of 14 different map layers to produce a wind farm suitability map for the study area. Two methods were use to combine the 14 layers. First, by considering all the constraint layers as being equally important and, consequently, giving them equal weight. Second, a suitability map was obtained by grouping the constraint layers and grading each group according to perceived importance and allocating weights based on a pairwise comparison of the importance of two layers. The outputs were composed of classes from 0 to 10, where 0 represents ideal locations and 10 represents unsuitable locations.

The spatial patterns on the outcomes from both methods strongly reflect the influence of the roads buffer and urban areas buffer. The second method seems to slightly favour the most suitable areas by increasing their geographical areas within the study area. In fact, this method allows the user to incorporate varying degrees of importance in each map. This flexible approach makes it useful as a planning tool as it provides the user with the freedom to use their individual expertise in the decision-making process. These maps can be used easily to assist in making informed decisions. Additional relevant layers of information, such as public satisfaction, could be formatted and easily integrated into the GIS and, consequently, be taken into consideration when locating wind farm sites.

The investigation could be taken a step further by using the GIS to assist in locating the most suitable site among several of the "ideal" sites from the constraint map by assessing their suitability on an individual basis. The role of the GIS here could be to act as a database for the in situ data collected for each potential site.

In terms of the accuracy of the outcomes, this type of investigation will use data from different sources with different levels of accuracy. The errors from any one map layer will have propagated through the analysis and, combined with errors from other layers, may cause inaccuracies in the output map. In other words, the errors in the wind farm site suitability map can be seen as the culmination of the errors from all of the other maps. As a rule of thumb, the composite map is less accurate than the least accurate layer used in its composition.

The GIS is potentially well suited for locating wind farms for the following reasons:

1. it has capabilities to manage and analyse the volumes of diverse multidisciplinary data needed in the application;
2. it has the functionality to perform "what if" scenarios which can be used either to evaluate the effects of different planning polices and to select those most suitable or to find the optimum wind farm site among a number of potential sites;
3. it has the ability to be used for "modelling impacts" of proposed and operational sites and suggest modifications to minimise them.

All the above, in association with clear indications that the demand for wind farms is on the increase in the UK and the EU, demonstrates clearly that the GIS has great potential in this field.

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