A GIS-driven approach to Siting a Prospective Wind Farm in South Central Wisconsin

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Abstract: *There is a growing need for renewable energy sources in South Central Wisconsin, one that could be met by installing a wind farm in the area. We used a GIS to analyze a variety of criteria and determine the most suitable location for a wind farm in the nine county study area. Based on this research, we concluded that a location in Northwest Rock County is the best possible location to site a wind farm. This conclusion provides valuable base research for a company looking to take advantage of the growing market for renewable energy in South Central Wisconsin.*

INTRODUCTION

Windmills have been in use around the world for hundreds of years, but it is not until recently that they have been widely developed as a reliable power source for large populations. The large-scale implementation of this technology began in the 1970's and has been rapidly expanding since. The state of Wisconsin has already taken advantage of this energy production strategy with nine established wind farms, and with plans to expand further (RENEW WI 2009). Determining the best location for new farms requires analysis of local wind speeds, elevation, land cover and proximity to existing electrical grids. Our research will utilize a GIS to analyze these factors to determine the most optimal turbine locations in South Central Wisconsin (Fig 1).

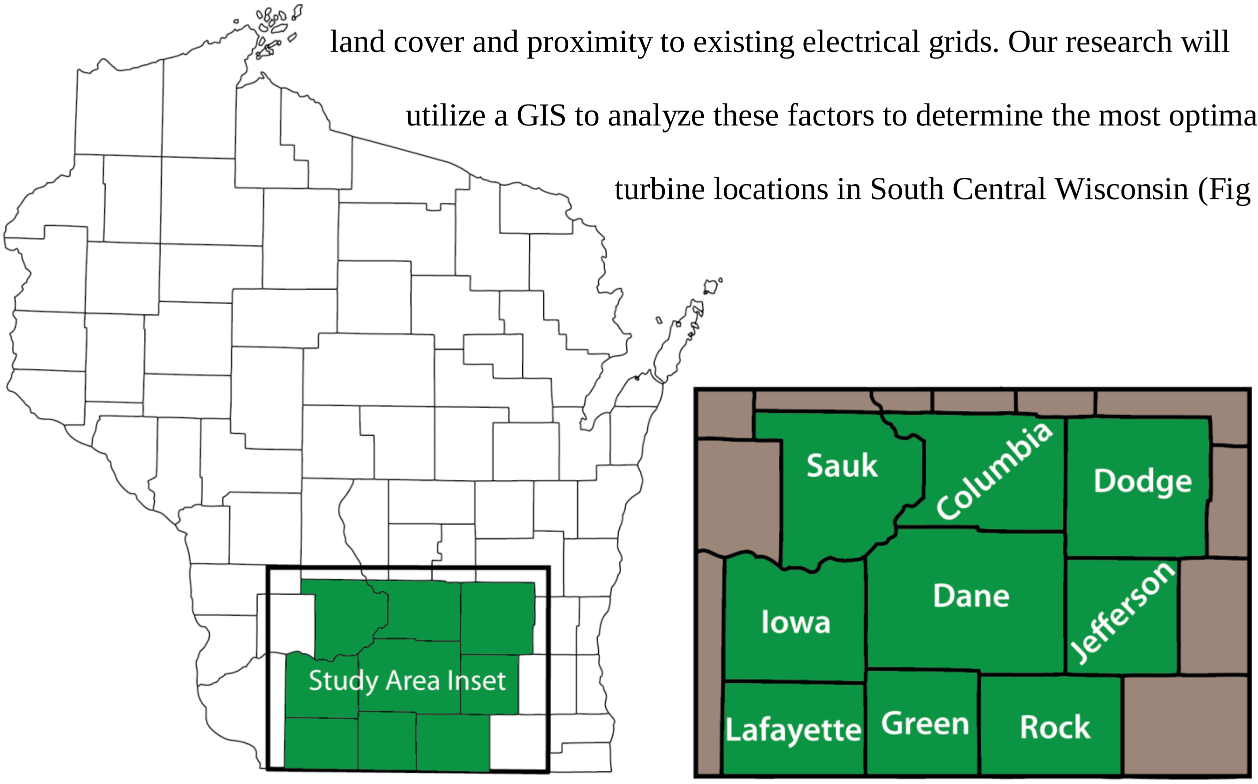

Figure 1. Our study area in South Central Wisconsin

LITERATURE REVIEW

In order to determine areas most suitable for wind farms, we must decide on the parameters that will affect (and be affected by) the wind turbines. Our criteria for site classification are broken down into environmental and human factors.

Environmental Factors

Wind Speed. Environmental constraints include wind speed, elevation, land cover, land cover and impacts on wildlife. The main characteristic to be considered for the location of a possible wind farm is clearly wind speed. Obviously, the higher the wind speed, the more energy produced, so comparing climate data from potential sites to determine mean annual wind speeds is ideal. These reference sites can be used to establish a "wind atlas" above the area of study (Burlando et al. 2009, 498). It is difficult to determine how homogenous the archived climate data is in each study. Metadata is often minimal or entirely unavailable with these records. This lack of information may mask differences in spatial or temporal resolution among climate data, as well as biases in measurement methods (Winkler 2010, 119).

Of course, most climatological wind speed data is observed near the ground; however, velocity can be extrapolated at any given height when surface roughness is considered (Jowder 2009, 340; Ganesan and Ahmed 2008, 132). In fact, innovations such as The Wind Atlas Analysis and Application Program serve that purpose (Burlando et al., 2009, 498; Ganesan and Ahmed 2007, 132; Hillring and Krieg 1998, 473). It is difficult to verify the effectiveness of this program specifically because it seems to be the only one that aims to estimate wind potential. Other studies simply define a minimum ground-level wind velocity for wind energy production to be effective (Yue and Wang 2006, 732). This method is probably less accurate because inconsistencies in ground-level and turbine-level wind flow are not considered.

Slope. Slope is the largest factor affecting the stability of the individual turbine and is generally not to exceed 10 percent, grades higher than this may still be considered, but will be considered much less desirable (Tegou et al. 2010, 2137). The presence of existing obstacles may be hard to judge remotely and must be assessed at the potential sites. This will inevitably affect the layout of the turbines, and in turn how many turbines will be capable of fitting within our potential areas. There are a variety of potential layouts however, such that this will not be a limiting factor for the purposes of this study (Dehnholm et al. 2009, 7).

Land Cover. Land cover requirements, another important consideration, are determined based on current use and long term effects to the immediate area. Every turbine has its own footprint on the ground, similar to a shadow, based on total rotor diameter (Dehnholm et al. 2009, 4). Area in question must be capable of housing the total area of the turbine as well as the temporary land/area effects inherent in the construction of the wind farm. Agricultural and cropland areas are considered most preferable because after construction they can be quickly returned back to their original use. This does not rule out undeveloped land, but it is not preferable for the sake of minimal habitat disturbance. Additionally, shrubland and grassland is far more favorable than forested areas (Rodman and Meetenmeyer 2006, 2142). The majority of wind farms in the US were built on previously developed land, while at least three plants in Wisconsin reside on crop and pasture land (Dehnholm et al. 2009, 39). Certain land types are deemed unsuitable and require a minimum distance away from the extent of the area. Several good proximity constraints include distances from woodlands, large settlements, single dwellings, park and similarly protected areas. Economic factors such as distance to roads and power grids will be considered at a maximum distance for the sake of minimizing construction costs and efforts. We are assuming an unlimited budget, but will still try to stay within a reasonable distance to ensure a client would feel confident undertaking the construction project. Baban and Perry take in all areas up to 10,000m from existing roads and the grid, whereas Tegou et al. used a distance of only 2000m (Baban and Perry 2001, 63; Tegou, Polatidis, and Haralambopoulos 2010, 2138). A reasonability distance unique to the area must be established, but the numerous factors that go into the reasons of this distance are beyond the scope of our study.

Wildlife Impacts. A final environmental consideration in wind farm siting is the effect on area wildlife, specifically birds and bats whose habitats and migration routes may be compromised. While there is little doubt that the topic is an important one, the research available is far from adequate. The main reason for this is the fact the subject can be studied in many different ways, leading to vast differences in the reported disruptions. For example, studies can choose to focus on habitat displacement or fatalities due to collision with the turbine rotors (Madders and Whitfield 2006). There is also internal variation within these two main categories. For instance, in collecting fatality data different scientists use different formulas to estimate the number of bird carcasses removed by predators, causing clear overestimations in some cases (Byrne 1983 as cited in WEST Inc. 2001, 12) and underestimation in others (Barclay, Baerwald and Gruver 2007, 383; Smallwood 2006, 2). Similarly, estimations of carcasses overlooked by searcher error are not standardized across the field (Smallwood 2006, 1). *Research Methods in Geography* warns of this type disparity in data standards, stating that “it is often not possible to share the data because their sampling and data collection protocols were not the same or were inadequate for another agency’s needs”, which is exactly the problem we have encountered in this comparison of studies on the number of deaths caused by collisions with turbines (Jensen and Shumway 2010, 86).

Additionally, researchers may choose to study vastly different species, such as pigeons (WEST Inc. 2006) raptors (Madders and Whitfield 2006) which means comparisons between the sites studied cannot be made. Even in studies of wind farm impacts on similar species there are variations in turbine height (WEST Inc. 2006, 12; Smallwood 2006, 1) and climate that need to be standardized before comparisons can be made. Much of the available literature on the subject concerns the Altamont Pass Wind Resource Area in California (e.g. Smallwood and Thelander 2004; 2005; WEST Inc 2006; Howell and Didonato 1991), which is not necessarily applicable to wind farms that may be constructed in other areas of the country.

At this time there are only two Wisconsin bird species listed as endangered and no bat species (US Fish and Wildlife Service 2010a). These species, the Kirtland's warbler and the piping plover, have only been identified in 8 counties in the state (US Fish and Wildlife Service 2010b), none of which are located in our study area. Considering this fact and the limited time and resources available for this study, bird and bat habitats will not be a major consideration in our work.

Human Factors

Public acceptance is another consideration for new wind energy projects. Objections to wind farm development are well-known; however, our analysis of recently published studies suggests that this may be due high publicity of the issue rather than wide-scale disapproval. There are multiple factors that garner complaints from the public, including noise, sun strobe effect, increased traffic and aesthetic concerns, with most literature on the topic stating that the main concerns are visual (e.g. Molina-Ruiz et al. forthcoming, 7; Gipe 1993, 234; Braunholtz 2003, 20).

Noise. One reason people cite for not wanting wind farms in their area is the mechanical noise they add to the countryside where they are normally built in. Other objectors (e.g. The Society for Wind Vigilance, Wisconsin Independent Citizens Opposing Windturbine Sites) go as far as to say that the noise from wind turbines is detrimental to their health. Experts on the subject however, have proven otherwise. For example, a 2009 report prepared by a panel of doctors, audiologists and acoustic professionals for the American and Canadian Wind Energy Associations clearly states "Sound from wind turbines does not pose a risk of hearing loss or any other adverse health effect in humans" (Colby et al. 2009, 1). Similarly, Health Canada reports that there are peer reviewed studies detailing the noise impacts on human health, but the articles they site claim that annoyance the main concern, rather than any diagnosable effects (e.g. Pedersen and Halmstad 2003; Keith, Michaud and Bly 2008).

Annoyance is a personal, rather than medical reaction to the noise level (Colby et al., 2009, 4), and though is it of much less concern that perceived health impacts, it should still receive at least minor consideration in the turbine siting process. An analysis of the literature available on the topic, however, reveals that this effect may also be exaggerated by disgruntled citizens. Educational material published by The Energy Center of Wisconsin explain that citizens should not be preoccupied with worries over the noise created by the turbines, since at a distance of 400ft the sound emitted is about 57dB, or similar to the sound of clothes dryer (The Energy Center of Wisconsin 2000, 2). Moreover, at a distance of 3000ft, the sound fades to about 30dB, or the noise of a soft whisper (The Energy Center of Wisconsin 2000, 2). It is reasonable to expect that it would be rare for any citizen to spend a large amount of time within 3000ft of a wind turbine, and thus we will consider the noise effects from wind turbines negligible in this study.

Sun Strobe Effects. Additionally, the strobe-like effects of sunlight being reflected off of rotating blades have stirred concern among some individuals and anti-wind groups (Molina-Ruiz et al. forthcoming, 1). Due to a lack of peer-reviewed evidence on the topic, this will also not play a role in our consideration of the best wind farms site in South Central Wisconsin.

Aesthetic Concerns. As stated, the most common concerns voiced by the public about wind farms are visual changes in the landscape (Molina-Ruiz et al. forthcoming, 7; Braunholtz 2003, 20, etc). This issue is difficult to address, because there is no universal set of values dictating which types of landscapes are appealing to the eye and which are not (Gipe 1993, 243). It seems, though, that the most common specific complaint is that the addition of wind turbines makes the landscape seem “cluttered” or “untidy” (Gipe 1993, 244). A list of simple solutions that can improve the visual perception of wind farms is provided by one author, including spacing the towers evenly, using turbines with uniform height, tower structure and blade length and choosing two blade turbines which may be more visually appealing to the public since the turbine rotors rest in a uniform horizontal position (Gipe 1993, 245-46).

Other studies based on scientific measurement of visual acuity and impacts are also available for wind farm planning. One such study from the Journal of Renewable Energy is of particularly great value to our group because it utilizes GIS to assess the impact of wind farm development. The researchers found that within 6 miles of a site the visual impact of the turbines is still high, but between 6 and 12 miles the impact is low and it is considered nonexistent from any distance greater than 16 miles from the site (Molina-Ruiz et al. forthcoming, 7). Using this optimal distance we can ensure our site is greater than 16 miles from any major population center and thus remove the visual impact of a wind farm from as many eyes as possible.

Again, while there has been much public outcry against the visual changes brought to an area by wind farms, this may be overrepresented by the vociferousness of a few citizens. Surprisingly, a large study from Scotland reported that those who live within 12 miles of a wind farm felt most positively about them, with ninety two percent of respondents stating that they felt either very good or fairly good about the existing project (Braunholtz 2003, 5). The report also stated the citizens who saw wind farms in their daily lives felt positively towards them (Braunholtz 2003, 5); conversely suggesting that the negative attitudes were voiced mostly from people who infrequently interact with or live near wind farms. Further research confirms that wind farms produce a higher visual impact for occasional visitors to the area than for residents (e.g. Molina-Ruiz et al. forthcoming, 7).

Solutions. There are several schemes utilized to decrease negative perceptions of wind farms from residents of potential sites. Many of these are proposed in Gipe's article promoting visual unity (Gipe 1993). Other articles go into extensive detail on the importance of public participation in the wind farm development process (e.g. Higgs et al. 2008, Braunholtz 2003). There are a variety of advantages to involving the public in the decision making process, including legitimizing the decision-making process, increasing democracy and indirectly increasing civic participation in general (Petts and Leach 2000 as citied in Higgs et al. 2008,1). The most obvious advantage of increasing participation in the process is greater acceptance of the wind farm by the public (Higgs et al. 2008,1). Public consultation and participation can take a variety of forms, including distribution of educational material, public hearings, surveys, or focus groups. Literature on the subject provides solid evidence that connects high levels of public participation with higher acceptance of a wind farm project, unfortunately due to the time and financial constraints of our project large-scale public participation in the process will not be possible. Instead we will focus on stringent siting criteria that will minimize the impact of our proposed wind farm for as many people as possible.

Decision-making Approaches

Due to the variety of criteria and constraints involved in decision making with respect to wind farm siting, significant sources of data are necessary. This abundance of information necessitates the use of a system that can manage different data layers for analysis. A GIS system is ideal because of their ability to manage multiple digital layers and integrate the data from each layer for management, manipulation, and analysis (Goodchild 2010, 381). GIS approaches to wind farm siting have been used in several previous studies such as Baban and Parry's study of wind farm locations in the UK (Baban and Parry 2001) and Tegou, Polatidis, and Haralambopoulos' study of wind farm locations on the island of Lesvos, Greece (Tegou, Polatidis, and Haralambopoulos 2010). A study done by Lee, Chen, and Kang in China utilized a mathematical model in collaboration with much of the same criteria (Lee, Chen, and Kang 2009). This approach seemed less organized and more mathematically demanding. All three of the above mentioned studies implemented some form of Multi Criteria Decision Making (MCDM) process—or Multi Criteria Analysis (MCA)—which is one of the most common approaches used for site selections (Tegou, Polatidis, and Haralambopoulos 2010, 2134). The study in UK and the study in Greece both detail very well how MCA approaches can be implemented in a GIS environment using an Analytic Hierarchy Process (AHP).

The core concept of an AHP—a type of MCA—is that each issue, or site location question, has a set of criteria that goes into the decision making process. These criteria—such as topography, climate, proximity to urban areas, etc.—are initially defined with constraints. Each potential location, in this case a cell, is assigned a code that signifies whether that constraint is met. These constraints are applied to each data layer and then the layers are overlaid to achieve a combined value for each cell (Baban and Parry 2001, 66; Tegou, Polatidis, and Haralambopoulos 2010, 2140). In the Baban and Parry study, cells are assigned a value ranging from 0-10 where 10 means the constraint is not met and 0 means the constraint is fully met. Most of the criteria is rated in a binary sense at either 0 or 10 but some criteria, such as distance to roads, is scaled with a value corresponding to the distance from the road. From this point, Baban and Parry suggest that one can either assume all constraints are of equal importance or that some criteria constraints are valued more than others. If all criteria are assumed to be of equal importance, each criterion are assigned an equal percentage value so that all the criteria values add up to 100 percent; if there are ten criteria, each is valued at 10 percent. The layers are then overlaid and added to produce an Index of Evaluation (IE) which gives the overall score for each cell.

Tegou, Polatidis, and Haralambopoulos take a minimally different approach in that they assign a binary value of 0 or 1 to a cell in each constraint layer to signify if it meets that constraint or not—0 meaning it does not and 1 meaning it does. By doing this, they avoid having to add totals for each cell; they merely overlay the layers then multiply a cells value in each layer. If all of the constraints are met, the cell will have a multiplied value of 1; if one or multiple constraints are not met, the cell’s value will be 0.

Each of the above schemes produces a suitability map based on criteria that are equally valued. Another more robust method is to use a pair-wise comparison matrix to weight each criterion to meet the overall goals of the project (Tegou, Polatidis, and Haralambopoulos 2010, 2143). Cells in each criteria layer are given a grade value that corresponds to the level of suitability of that cell. For example, in the land cover layer, a cell that is ideal land will be given the highest grade value and a cell that is marshland or urban will be given the lowest. Once all of the cells have a grade value, they are standardized using the maximum score procedure to a value between 0 and 1 and create the Evaluation Layers (ELs). This method is effective because the relative order of magnitude of the grade values is maintained (Tegou, Polatidis, and Haralambopoulos 2010, 2143). Because all evaluation criteria are not usually equally valued, weights can be assigned using a pair-wise comparison matrix to estimate weight values (Tegou, Polatidis, and Haralambopoulos 2010, 2143; Baban and Parry 2001, 67). The cells in each Evaluation Layer are then multiplied by their respective weight and then the Evaluation Layers are once again added together to produce a criteria-weighted suitability map. The final suitability map is then overlaid with the constraint map to eliminate the cells that did not meet the constraint criteria.

METHODS

In our analysis of South Central Wisconsin's wind farm potential, we first obtained necessary data layers from a variety of sources (Table 1) and made necessary modifications.

Layer	Source
Topography	WI Dept Natural Resources
Wind	Wind Powering America
Land Cover	WI Dept Natural Resources
Airports, Railroads, Roads	US Geological Survey
Protected Areas	National Biological Information Infrastructure
Transmission Lines	American Transmission Company, Public Service Commission

Table 1. Data layers and their sources

The wind speed layer, for example was appropriated from a map of Wisconsin annual average wind speed at 80m created by Wind Powering America, in collaboration with the renewable energy consultant AWS Truewind (Wind Powering America 2010). The information on wind resource potential is based on data with a spatial resolution of 2.5 km, and the data for intermediate points is interpolated. Pixels are separated into ranges based on the calculated speed. In our study area, five classes span the region, with interval of 0.5 m/s. Since the data was obtained from a secondary source, it was necessary to examine the validity of the wind map. To do so, we compared the data to recorded wind speed observations archived by the National Climatic Data Center (NCDC 2010). Wind readings were recorded at four airport weather stations, in ten minute intervals between October 2000 and October 2010. One of these stations is near the center of our study area, Dane County Regional, and three are near the periphery, Tri-County Regional at Lone Rock, Fond du Lac Regional, and Mitchell International. We employed a wind speed extrapolation equation to project the data from its observation altitude of 1.5m to an altitude of 80m using a surface roughness factor of 0.05, which is considered to be typical for airport runways (Danish Wind Industry Association 2003). The sites at Madison, Milwaukee, and Fond du Lac fell into the same classes that the Wind Powering America map depicted, but the Lone Rock site was represented one class higher than expected in the 80 meter map; the calculated 80m wind speed there was 4.87 m/s, while the map suggested that the area should experience an average annual wind speed between 5 and 5.5m/s. Differences between the two data sources could be due to inconsistencies in the methods of recording wind speeds, such as height of the recording device and varying levels of interference caused by nearby obstacles, or different sample years. Although the map and the weather station data do not correspond exactly, the difference is negligible enough that the map is still an accurate representation of average wind speeds in Wisconsin, and more specifically, in South Central Wisconsin.

The protected areas data layer contains spatial information on all state and federal owned land in Wisconsin, as well as privately operated conservation areas. For our purposes, we will treat all types of protected areas equally as undevelopable. Similarly, the transmission lines layer contained information distinguishing above ground and below ground lines; however, we chose not to differentiate between the two. The airports layer contained both commercial and non-primary airstrips. However, since the volume of air traffic varies greatly between these airport types, we separated large airports (area > 2,500 acres) from smaller ones. Our roads layer contained roads of varying magnitudes. Following the literature, we considered primary and secondary roads to be major roads, but evaluated local roads separately.

We had to make several changes in the land cover layer, as it originally contained subcategories that were not pertinent to our study. We aggregated several subcategories, deciduous and coniferous forests, for example, to simplify the data set. The product of our simplification was a layer that contained eight relevant categories: cultivated land, pasture, grassland, scrub/shrubland, barren land, forest, urban, and surface water/wetland.

We received the county boundaries, railroad, and digital elevation model layers in a format that was immediately usable in our GIS analysis and required no editing.

Layer Type	**Criteria**
Topography (constraint)	Slope Angle >20%
Land cover (constraint)	100m from Water / Wetlands
	1000m from Developed
	Undevloped Barren
Protected (constraint)	State / Federal Land
	All Other Undevelopable Land
Features (constraint)	3000m from Major Airports
	1000m from MinorAirports
	250m from Railroads
	250m from Primary and Secondary Roads
Land cover (graded)	Cropland, Grazing land, Shrubs
	100m from Wooded
Transmission lines (graded)	within 10,000m of transmission lines
Wind (graded)	≥ 5m/s Avg. Wind Speed

Table 2. Criteria for constrained and graded layers

The next step in the process was to determine the constraint criteria and create appropriate buffers for the layers where they were necessary. Following the literature from similar studies, we applied the following constraints and buffers (Table 2).

Areas that did not fit our constraints were given a cell-value of zero while areas that meet our constraints will be given a cell-value of one. Additionally, each of the components that did fit the criteria was ranked according to suitability to create standardized evaluation layers (EL). We applied the following grading scheme for each layer using Fuzzy Logic for the wind speed, slope, and transmission lines layers (Tables 3-6).

Land Cover Type	Grading Value
Cultivated Crops	10
Pasture	10
Grassland	9
Shrub/Scrub	6
Barren	5
Forest	3

Table 3. Land cover grading values

Avg. Wind Speed (m/s)	Grading Value
>7	10
6.5-7	9
6-6.5	8
5.5-6	7
5-5.5	6

Table 4. Wind speed grading values

Slope (%)	Grading Value
0	10
0-5	9
5-10	8
10-15	7
15-20	6

Table 5. Slope grading values

Proximity to Transmission lines (m)	Grading Value
0-1,000	10
1,000-2,000	9
2,000-3,000	8
3,000-4,000	7
4,000-5,000	6
5,000-6,000	5
6,000-7,000	4
7,000-8,000	3
8,000-9,000	2
9,000-10,000	1

Table 6. Grading values for distances from transmission lines

Once an EL was created for each criterion, we applied weights to these layers. Certain components of our study hold a higher value than others and applying weights to our evaluation layers allows us to designate greater value to these components (Table 7). After the weights were assigned, the ELs are overlaid and summed to create an overall suitability layer for the entire study area (Figure 2).

Layer	Weight (%)
Wind	40
Land cover	30
Transmission Line Proximity	20
Slope	10

Table 7. Values designating layer weight

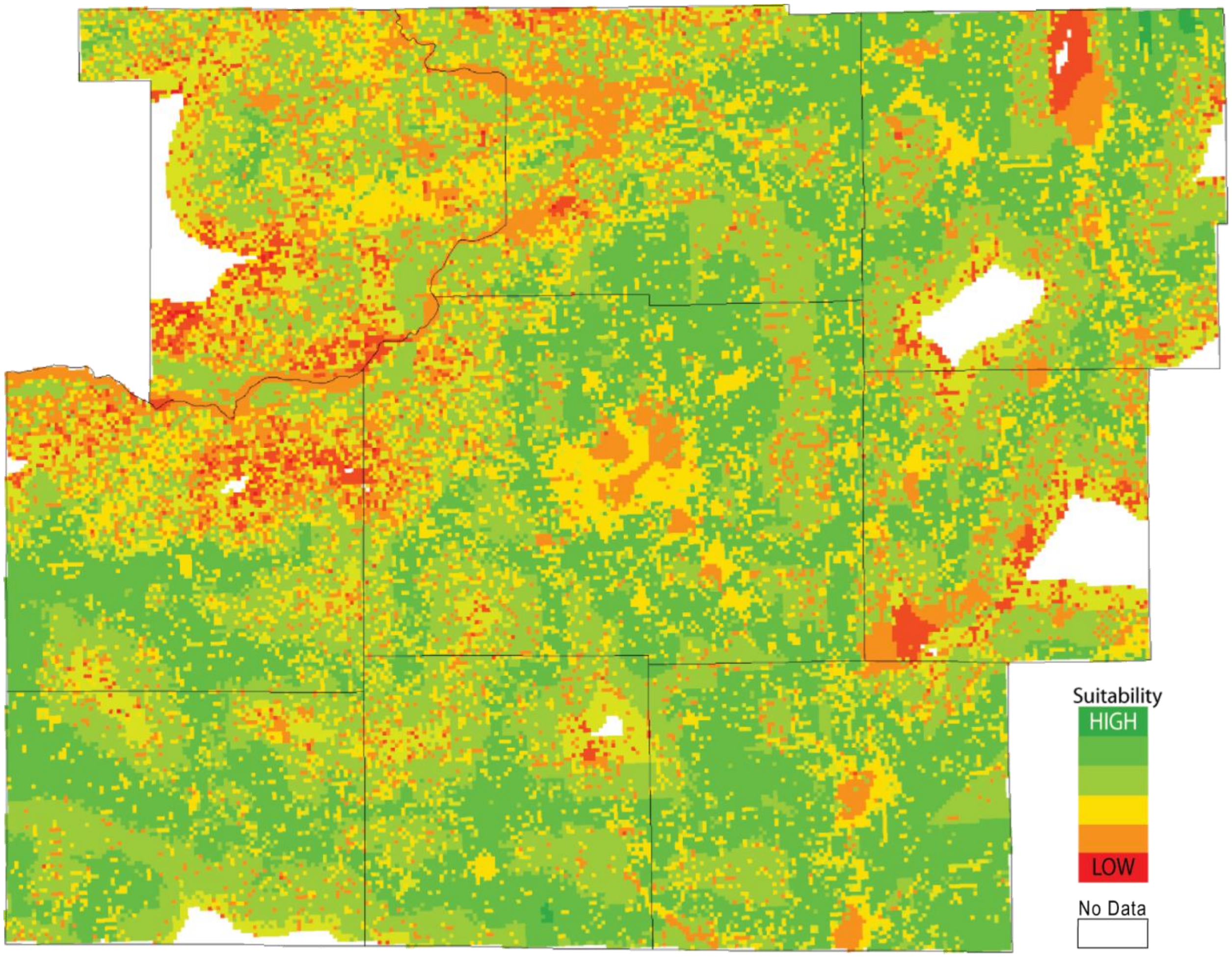

Figure 2. Suitability Layer

Finally, we excluded cells in the study area that do not meet our constraints by overlaying the overall suitability layer with the overall component constraints layer and multiplying the cell-values from each. In doing so, cells in the overall suitability layer that correspond to constraint cells in the overall component constraints layer—cells assigned a value of zero—were not included in the final assessment. This created the following final suitability map that highlights the five most suitable locations (Figure 3). For a visual representation of the process, see figures 4-6 in the appendix.

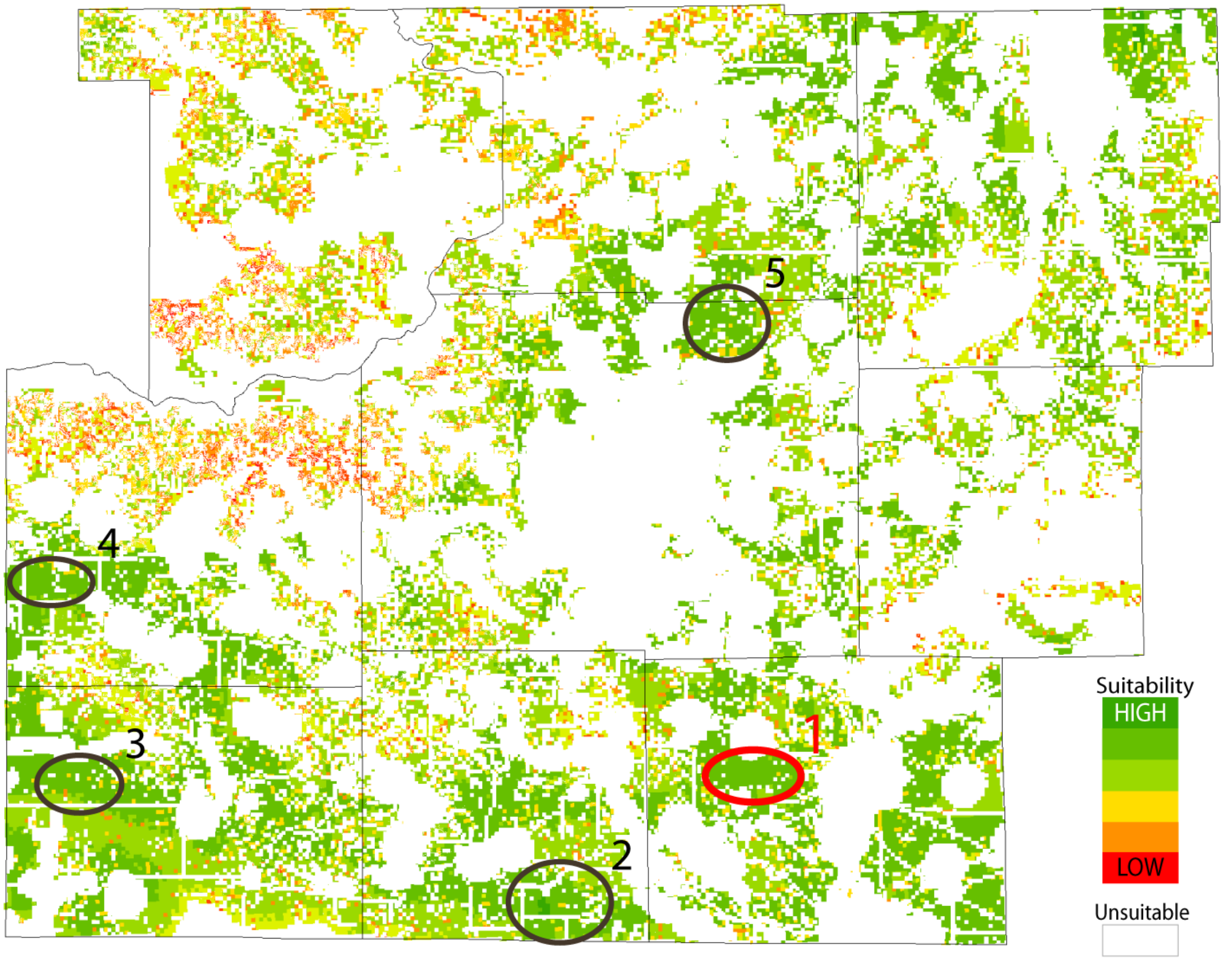

Figure 3. Final suitability map

RESULTS

From the final suitability map we determined that the following locations are most suitable to construct a wind farm (referenced in the above map): 1) Northwest Rock County, 2) Southeast Green County, 3) Northwest Lafayette County, 4) West Iowa County, and 5) Northeast Dane County. These locations were selected because they exhibit the best balance between suitability and size. Based on the previously stated criteria, available space and a visual assessment of the area via remote imagery we concluded that the location in Northwest Rock County is the most ideal of the five options.

FURTHER RESEARCH

The goal throughout our research was to provide the most accurate and complete analysis of the data available to us. However, we realize that nature of our project posed a few inherent limitations, therefore we advise any further research should include three additional considerations. First, the accuracy of the selected location could be improved by incorporating a wind data set with more sample locations concentrated within the study area, rather than points distributed throughout the entire state. Increasing the number of locations considered would improve the spatial resolution of the data, resulting in conclusions that rely less on interpolation and more on specific observations, and thus produce more precise results. Additionally, wind data that includes direction could be incorporated to determine the most efficient way of orienting the individual turbines on the site.

Another topic that needs more consideration is the negative environmental impacts of wind turbines. In our review of the current literature we found that conclusions on the degree to which wind turbines affect wildlife vary greatly, as do the methods for interpolation and data collection. For this reason we simply created 1000m buffer around any protected habitat areas.

We hope that in the future more clear conclusions on the impacts to wildlife will be established, allowing for a less generalized approach to siting turbines.

Impacts of alternative energy production on the pre-existing power grid could also be examined. Wind power is known to influence the transmission efficiency of grid systems, chiefly due to the natural intermittency of wind itself (Albadi 2010, 628). This lessened effectiveness can result in economic losses and stress on the power system. With more time and technical information, this could be taken into account by factoring the distribution of wind velocities, as well as characteristics of South Central Wisconsin's power grid, such as energy capacity and reserve capabilities (Albadi 2010, 630). Based on these findings, further recommendations should be made to minimize strains on the electrical grid.

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APPENDIX

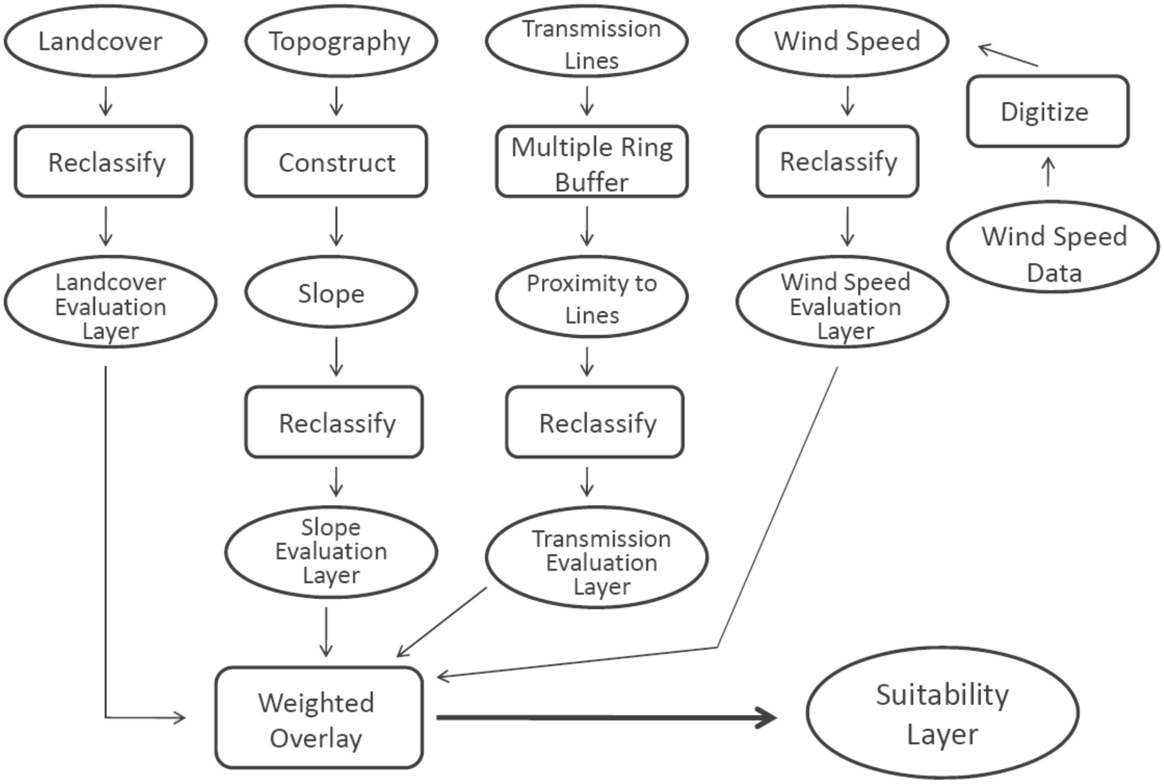

Figure 4. Suitability layer implementation process

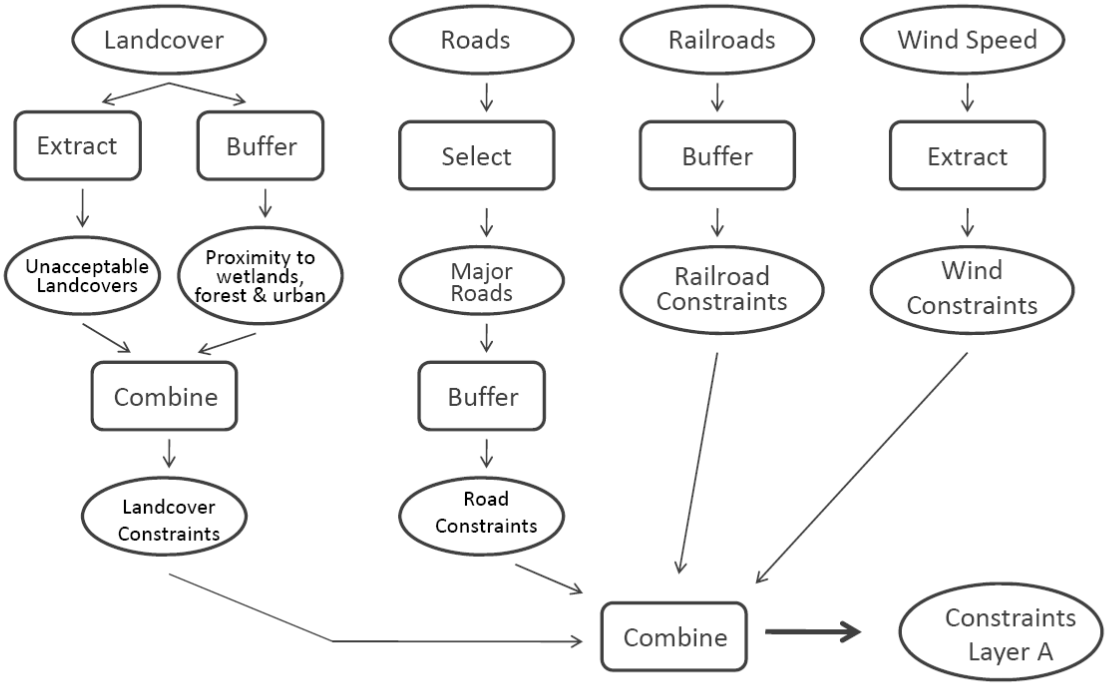

Figure 5. Constraint Layer A implementation

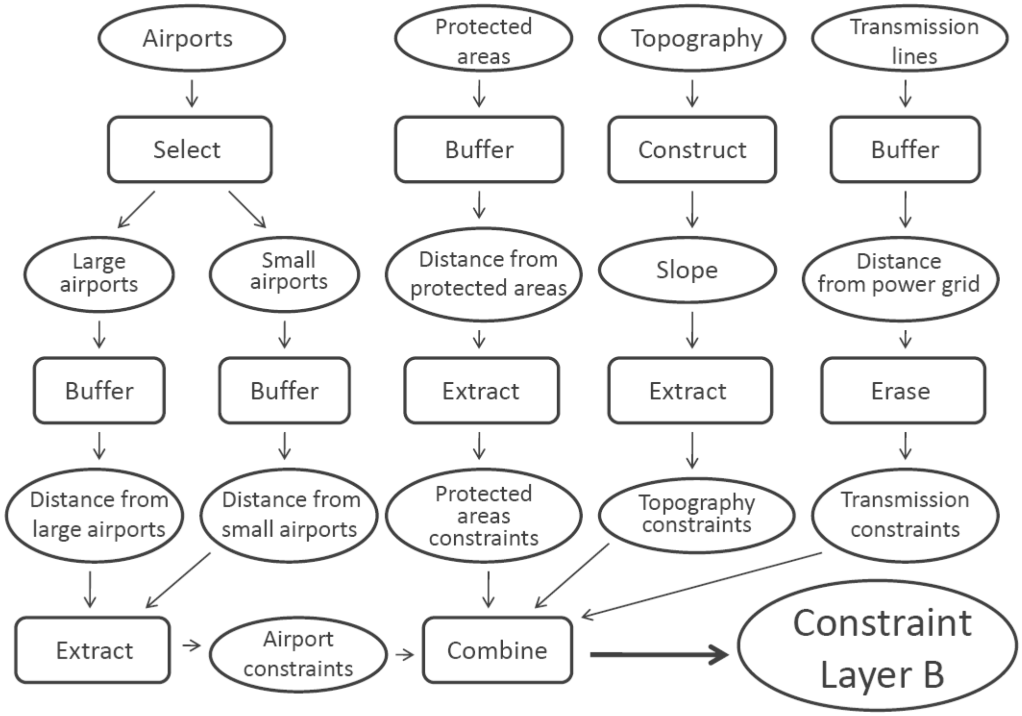

Figure 6. Constraint Layer B implementation

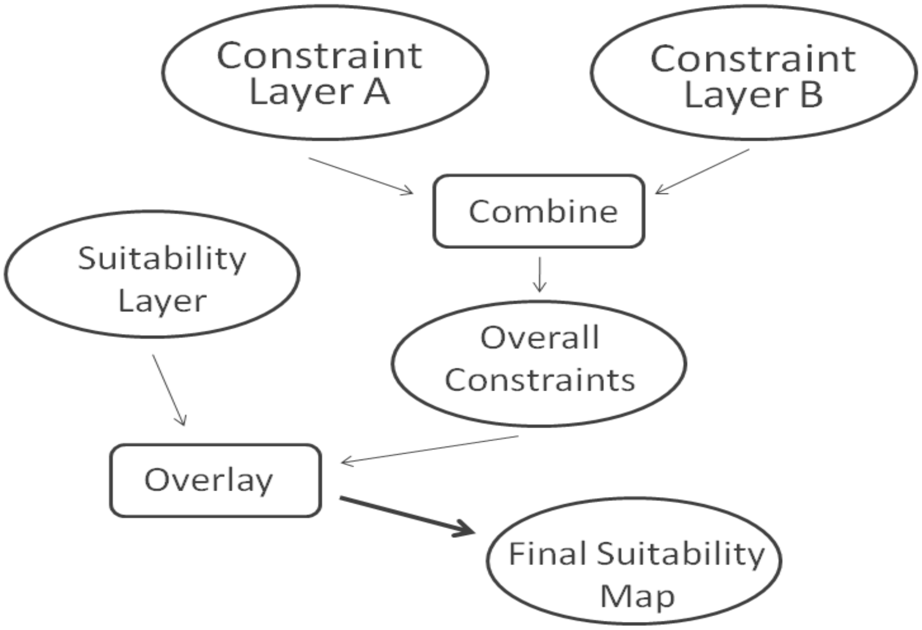

Figure 7. Final Suitability Map implementation