# Using GIS to Determine Wind Energy Potential in Minnesota, USA

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## Abstract

Wind power is an alternative to fossil fuels. It is plentiful, renewable, widely distributed, clean, produces no greenhouse gas emissions during operation and uses relatively little land. Recent studies indicate that Minnesota has plentiful wind energy potential including the possibility to use wind to generate 25 times the electricity Minnesota used in 2010 (American Wind Energy Association, 2012a). This study evaluates the potential wind energy resources in Minnesota by analyzing technical, environmental, and political criteria for developing local renewable wind energy resources. The approach assesses suitable locations for exploring wind turbines energy sources with the aid of a geographic information system. The study considers local wind conditions and other restrictions such as terrain, land use, environment, and human activities. The model identifies areas that have an excellent suitability for future wind turbine placement in Minnesota. When it compares to the approximate estimations based solely on analysis of wind speed, this rule-based model may provide a more accurate method to evaluate wind energy in Minnesota.

## Introduction

The issue of global warming is becoming a potential severe challenge that nations around the world would be wise to confront. The Intergovernmental Panel on Climate Change (IPCC) indicated during the twenty-first century the average global surface temperature will likely rise between 1.1° and 2.9° C (2° to 5.2° F) according to their lowest emissions scenario and between 2.4° and 6.4° C (4.3° to 11.5° F) according to their highest emissions scenario (IPCC, 2007). Scientists have confirmed that a contributing cause of global warming is the emission of greenhouse gases (in particular carbon dioxide), mainly generated by fossil fuel combustion (United States Environmental Protection Agency, 2010).

The negative effects of fossil fuel combustion on the environment, in addition to limited fossil fuel supply, have forced many countries to explore and change to environmentally friendly renewable alternatives in order to meet increasing energy demands. Currently, wind energy is one of the fastest developing renewable energy technologies around the world

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(Ramachandra and Shruthi, 2005).

According to a report by the American Wind Energy Association (AWEA, 2012b), by the end of 2012 the United States (US) wind industry totaled 60,007 MW of cumulative wind capacity (from more than 45,100 turbines). Over one fifth of the world's installed wind power capacity is located in the US (BP p.1.c., 2013). Although the US wind industry has already made significant strides in developing electric energy from wind turbines, there is still plenty of opportunity for growth (Schrader, 2012).

"Minnesota ranked 3rd in the US in 2010 for percentage of electricity derived from wind" (AWEA, 2012a). This fact sent a signal to wind energy companies that Minnesota is a wind-friendly state. According to National Wind (2012), Minnesota has a total wind resource of 489,271 MW, and this capacity of wind power could support nearly 25 times the amount of electricity Minnesota currently needs. Thus, there are many potential areas for wind turbines.

However, the locations with the highest wind resources are not always feasible sites for wind farms. A variety of factors are decisive in the site selection of wind turbine farms. In this study, a rule-based modeling method was used to evaluate and target suitable wind power sites. Using a similar approach as Rodman and Meentemeyer (2006), this model incorporated the following factors:

(1) Physical criteria such as wind resources, obstacles, and terrain.
(2) Environmental constraints such as wildlife conservation areas and bodies of water.
(3) Human impact factors such as major roads, noise, state parkland, and electric lines.

Datasets for the project were obtained or derived from existing datasets and analyzed using separate physical, environmental, and human impact models. This rule-based model integrated individual outputs into one final result which identified suitable sites for wind turbines in Minnesota.

## Methods

### *Database Development*

The rule-based model used in this study was a spatial multi-criteria model using diverse variables to represent the physical, environmental, and human impact factors determining wind turbine site suitability. By using Esri's ArcMap software, data for each of these criteria were converted from vector format to raster format and assessed using overlay analysis. All tools referenced in this paper are from Esri's ArcMap software.

The study area for this project included the entire state of Minnesota. In 2006, the Minnesota Department of Commerce developed maps of Minnesota wind resources at different heights, 30, 80, and 100 m above ground. Since the height of large wind turbines is generally between 50 and 80 m above ground, wind speed data at 80 m was used in this study (Figure 1).

Terrain strongly affects the performance of wind turbines;

therefore, a slope dataset was derived from a 30 m digital elevation model (DEM) developed by the United States Geological Survey (USGS, 2009).

The environmental data for Minnesota, such as wildlife conservation areas and open water areas were obtained by the Minnesota Department of Natural Resources (MNDNR, 2013). Human impact factors such as populated areas, major roads, and state parkland were also obtained from the MNDNR (2013). The energy grid dataset for Minnesota was obtained from the Minnesota Land Management Information Center (2007). The data above were converted to 30 m resolution raster datasets for the raster overlay analysis.

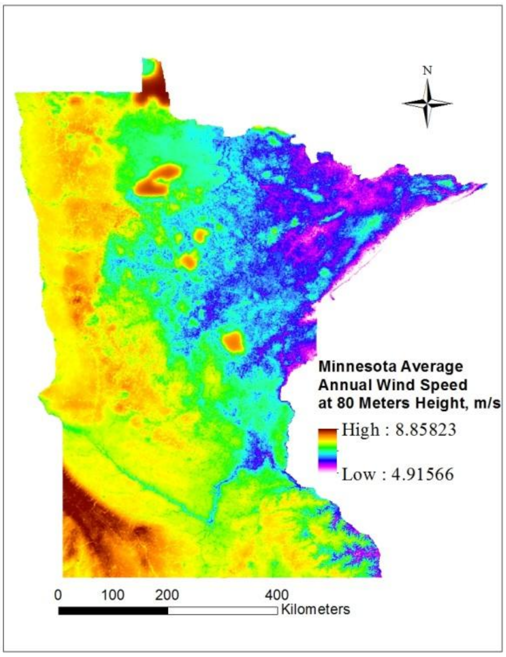

Figure 1. Minnesota average annual wind speed at 80 m height.

## *Model Development*

### Physical Model

The physical model incorporated three components: average annual wind speed at 80 m height, obstacles, and terrain.

The annual average wind speed is useful as a predominant indicator of wind resources. Ten meters is the standard height for a typical meteorological station to measure wind speed. The wind speed suitability for developing wind turbines was classified into four categories based on wind velocity at 10 m: poor, marginal, good, and excellent (Table 1) (Ramachandra and Shruthi, 2005).

Table 1. Annual mean wind speed and potential value of the wind energy resource at 10 m height (Ramachandra and Shruthi, 2005.)

| Annual mean wind speed at 10 m | Indicated value of wind resource |
|---|---|
| <4.5 m/s | Poor |
| 4.5-5.4 m/s | Marginal |
| 5.4-6.7 m/s | Good |
| >6.7 m/s | Excellent |

Since the hub height of a modern wind turbine is greater than 50 m and the available wind speed data was measured at 80 m above ground, the wind speed classification at 10 m was converted to the wind speed at 80 m in order to provide a uniform standard for analysis. The following formula developed by Davenport (1960) was used to extrapolate wind speed at different heights:

$$\frac{\bar{V}_Z}{\bar{V}_G} = \left[\frac{Z}{Z_G}\right]^{\partial} \quad (1)$$

$\bar{V}_Z$ = the known mean wind speed at height Z in the study area (m/s)
$\bar{V}_G$ = the mean wind speed at height $Z_{G,}$

which needs to be extrapolated (m/s)

$Z$ = the height for which the wind speed $\overline{V}_Z$ is computed (m)

$Z_G$ = the height at which $\overline{V}_G$ is first observed in the same terrain

$\alpha$ = an empirical exponent, which depends on the roughness of the surface.

According to the available wind data in this research, formula (1) was adapted as the following equation (2), which estimated wind speed in the same terrain for 80 m height.

$$\overline{V}_Z = \left[\frac{80}{10}\right]^{0.14} \times \overline{V}_{10} \quad (2)$$

By using equation (2), the new wind classification at 80 m height was developed (Table 2).

Table 2. Annual mean wind speed and potential value of the wind energy resource at 80 m height.

| Annual mean wind speed at 80 m | Indicated value of wind resource |
|---|---|
| <6.03 m/s | Poor |
| 6.03-7.24 m/s | Marginal |
| 7.24-8.98 m/s | Good |
| >8.98 m/s | Excellent |

However, the range of wind speed values published by the Minnesota Department of Commerce (4.92 m/s to 8.86 m/s) was narrower than the resulting suitability classification. Therefore, the wind speed criterion at 80 m above ground was modified as displayed in Table 3.

Tall obstacles can obstruct wind flow and decrease the efficiency of wind power generation. Since wind turbines sites are best located away from highly populated areas (described later), obstructions such as buildings are unlikely obstacles. The presence of trees is recognized as an obstacle in open areas. Wind turbine suitability decreases as the density of trees increase (Rodman and Meentemeyer, 2006). For this model, a forest layer was derived from the National Gap Analysis Program (2001) Land Cover Data. Forest densities were determined from vegetation types at a given location. If the attribute table of the vegetation dataset showed the land was occupied by trees in the study area, it was defined as a high density forest. If the attribute table showed there were no trees in the study area, it was defined as no forest.

Table 3. Annual mean wind speed and potential value of the wind energy resource at 80 m above ground in Minnesota.

| Annual mean wind speed at 80 m | Indicated value of wind resource |
|---|---|
| <6.03 m/s | Poor (1) |
| 6.03-7.24 m/s | Good (2) |
| >7.24 m/s | Excellent (3) |

The “no forest” class was further divided into two subclasses. These were “Shrub Land and Grassland” and “Agricultural Vegetation.” The Ames Laboratory (2010) reported “wind turbines help channel beneficial breezes over nearby plants.” This can keep the crops cooler and drier, which helps them fend off fungal infestations. Meanwhile, the ability of crops to absorb carbon dioxide ($CO_2$) from the air and soil can be improved by wind turbines (Ames

Laboratory, 2010). Also, agricultural producers can generate additional revenue by using their land to generate wind energy (Rodman and Meentemeyer, 2006). Therefore, agricultural land was considered more suitable than general shrub land and grassland (Table 4).

Table 4. Land obstacles and corresponding suitability score.

| Obstacles | Suitability |
|---|---|
| High Density Forest | Poor (1) |
| Shrub Land & Grassland | Good (2) |
| Agricultural Vegetation | Excellent (3) |

Construction of turbines on slopes greater than 10% is difficult because the turbine components are generally large and heavy. If the slope is too steep, it limits the accessibility of the cranes needed to lift such heavy equipment (van Haaren and Fthenakis, 2011). Rodman and Meentemeyer (2006) classified the degree of slope further by dividing slope into several suitability classes (Table 5). This classification was adapted for the model used in this study.

Table 5. The slope degree intervals and corresponding suitability score (Rodman and Meentemeyer, 2006).

| Slope | Suitability |
|---|---|
| >30° | Unsuitable (NA) |
| 16-30° | Poor (1) |
| 7-16° | Good (2) |
| 0-7° | Excellent (3) |

Environmental Model

“Two general types of local impacts to birds have been demonstrated at existing wind facilities: (1) direct mortality from collisions and (2) indirect impacts from avoidance of an area, habitat disruption and behavioral effects” (National Wind Coordinating Collaborative (NWCC), 2010). Only direct mortality has been shown in bat populations (NWCC, 2010). Strategic placement of turbines away from important breeding grounds and high population areas can reduce their environmental impact (van Haaren and Fthenakis, 2011). Therefore, to prevent birds or bats from being killed by wind turbines, wind facilities need to be established as least 500 m from wildlife conservation areas or areas of known high use (Yue and Wang, 2006). The wildlife conservation area dataset was obtained from the MNDNR (2013). After converting the data format from vector to raster, a raster dataset depicting distance from wildlife conservation areas was developed. Then, the areas less than 500 m from wildlife conservation areas were designated as “Unsuitable Area” and the areas farther than 500 m from wildlife conservation areas as “Suitable Area”.

Although there are no strict regulations that dictate the appropriate distance to water bodies, Baban and Parry (2001) noted guidelines from 60 local authorities in the United Kingdom by means of a survey and determined a representative distance of 400 m to water bodies was recommended (van Haaren and Fthenakis, 2011). The water body dataset was derived from the National Gap Analysis Program (2001) Land Cover Data. This raster dataset included all open water in Minnesota, including wetlands, lakes, and rivers. Areas within 400 m from water bodies were defined as “Unsuitable Area” and the areas over 400 m from water bodies were defined as “Suitable Area”.

### Human Impact Model

In consideration of safety, visual pollution, and noise impact for humans, wind turbines should be placed away from populated areas. HGC Engineering (2007) conducted a summary of guidelines for the maximum sound pressure level in provinces of Canada in 2007. The level between 40 and 55 dB is considered an ideal range for human settlement within a distance of 500 m from wind turbines (HGC Engineering, 2007).

Public opposition to sight of wind turbines in recreational areas was taken into consideration in the human impact model by Rodman and Meentemeyer (2006). Therefore, a criterion that wind turbines be at least 1,000 m from public parkland was included. The parkland dataset was converted from vector format to raster format. Then, parkland and the areas within 1,000 m of parkland were defined as “Unsuitable Area”; the areas 1,000 m from parkland were defined as “Suitable Area”.

A goal of wind energy developers is to maximize profits for themselves and for investors (van Haaren and Fthenakis, 2011). Therefore, the utilization of the existing grid connections and roads is a critical element that needs to be considered in the human impact model. Baban and Parry (2001) included a maximum distance of 10 km to the electric grid as a criterion in their study. The electric transmission lines dataset was obtained from the Minnesota Land Management Information Center. Areas within 10 km of the electric grid were regarded as “Suitable Area”, and the remaining areas were regarded as “Unsuitable Area”. Additionally, since heavy cranes and trucks carrying components need to be navigated to the turbine sites, wind turbines should not be located farther than 10 km from roads (Baban and Parry, 2001). A dataset including all the major roads in Minnesota was obtained from the MNDNR. The areas less than 10 km from major roads were regarded as “Suitable Area”, and the remaining areas were regarded as “Unsuitable Area”.

### ***Model Integration***

The performance of wind turbines can be influenced by every factor discussed above; however, each factor presents an entirely different element of importance to the overall suitability measurement.

In the physical model, there were three components: average annual wind speed, obstacles, and terrain. A weighting scheme similar to the one used by Rodman and Meentemeyer (2006) was adopted. Since the availability of adequate wind resources is the most important criterion for the physical model, it was assigned the value of three as its weight. Because the sufficient wind resource is the most critical criterion compared to the presence of obstacles, the obstacle layer was assigned the lesser weight of two (Rodman and Meentemeyer, 2006). A weight of one was given to the terrain dataset. Terrain was considered only in terms of initial turbine construction suitability and not in regards to its impact on long-term operation; therefore, it was considered less critical than the wind resource and presence of obstacles.

The datasets were reclassified into several suitability categories or values, as described in Tables 3-5. To evaluate the physical model, not only the suitability score of each criterion was needed, but also the weight of each criterion's importance to the overall model. Thus, the equation from Rodman and Meentemeyer (2006) was used to evaluate the physical model as follows:

$$\bar{S} = \frac{\sum_{i}^{n} S_{ij} W_i}{\sum_{i}^{n} W_i},$$

where n is the number of input layers, $S_{ij}$ is the score for the $j$th class of the $i$th input layer, $W_i$ is the weights of the $i$th input layer, and $\bar{S}$ is the calculated suitability factor for each grid cell location in the model output. Each cell in the resulting raster dataset generated using the above equation had a value between one and three. If the calculated value equaled three, the corresponding suitability of the cell was classified as "excellent", since it has the best performance in every category. If the calculated value fell between two and three ($3 > \bar{S} \geq 2$), the suitability was considered "good"; if the calculated value was less than two, the suitability was regarded as "poor".

For the environmental model and human impact model, a binary scoring system was applied rather than a continuous system. The constraints, such as wildlife conservation areas, water bodies, populated areas, roads, grid lines, and state parkland, were used to further identify the locations where wind turbines are either suitable or not suitable. Therefore, there was no need to assign any score or weight for these layers. For the locations where the unsuitable factors were found, the cell in the resulting raster dataset was set to "0"; for the suitable areas, the cell was assigned the value "1".

A composite of all three suitability models was also generated. If any suitable area defined by the physical model corresponded with an area that had been recognized as unsuitable according to either the environmental or human impact model, then the overall suitability rating was considered to be "unsuitable" at that location, regardless of the score from the physical model and the area was removed from the resulting map.

## Result

A summary of the criteria for wind turbine placement included in the physical model, environmental model, and human impact model is shown in Table 6. The physical model encompassed the locations where there is sufficient wind, a flat gradient, and few obstacles. According to the result of the physical model (Figure 2), the most suitable areas are located in southwestern Minnesota. Abundant wind resources and the lack of vegetation obstacles in southwestern Minnesota were decisive characteristics. Areas of excellent physical suitability (score = 3) for large wind turbines contained 8,473,152.42 ha, good suitability (score = 2) contained 3,429,473.22 ha, and poor suitability (score = 1) contained 6,870,818.97 ha.

Figure 3 indicates the result of the environmental model. As explained earlier, wildlife conservation areas and open water areas were recognized as unsuitable areas for wind facilities due to environmental concerns and physical constraints. These layers were merged together to exclude any areas that were within a certain distance of wildlife conservation areas and open water (Figure 4).

Considering the aspects of accessibility and economy, only the areas within 10 km of major roads and energy lines were selected as suitable. Populated areas and state parkland were considered unsuitable due to noise and visual impact concerns.

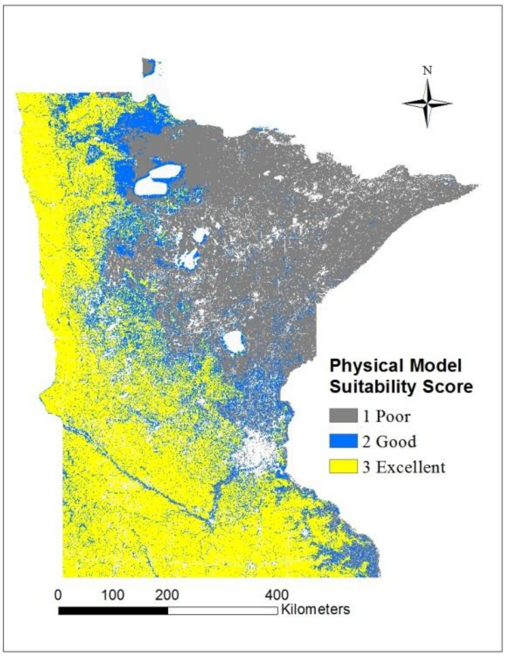

Figure 2. The suitability result of the physical model.

Table 6. Summary of wind farm location criteria.

| Objective | Criteria |
|---|---|
| Physical Model: | |
| 1. Wind Speed | Greater than 7.24 m/s at 80 m height |
| 2. Obstacle | Should be located in low vegetation area |
| 3. Terrain Slope | Should not be located in areas with steep slopes |
| Environmental Model: | |
| 1. Wildlife Conservation Areas | At least 500 m away from wildlife conservation areas |
| 2. Open Water | At least 400 m away from open water |
| Human Impact Model: | |
| 1. Populated Area | 500 m away from nearest populated area |
| 2. Road | Should not be located greater than 10 km from road |
| 3. Grid Line | Should not be located greater than 10 km from grid |
| 4. State Parkland | Should be located 1,000 m away from parkland |

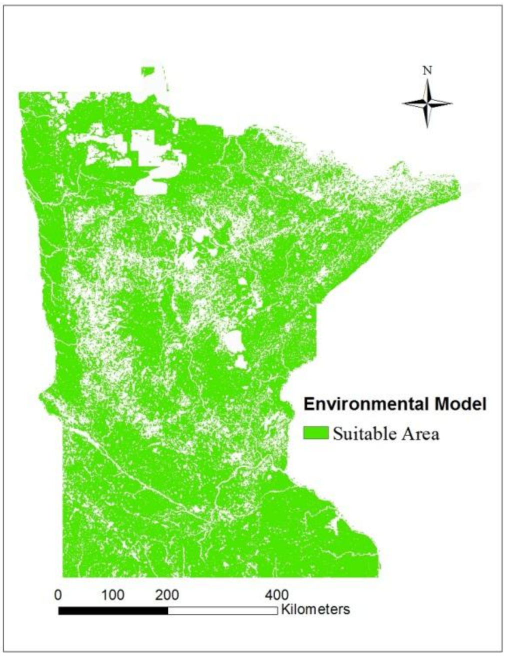

Figure 3. The suitable areas defined by the environmental model.

Combining the three models resulted in areas of suitable areas amassing 6,176,487.33 ha. This area only includes locations deemed to have excellent suitability (Appendix A).

## Discussion

The amount of remaining wind energy resources can be estimated using the model and mathematical deduction. Kimballa (2010) indicated a typical wind farm consists of approximately 15 wind turbines per 1,000 acres. By converting the acres to hectares, a large turbine usually occupies 27 ha. The Pipestone, Minnesota Chamber of Commerce (2013) has compiled data suggesting there are approximately 1,000 existing wind turbines in Minnesota.

If the area occupied by one wind turbine is 27 ha, 1,000 wind turbines will cover 27,000 ha. The suitability model concluded there are 6,176,487.33 ha areas suitable to build wind turbines. If areas occupied by existing wind turbines are subtracted, the remaining potential area is 6,149,487.33 ha.

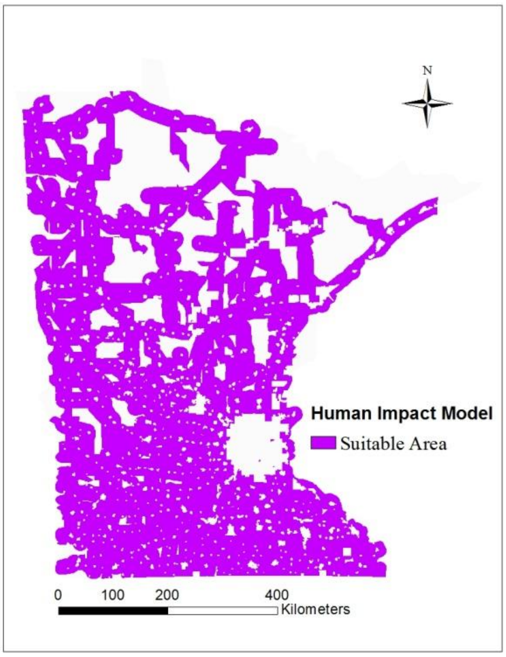

Figure 4. The suitable areas defined by the human impact model.

According to a study announced by the United States Department of Energy (2013), at the end of 2012 the installed capacity for wind power in Minnesota was 2,986 MW, with wind power accounting for 14.3% of the electricity generated in the state. Therefore, this model predicts that Minnesota has a potential capacity of 680,088 MW from wind power. If this amount of energy is developed, the fossil fuel power generation industry in Minnesota could be drastically reduced.

There are four large clustered wind farms in Minnesota. By comparing the results of this research with the existing wind farm locations shown in Appendix A, all existing wind farm locations fall within areas the model deemed suitable. In addition, these four wind farms (Buffalo Ridge Wind Farm, Fenton Wind Farm, Nobles Wind Farm, and Bent Tree Wind Farm) are generally distributed in the south and southwest portions of Minnesota. The western and mid-western areas of Minnesota also have vast potential for building wind turbines, especially the areas bordering North Dakota. Moreover, the overwhelming land use in these areas is farmland. Therefore, placing wind turbines there would neither jeopardize the ecological environment nor severely impact human life.

## Conclusion

The development of wind energy is one of the most important tasks for the future, not only because greenhouse gas emissions will likely continue to impact global warming, but also because fossil fuels, the most widely used energy source are limited in abundance.

Wind, an alternative energy source, is clean and widely distributed around the world. This research evaluated the suitability of building wind turbines in Minnesota. By integrating the corresponding criteria, three models related to physical, environmental, and human impact constraints were created. By using spatial analysis in a geographic information system, the models were combined to produce a final result of potential wind farm locations (Appendix A). The suitable areas for building wind turbines were generally aggregated in the southwest portion of Minnesota. Additionally, the part of western Minnesota that borders North Dakota and the southern portion that borders Iowa also has a high suitability for building wind turbines. The final model was verified by comparing the results to existing wind farm locations in Minnesota.

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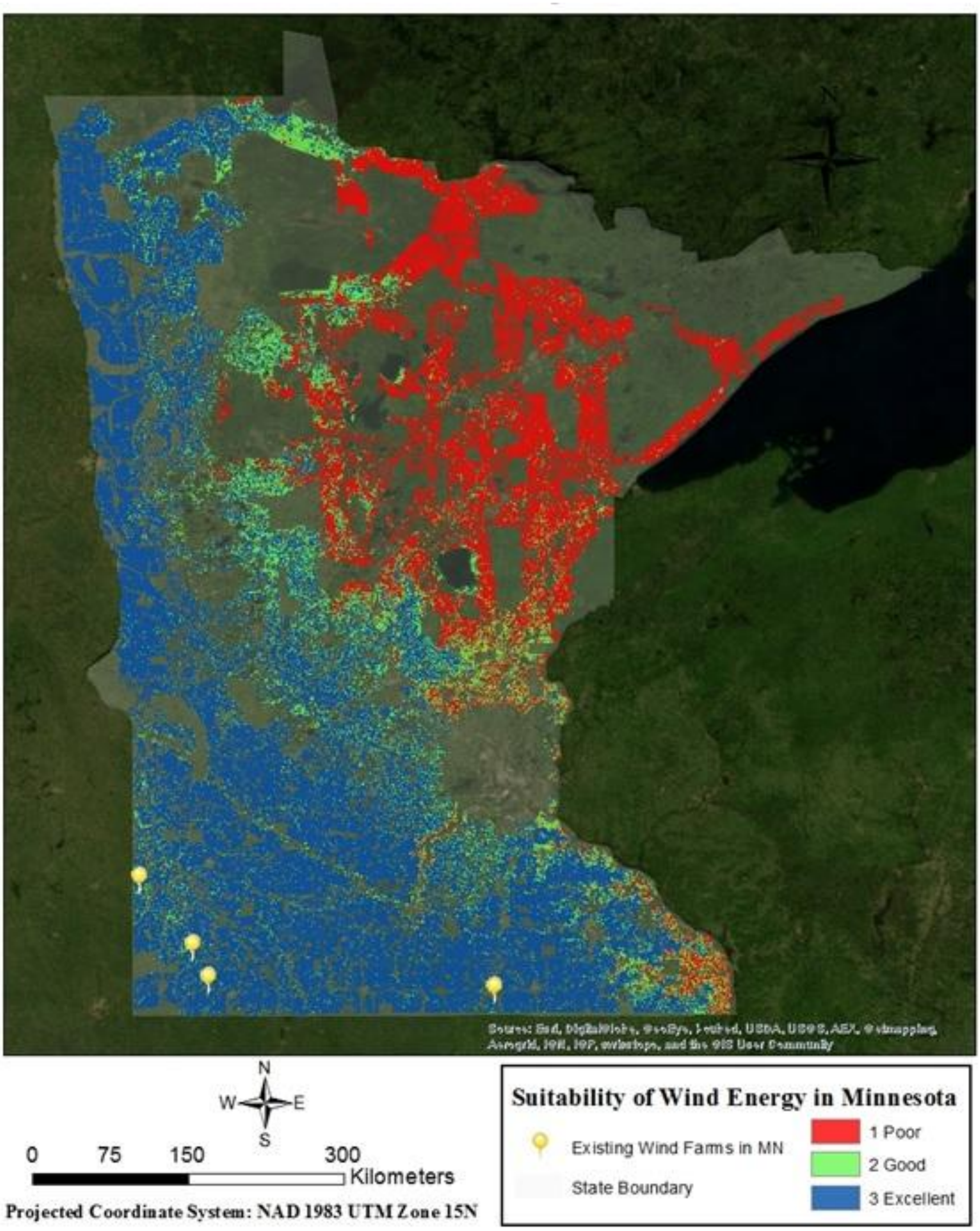
Appendix A. The Potential Suitable Areas for Building Wind Turbines in Minnesota.



Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community