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Using GIS to Determine Wind Harvesting Potential to Help Offset Boulder County's Yearly Energy Usage to Become a More Sustainable County

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This project focuses on Boulder County, Colorado as a case study to demonstrate how a Geographic Information System (GIS) can identify potential wind harvesting areas. A step by step demonstration will illustrate the steps needed to determine such harvesting areas and their wind potential. Once potential wind harvesting areas have been identified, concluding analysis will determine the amount of energy generated in efforts to offset current energy use. Harvesting wind has dated back to the 7th century and is looked at as a mature technology (Edwards 2003). Over the past few decades, public attitudes towards wind harvesting is becoming increasingly popular in efforts to become more sustainable. Boulder County's unique terrain and complex weather patterns creates a challenging case study to determine optimum locations to harvest wind. The results of this analysis will help to determine whether harvesting wind energy will in fact help offset the County's energy needs in efforts to becoming a more sustainable county.

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Capstone Project
for
Master of Science in Geographic Information System
May 2010

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Abstract

This project focuses on Boulder County, Colorado as a case study to demonstrate how a Geographic Information System (GIS) can identify potential wind harvesting areas. A step by step demonstration will illustrate the steps needed to determine such harvesting areas and their wind potential. Once potential wind harvesting areas have been identified, concluding analysis will determine the amount of energy generated in efforts to offset current energy use. Harvesting wind has dated back to the 7th century and is looked at as a mature technology (Edwards 2003). Over the past few decades, public attitudes towards wind harvesting is becoming increasingly popular in efforts to become more sustainable. Boulder County's unique terrain and complex weather patterns creates a challenging case study to determine optimum locations to harvest wind. The results of this analysis will help to determine whether harvesting wind energy will in fact help offset the County's energy needs in efforts to becoming a more sustainable county.

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Chapter 1
Introduction

1.1 Significance of this Study

The ability to integrate spatial information with statistical and analytical processes to derive spatial patterns not readily apparent to the observer is what makes GIS so powerful (Dempsey 2000). This project implements spatial wind potential data and analyzes optimal[1] wind harvesting locations to determine the amount of offsetting energy it can produce. This project demonstrates the steps taken to analyze wind data and determine potential wind power. Issues that evolved in this research while processing spatial data, such as available information and methodologies of processing the data will be addressed.

1.2 Objectives, Methodology and Structure

To understand the interaction between GIS and wind power data, we must first understand the technology and capabilities of GIS and how it can assist in determining optimal wind harvesting areas. This project relied on the use of ArcGIS with the extension tools 3D Analyst and Spatial Analyst to help determine geographic area of optimum wind potential. The objective of this project was to focus on the GIS processes and capabilities and how they can be used to help identify optimal wind harvesting areas. The methodology used existing wind power data available through the National

1 This project defines optimal as Wind Potential Classes (WPC) 4,5, 6 and 7

Renewable Energy laboratory (NREL) website for potential wind power and applied shapefile data sets obtained from the Boulder County government website for analysis such as critical wildlife areas and floodplains.

The structure of this project is divided into five chapters: Introduction, Data and Geographic Regions within the Study Area, Examinations of Wind Potential Data and Environmental Effects, Data Analysis and Interpretation of Results, and Final Considerations.

1.3 Literature Review

The literature surveyed demonstrates the consensus of authors agreed that harvesting wind energy is one of the most viable natural resources (Edwards 2003; Chiras 2009). Much has been written how the advantages of harvesting wind energy are totally non-polluting, abundant, natural, sustainable, safe and economically competitive with other renewable and conventional energy generation (Edwards 2003; Eckhart 2006; Nastu 2008). Some of the disadvantages of wind energy focused on negative perceptions, impacts on wildlife, and inadequate weather forecasting (Panjaitan 2005; Rosenbloom 2006; Yang 2009;). Some community concerns center around the issues of public safety and the noise wind turbines generate. Other issues include falling ice potential during the winter months, the threats to birds migrating over the diameter of the rotor, and whether or not wind turbines have a negative impact on wildlife. Most studies find that wind turbines do not impact grazing animals such as cattle, who appear to not be affected by the sight and sound (Edwards 2003). Occasionally wind turbines will kill birds and bats, but like any form of development, wind projects can also negatively impact wildlife by altering habits (Department of Energy 2010). A Wisconsin wind farm indicated that wind turbines were affecting local weather radar and disrupting television signals (Williams 2009). Since this small wind farm was clearly to blame, the false weather reports were disregarded (Williams 2009).

1.4 Wind Energy Background

Wind energy is one of the fastest growing sources of electricity in the world today. Due to technological advances, policy initiatives, and economic drivers, wind energy is now able to make a cost-competitive contribution to our growing energy needs (Wind Industry 2010). Wind energy is looked at as a mature technology which dates back to the 7th century. Persians harvested wind energy for pumping water and grinding corn as a part of their daily routines (Edwards 2003). During the 11th century, windmills were used extensively in the Middle East in the production of food (The Solar Guide 2010). Most notably, the Dutch used windmills for pumping and draining of water in marshes and lakes. In the 1970's, during the "Arab Oil Crisis" the US Government stepped up its efforts in developing and implementing large multi-megawatt wind turbines to generate electricity (The Solar Guide 2010). During the 1980's and 1990's, the economic recession hurt funding and incentives for renewable energy as a whole. Also during this time, oil prices stabilized. During the Clinton administration, a promotion of "green power" was enacted and a number of wind energy project were approved. In a time when coalfields are depleting, fossil fuels are rapidly adding more and more carbon emissions into the atmosphere and foreign oil is becoming more expensive and less politically stable the momentum is rapidly shifting towards the use and implementation of wind energy.

1.5 Boulder County as a Case Study

This project uses Boulder County, Colorado as a case study due to its unique terrain, complex weather patterns and progressive initiatives. Boulder County is uniquely situated where the Great Plains meet the Rocky Mountains creating a multitude of potential wind harvesting locations. Elevations start at 4,880 feet AMSL (above mean sea level) in the eastern plains and peaking at 14,225 feet AMSL at Long's Peak. The diverse mountainous terrain creates a unique topography for wind swept canyons and gusty plains. Complex weather patterns often develop due to the influence of the jet stream's interactions with the continental divide. Boulder County is located close to the Denver Convergence Vorticity Zone (DCVZ) an area where the winds converge during the summer afternoons creating turbulent winds (Nelson 2007) NREL created a dataset (shapefile format) that illustrates such complex wind patterns and will be used extensively during this project to demonstrate area for optimal wind harvesting potential.

1.5.1 Project Area Map

The scope of this project focused on the Boulder County jurisdiction. Figure 1 illustrates the diverse mountainous terrain and city landscapes along the plains.

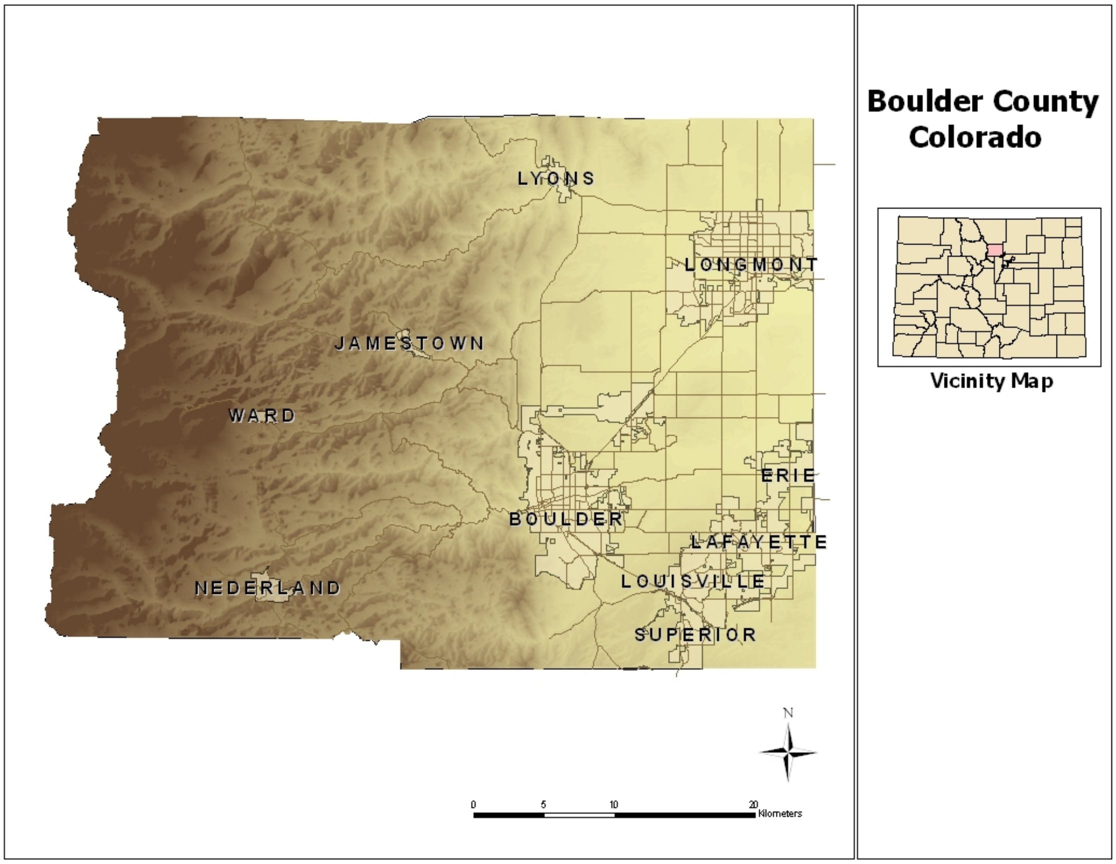

Figure 1. Project Area, (http://www.spatialinsights.com; http://www.bouldercounty.org; Coventry 2010)

Chapter 2
Data and Geographic Regions within the Study Area

2.1 Background

A geographic information system (GIS) integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information (ESRI 2010). Such a tool allowed for detailed analysis of wind harvesting potential. The following chapter details the steps taken to establish a working area within GIS to examine determine wind harvesting potential in Boulder County, Colorado.

2.2 Data Collection

The data collection approach to this project was based on quantitative methods and gathering secondary data. Data was readily available on public and private sector websites and downloaded from the Internet. This project displays each piece of data used in a detailed step-by-step approach.

Data Dictionary

Theme	Data Type	Projection	Source
Boulder County Digital Elevation Model	Raster	GCS_WGS_1984	Spatial Insights, Inc. - http://www.spatialinsights.com/catalog
Boulder County Jurisdiction Boundary	Line	Lambert Conformal Secant Cone	Boulder County Geographic Information Services - http://www.bouldercounty.org/gis/downloads
Colorado County Boundaries	Polygon	GCS North American 1983	Colorado Division of Local Government -http://www.dola.state.co.us/oem/cartography/datasset.htm
Critical Wildlife	Polygon	Lambert Conformal Secant Cone	Boulder County Geographic Information Services - http://www.bouldercounty.org/gis/downloads
Flood Plains	Polygon	Lambert Conformal Secant Cone	Boulder County Geographic Information Services - http://www.bouldercounty.org/gis/downloads
Major Roads	Line	Lambert Conformal Secant Cone	Boulder County Geographic Information Services - http://www.bouldercounty.org/gis/downloads
Municipalities	Polygon	Lambert Conformal Secant Cone	Boulder County Geographic Information Services - http://www.bouldercounty.org/gis/downloads
NREL Wind Potential	Polygon	GCS WGS 1984	National Renewable Energy laboratory - http://www.nrel.gov

Table 1. Data Dictionary, (http://www.spatialinsights.com; http://www.bouldercounty.org; http://www.nrel.gov; http://www.dola.state.co.us; Coventry 2010)

This project uses the National Renewable Laboratory's (NREL) Wind Potential shapefile data to identify optimal wind harvesting locations within Boulder County. This shapefile was created with collaboration with AWS Truewind in order to provide wind potential estimates for the state of Colorado. To produce the new wind potential estimates, NREL estimated the windy land area and wind energy potential in various capacity factor ranges for each state using the gross capacity factor data from *windNavigator* (AWS True Wind 2010). NREL reduced the wind potential estimates by excluding areas unlikely to be developed such as wilderness areas, parks, urban areas, and water features (AWS True Wind 2010). The shapefile uses wind data at a height of 50 meters above ground, during the year 2003.

NREL uses a wind class potential density that will serve as a benchmark throughout this project.

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m ^{2}	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
1	Poor	0 - 200	0.0 - 5.9	0.0 - 13.2
2	Marginal	200 - 300	5.9 - 6.7	13.2 - 15.0
3	Fair	300 - 400	6.7 - 7.4	15.0 - 16.6
4	Good	400 - 500	7.4 - 7.9	16.6 - 17.7
5	Excellent	500 - 600	7.9 - 8.4	17.7 - 18.8
6	Outstanding	600 - 800	8.4 - 9.3	18.8 - 20.8
7	Superb	> 800	> 9.3	> 20.8

[a] Wind speeds are based on a Weibull k of 2.0 at 1500 m elevation.

Source: National Renewable Energy Laboratory, 2003

Table 2. Wind Power Classification

2.3 Reliability & Validity

The data collected for this project was gathered from two main sources: the National Renewable Energy laboratory (NREL) and the Boulder County Government website. Data taken from these sites, in the shapefile format, are the most current and up-to-date files available for public use and therefore suitable for this project.

2.4 Geographic Regions

For this project, the Boulder County study area was divided into three geographic regions: Mountains, Cities, and Plains. These unique geographic regions were created to demonstrate how different regions are able to harvest wind for personal use and/or tie back into the electrical grid. Each geographic region has unique wind potential and therefore has specific wind turbine needs such as size and location.

Each geographic region was created through a process of grouping similar geographic characteristics. The Mountain Region was created by selecting a contour line dividing the Front Range. This contour line includes all of the mountainous regions above 1,900 meters (approximately 6,233 feet AMSL), including mountain communities such as Nederland, Ward and Allenspark. The Cities Region was created by selecting all of the Front Range cities within the Boulder County jurisdiction: Boulder, Erie, Lafayette, Longmont, Louisville, Lyons and Superior. The Plains Region was created by including all of the unincorporated areas east of the 1,900 meter contour line and excluding the Front Range cities. Figure 2 illustrates the three regions in this project.

Figure 2. Geographic Regions, (http://www.spatialinsights.com; http://www.bouldercounty.org; Coventry 2010)

Chapter 3
Examination of Wind Potential Data and Environmental Effect

In order to examine wind potential at the Boulder County jurisdiction and case study level, NREL's Wind Potential shapefile was clipped from the original state wide level. To extract Boulder County wind potential data, the use of ArcGIS's Clip tool needed to be employed as illustrated in Figure 3.

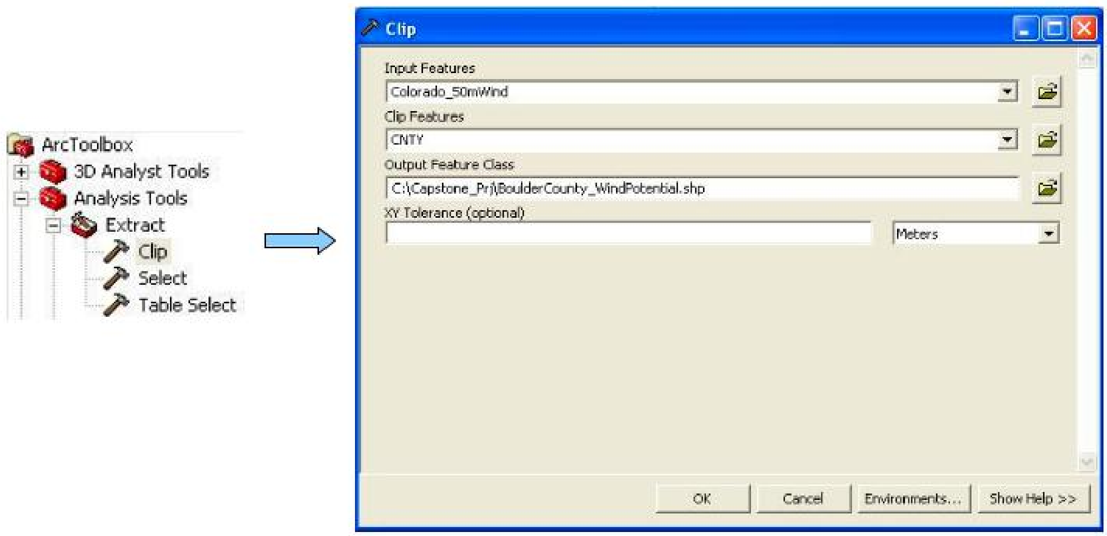

Figure 3. NREL's Wind Potential shapefile Clip, (Coventry 2010)

The resulting shapefile includes all wind potential data within the Boulder County jurisdiction. This project will now refer to this shapefile as the BOCO WPC.

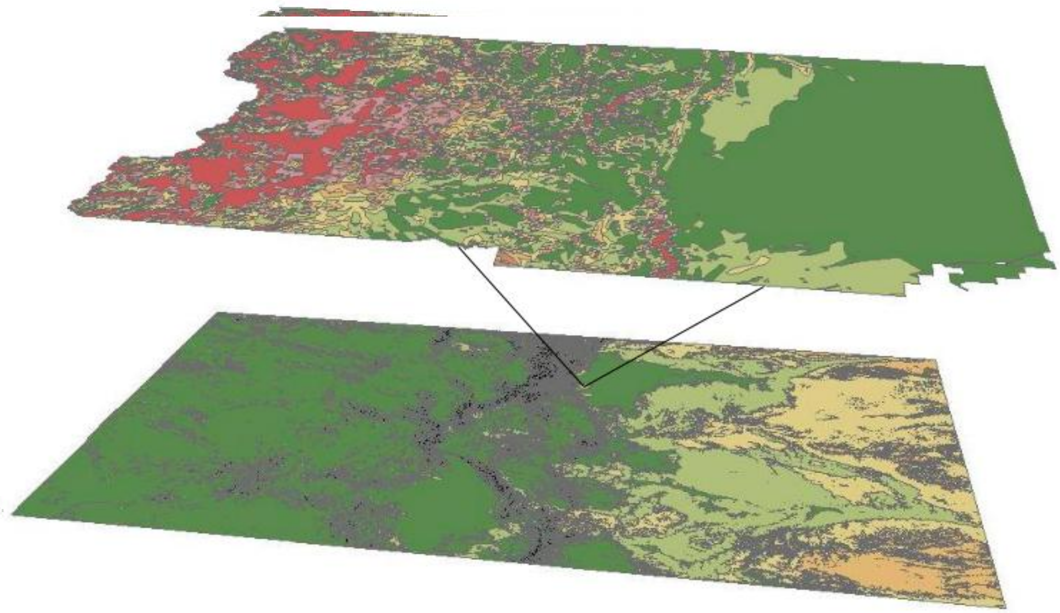

Figure 4. NREL Wind Potential Extraction of Boulder County, (Coventry 2010)

This project uses the BOCO WPC shapefile as a basis for analysis pertaining to wind potential, environmental effects and offsetting energy.

3.3 Assessment of Environmental Effects

The BOCO WPC shapefile serves as a basis for analyzing environmental effects within optimum wind harvesting area in the project area. Shapefile data sets were added to the BOCO WPC to illustrate the total geographic regions affected by each restriction.

3.2.1 Critical Wildlife Area

The Critical Wildlife Area shapefile was created by the Boulder County Land Use department in efforts to locate and protect critical wildlife habitats within the Boulder County jurisdiction. The shapefile contains metadata that identifies 58 habitats ranging from Greenback Cutthroat trout, elk, prairie dog colonies, and Fox Sparrows. Each of these habitats have detailed attributes of designation descriptions, key species, habitat descriptions and land ownership.

Birds occasionally collide with wind turbines, as they do with other tall structures such as buildings (American Wind Energy Association 2010). Detailed studies, and monitoring following construction, at other wind development areas indicate that this is a site-specific issue that will not be a problem at most potential wind sites (American Wind Energy Association 2010). Also, wind's overall impact on birds is low compared with other human-related sources of avian mortality (American Wind Energy Association 2010). Such interaction with birds are illustrated in Table 3.

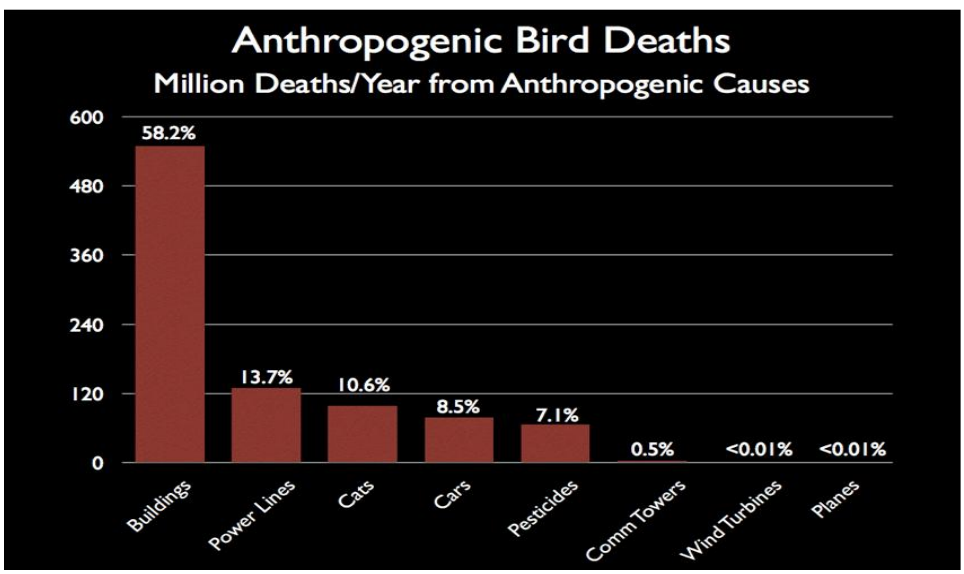

Table 3. Anthropogenic Bird Deaths (Source: www.lotuslive.org/energy/wind.php)

To compare the Critical Wildlife shapefile with the BOCO WPC shapefile a union of the two shapefiles was conducted. The results of the union created a new shapefile with both attributes merged into one. After the union was conducted, the geographic areas attributed needed to be updated to reflect the new calculations within the geographic region. To perform this task, the Calculate Geometry tool was utilized to correctly calculate each geographic area.

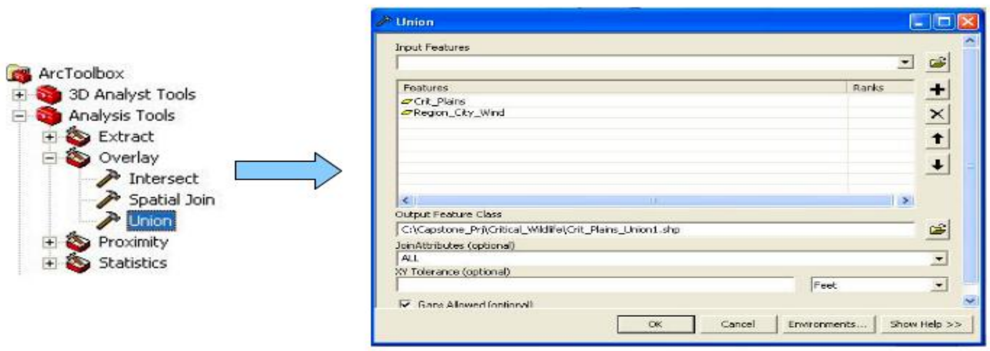

Figure 5. Critical Wildlife Union, (Coventry 2010)

The outcomes are as follows:

City Region

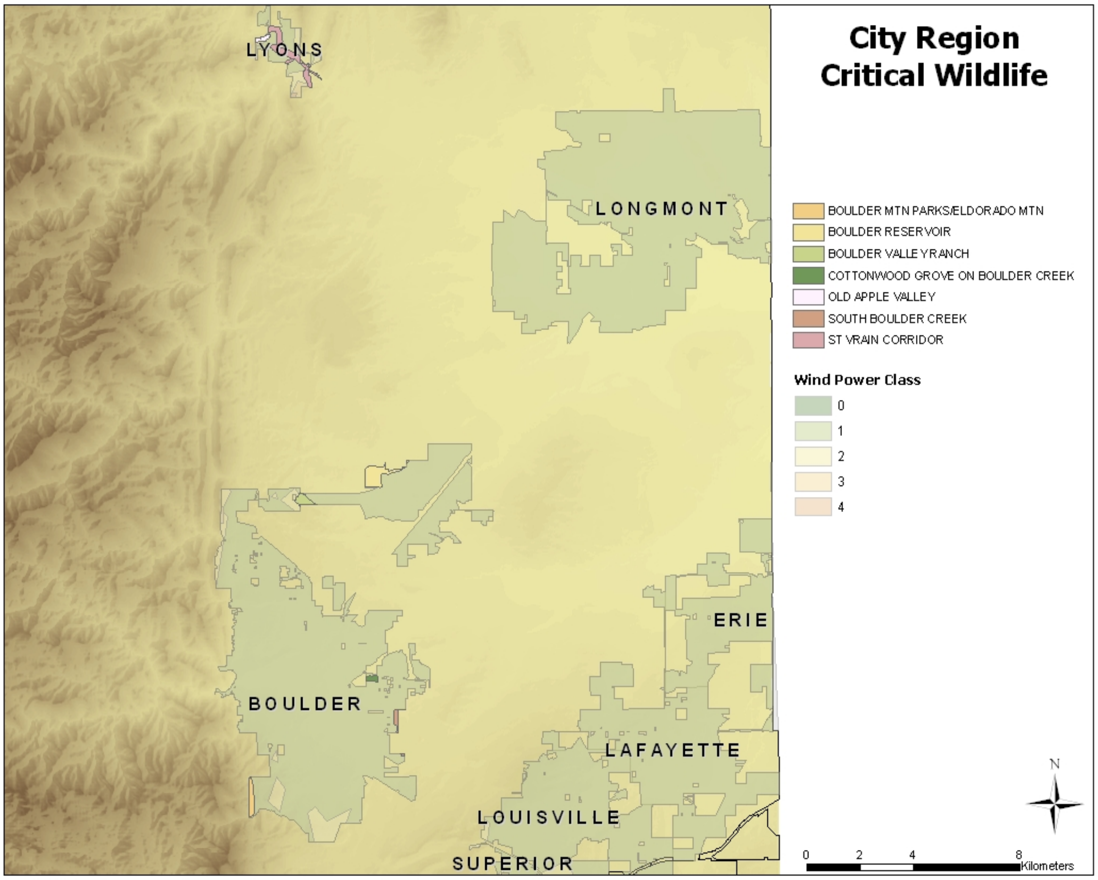

Figure 6. City Region Critical Wildlife, (http://www.spatialinsights.com; http://www.bouldercounty.org; Coventry 2010)

Figure 6 illustrates that there are a few critical wildlife area within the City Region of the project area. Since there are no optimal wind potential in the city, there are no conflicts between these two issues.

Plains Region

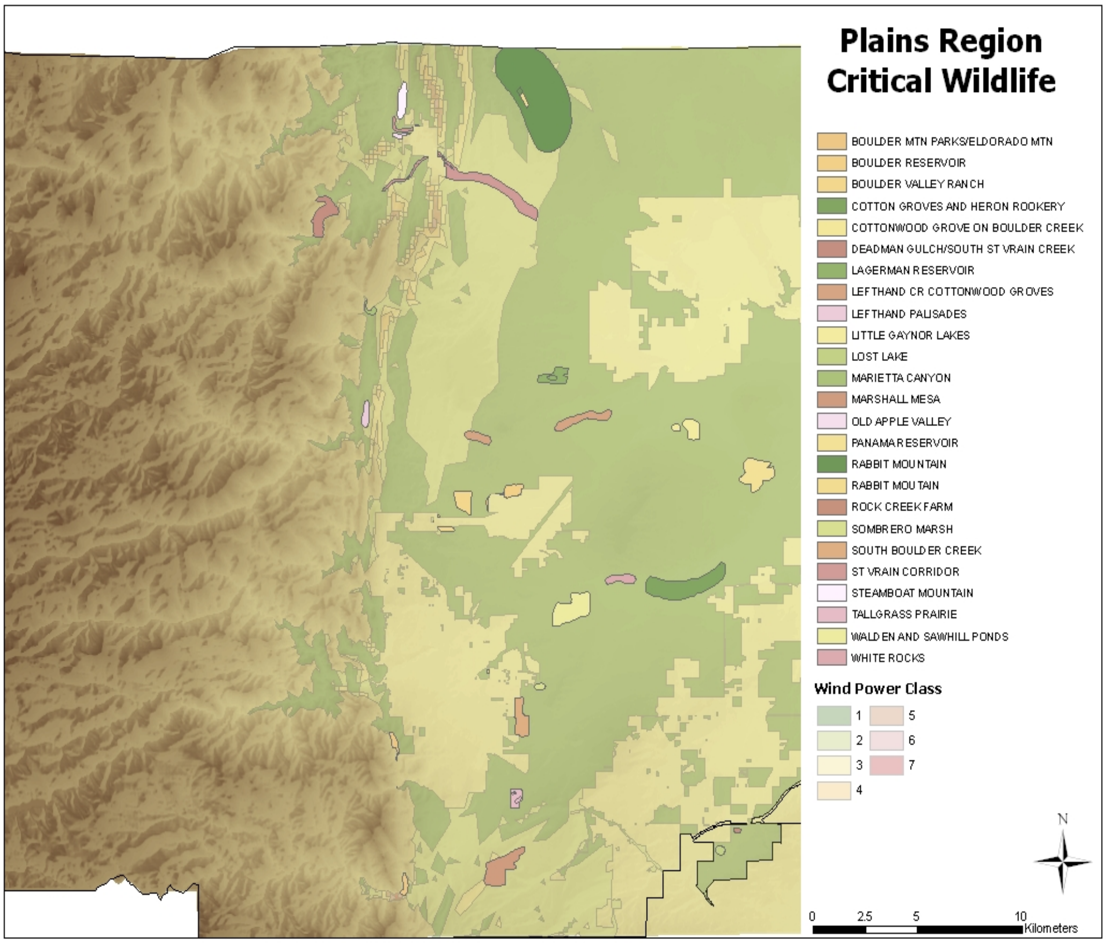

Figure 7. Plains Region Critical Wildlife, (http://www.spatialinsights.com; http://www.bouldercounty.org; Coventry 2010)

Figure 7 illustrates that there are a several critical wildlife area within the Plains Region of the project area. Since there are optimal wind potential in the plains, conflicts exist between these two issues. Table 4 details the critical wildlife and the geographic area affected by the wildlife areas.

CRITICAL WILDLIFE AREA	WPC	Acres Calc	Region
BOULDER MTN PARKS/ELDORADO MTN	6	1.94	Plains
BOULDER MTN PARKS/ELDORADO MTN	5	2.97	Plains
BOULDER MTN PARKS/ELDORADO MTN	4	3.67	Plains
DEADMAN GULCH/SOUTH ST VRAIN CREEK	4	1.75	Plains
RABBIT MOUNTAIN	4	20.3	Plains
		Total = 30.62	

Table 4. Plains Region Critical Wildlife Summary, (http://www.spatialinsights.com; http://www.bouldercounty.org; Coventry 2010)

Mountain Region

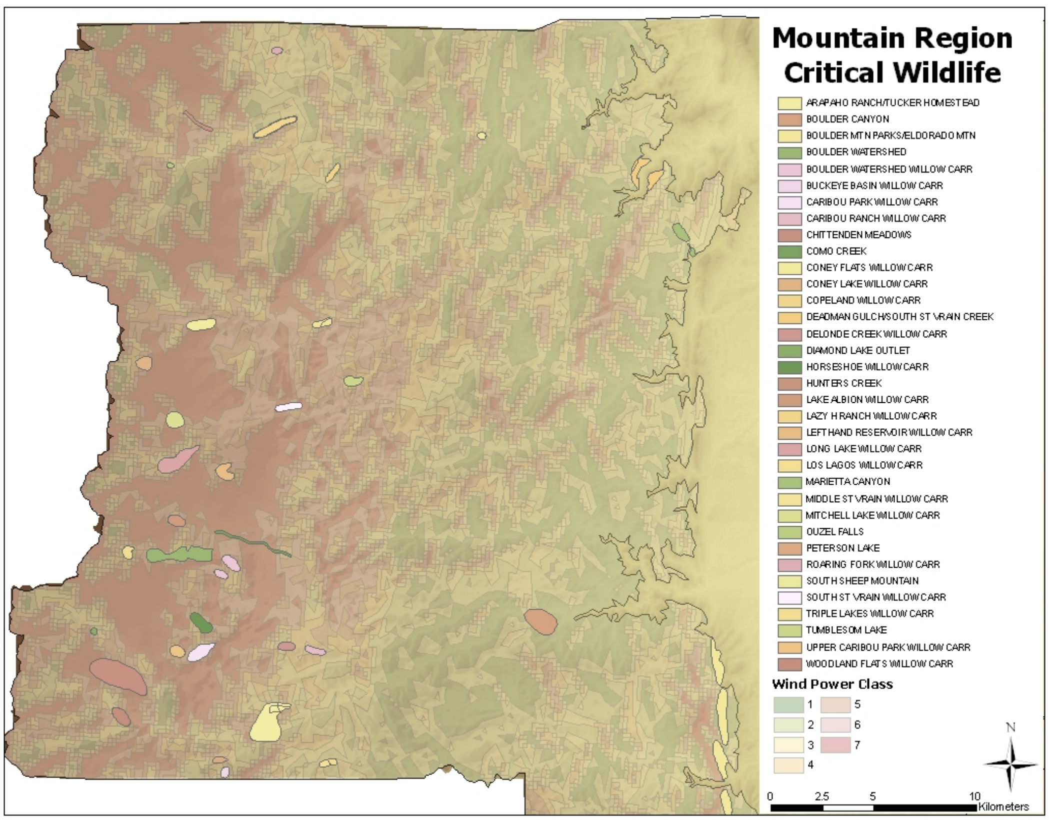

Figure 8. Mountain Region Critical Wildlife, (http://www.spatialinsights.com; http://www.bouldercounty.org; Coventry 2010)

Figure 8 illustrates that there are a several critical wildlife area within the Mountain Region of the project area. Since the majority of the optimal wind potential areas are located within this region, there is a greater number of conflicts between the Critical Wildlife areas. Table 5 details the critical wildlife and the geographic region they encompass.

CRITICAL WILDLIFE AREA	WPC	Acres_Calc	Region
ARAPAHO RANCH/TUCKER HOMESTEAD	7	6.09	Mountains
BOULDER MTN PARKS/ELDORADO MTN	7	19.24	Mountains
BOULDER WATERSHED	7	111.26	Mountains
BOULDER WATERSHED WILLOW CARR	7	4.33	Mountains
CARIBOU PARK WILLOW CARR	7	3.88	Mountains
CHITTENDEN MEADOWS	7	470.03	Mountains
COMO CREEK	7	84.53	Mountains
CONEY FLATS WILLOW CARR	7	90.16	Mountains
HORSESHOE WILLOW CARR	7	0.84	Mountains
HUNTERS CREEK	7	10.2	Mountains
LAKE ALBION WILLOW CARR	7	3.01	Mountains
LONG LAKE WILLOW CARR	7	1.44	Mountains
MIDDLE ST VRAIN WILLOW CARR	7	0.22	Mountains
MITCHELL LAKE WILLOW CARR	7	27.13	Mountains
SOUTH ST VRAIN WILLOW CARR	7	46.51	Mountains
UPPER CARIBOU PARK WILLOW CARR	7	0.01	Mountains
WOODLAND FLATS WILLOW CARR	7	7.53	Mountains
ARAPAHO RANCH/TUCKER HOMESTEAD	6	7.37	Mountains
BOULDER MTN PARKS/ELDORADO MTN	6	18.33	Mountains
BOULDER WATERSHED	6	106.92	Mountains
BOULDER WATERSHED WILLOW CARR	6	63.12	Mountains
CARIBOU PARK WILLOW CARR	6	29.68	Mountains
CHITTENDEN MEADOWS	6	208	Mountains
COMO CREEK	6	0.6	Mountains
CONEY FLATS WILLOW CARR	6	88.45	Mountains
CONEY LAKE WILLOW CARR	6	21.56	Mountains
COPELAND WILLOW CARR	6	4.12	Mountains
DIAMOND LAKE OUTLET	6	0.67	Mountains
HORSESHOE WILLOW CARR	6	41.59	Mountains
HUNTERS CREEK	6	31.86	Mountains
LAKE ALBION WILLOW CARR	6	71.25	Mountains
LEFTHAND RESERVOIR WILLOW CARR	6	31.04	Mountains
LONG LAKE WILLOW CARR	6	17.9	Mountains
MIDDLE ST VRAIN WILLOW CARR	6	49.75	Mountains
MITCHELL LAKE WILLOW CARR	6	111.64	Mountains
OUZEL FALLS	6	1.76	Mountains
SOUTH SHEEP MOUNTAIN	6	7.51	Mountains
SOUTH ST VRAIN WILLOW CARR	6	42.41	Mountains
TUMBLESOM LAKE	6	7.78	Mountains
UPPER CARIBOU PARK WILLOW CARR	6	23.03	Mountains
WOODLAND FLATS WILLOW CARR	6	11.07	Mountains
ARAPAHO RANCH/TUCKER HOMESTEAD	5	37.72	Mountains
BOULDER MTN PARKS/ELDORADO MTN	5	22.55	Mountains
BOULDER WATERSHED	5	92.72	Mountains
BOULDER WATERSHED WILLOW CARR	5	36.18	Mountains
CARIBOU PARK WILLOW CARR	5	47.54	Mountains
CHITTENDEN MEADOWS	5	17.35	Mountains
COMO CREEK	5	9.66	Mountains
CONEY FLATS WILLOW CARR	5	31.18	Mountains
COPELAND WILLOW CARR	5	0.43	Mountains
DEADMAN GULCH/SOUTH ST VRAIN CREEK	5	11.66	Mountains
DELONDE CREEK WILLOW CARR	5	5.52	Mountains
HORSESHOE WILLOW CARR	5	28.02	Mountains
HUNTERS CREEK	5	24.35	Mountains
LAKE ALBION WILLOW CARR	5	7.77	Mountains
LEFTHAND RESERVOIR WILLOW CARR	5	66.2	Mountains
MIDDLE ST VRAIN WILLOW CARR	5	11.55	Mountains
OUZEL FALLS	5	3.8	Mountains
SOUTH SHEEP MOUNTAIN	5	16.31	Mountains
SOUTH ST VRAIN WILLOW CARR	5	6.13	Mountains
TUMBLESOM LAKE	5	10.25	Mountains
UPPER CARIBOU PARK WILLOW CARR	5	37.86	Mountains
WOODLAND FLATS WILLOW CARR	5	16.86	Mountains
ARAPAHO RANCH/TUCKER HOMESTEAD	4	64.1	Mountains
BOULDER MTN PARKS/ELDORADO MTN	4	10.97	Mountains
BOULDER WATERSHED	4	88.58	Mountains
BOULDER WATERSHED WILLOW CARR	4	35.36	Mountains
CARIBOU RANCH WILLOW CARR	4	37.75	Mountains
CHITTENDEN MEADOWS	4	5.55	Mountains
COMO CREEK	4	9.49	Mountains
CONEY LAKE WILLOW CARR	4	24.9	Mountains
COPELAND WILLOW CARR	4	54.7	Mountains
DEADMAN GULCH/SOUTH ST VRAIN CREEK	4	32.81	Mountains
DELONDE CREEK WILLOW CARR	4	21.41	Mountains
HORSESHOE WILLOW CARR	4	31.93	Mountains
LAKE ALBION WILLOW CARR	4	5	Mountains
LEFTHAND RESERVOIR WILLOW CARR	4	24.6	Mountains
LONG LAKE WILLOW CARR	4	10.12	Mountains
MARIETTA CANYON	4	6.09	Mountains
MIDDLE ST VRAIN WILLOW CARR	4	9.83	Mountains
OUZEL FALLS	4	7.63	Mountains
SOUTH SHEEP MOUNTAIN	4	6.91	Mountains
TRIPLE LAKES WILLOW CARR	4	2.46	Mountains
TUMBLESOM LAKE	4	61.43	Mountains
UPPER CARIBOU PARK WILLOW CARR	4	8.91	Mountains
WOODLAND FLATS WILLOW CARR	4	70.02	Mountains
		Total = 3,055.96	

Table 5. Mountain Region Critical Wildlife Summary, (http://www.spatialinsights.com; http://www.bouldercounty.org; Coventry 2010)

3.2.2 Floodplains

An analysis of floodplains within the project area were examined (Figure 9). If optimal wind harvesting locations were identified within a floodplain, then the site would not be a viable location due to the potential hazard. For this analysis, the Floodplains shapefile was added to the BOCO WPC. An arbitrary buffer was added to the Floodplains layer by adding 200 meter in either direction of the polygon. This arbitrary buffer was added to ensure adequate locations were identified. Table 6 identifies optimal wind areas affected by the 200 meter buffer.

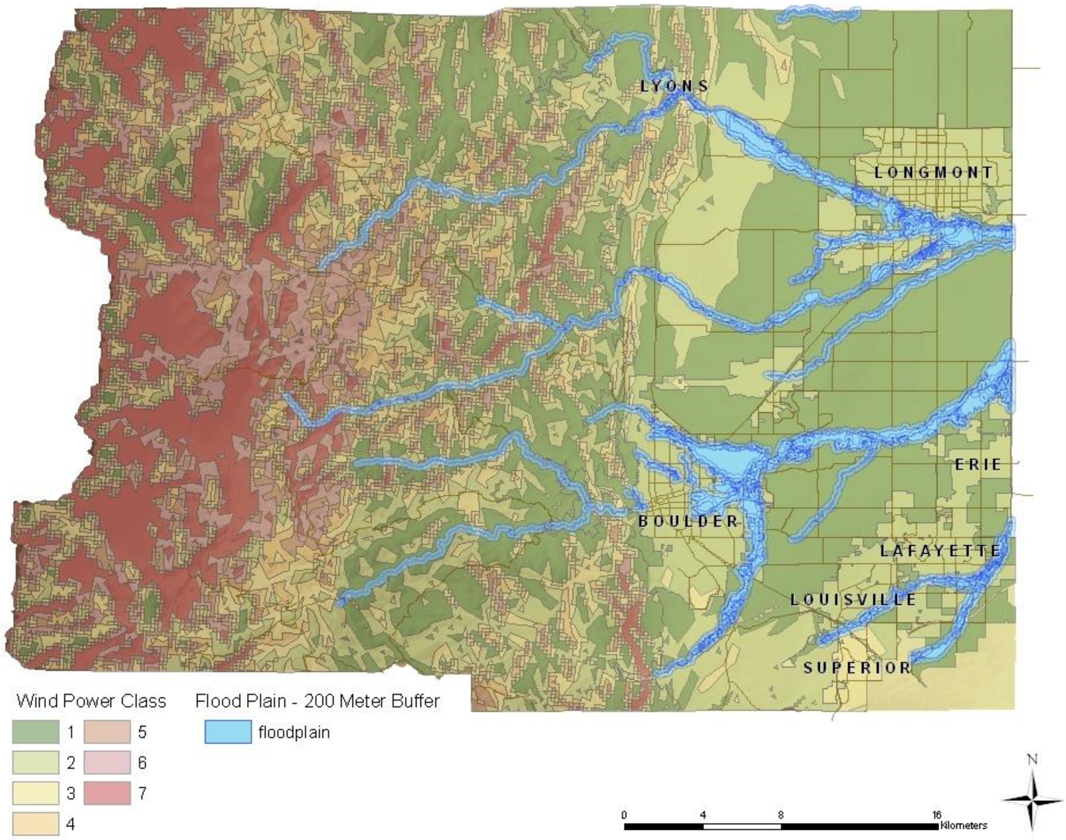

Figure 9. Flood Plain, (http://www.spatialinsights.com; http://www.bouldercounty.org; Coventry 2010)

Optimal wind areas affected by 200 meter buffer along floodplains in the project area:

WPC	Acres_Calc	Region
7	1100.47	Mountains
6	577.92	Mountains
5	702.51	Mountains
4	1244.12	Mountains
4	25.01	Plains

Table 6. Flood Plain Summary, (http://www.spatialinsights.com; http://www.bouldercounty.org; Coventry 2010)

3.2.3 Urban Constraints

There are several factors that could influence wind harvesting within urbanized areas. Such factors include: the size of the wind turbine, noise it creates, proximity to the electrical grid, environmental impact on birds, falling ice from a standing blade and overall community approval. The BOCO WPC analysis determined that no optimal wind potential is found in the City Region. For this project, there are no urban constraints.

3.2.4 Slope

A slope analysis was considered in the project to determine the amount of slope within the project area. If optimal wind potential areas are determined, but severe slope exists, then the development and implementation of a wind farm may become costly, inaccessible and ultimately not viable. Wind turbines have been developed along steep slopes for the purposes of adequate wind production, but this slope analysis will merely point out the percent of slope as a deciding factor whether or not the site would be viable.

To determine slope, this project examined the Boulder County raster dataset and by using the Slope tool within the Spatial Analyst extension and applied a percentage of slope. The resulting dataset illustrates percentage of slope county wide (Figure 10).

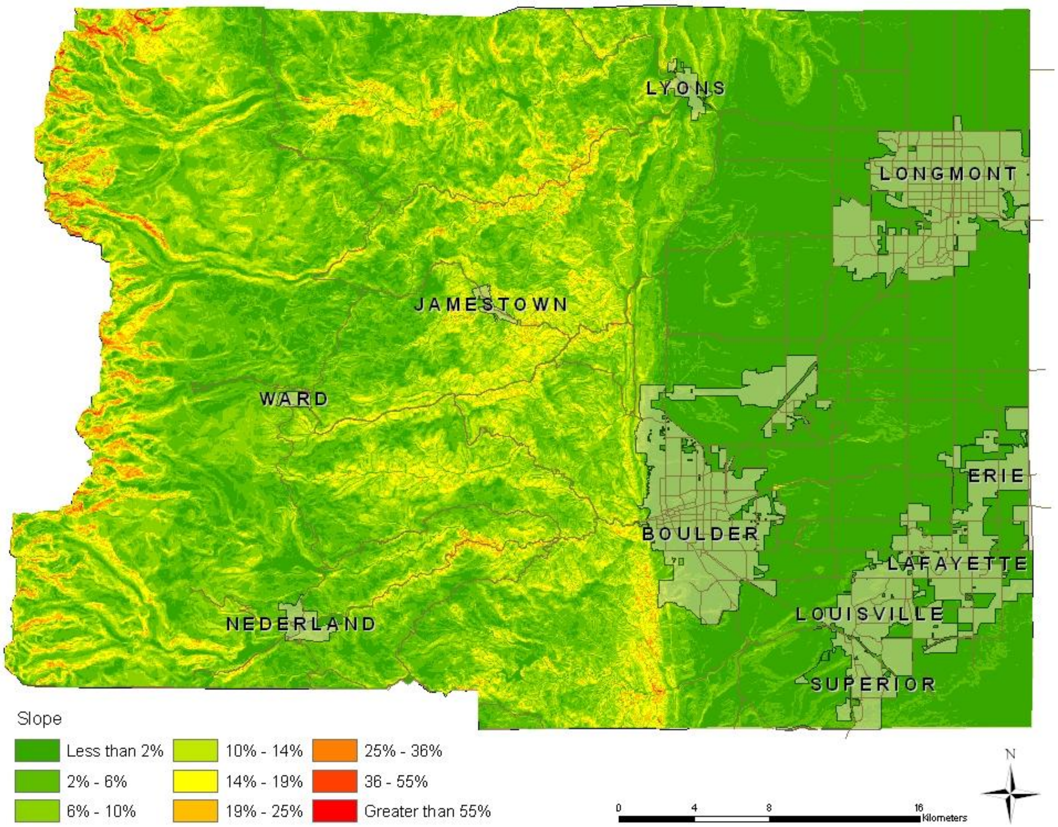

Figure 10. Slope, (http://www.spatialinsights.com, http://www.bouldercounty.org, Coventry 2010)

3.2.5 Energy Grid

The proximity of the electrical grid in relation to optimal wind harvesting sites is an important relationship to determine when proposing a wind turbine site. Distance from a grid-tied wind turbine would ultimately become costly and not feasible. Figure 11 illustrates a 10 kilometer buffer surrounding the electrical grid in relation to optimal wind harvesting sites. Figure 12 has a larger buffer extending to 20 kilometers surrounding the electrical grid and encompassing a greater amount of wind harvesting area.

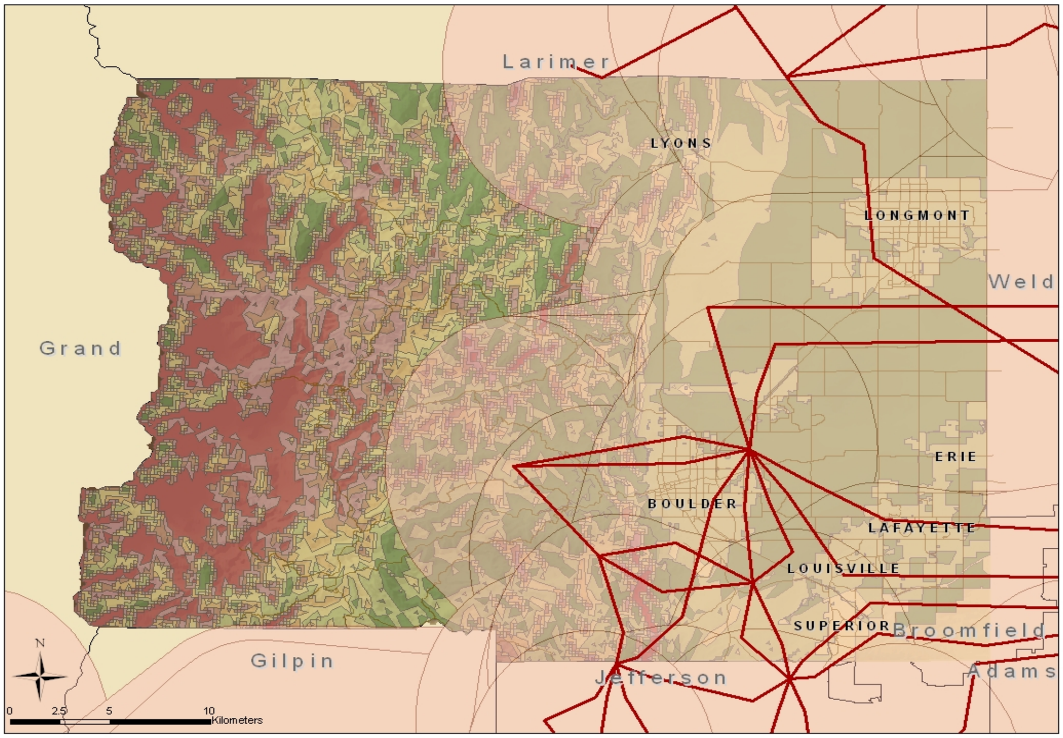

Figure 11. Energy Grid 10KM Buffer, (http://www.spatialinsights.com, http://www.bouldercounty.org, Coventry 2010)

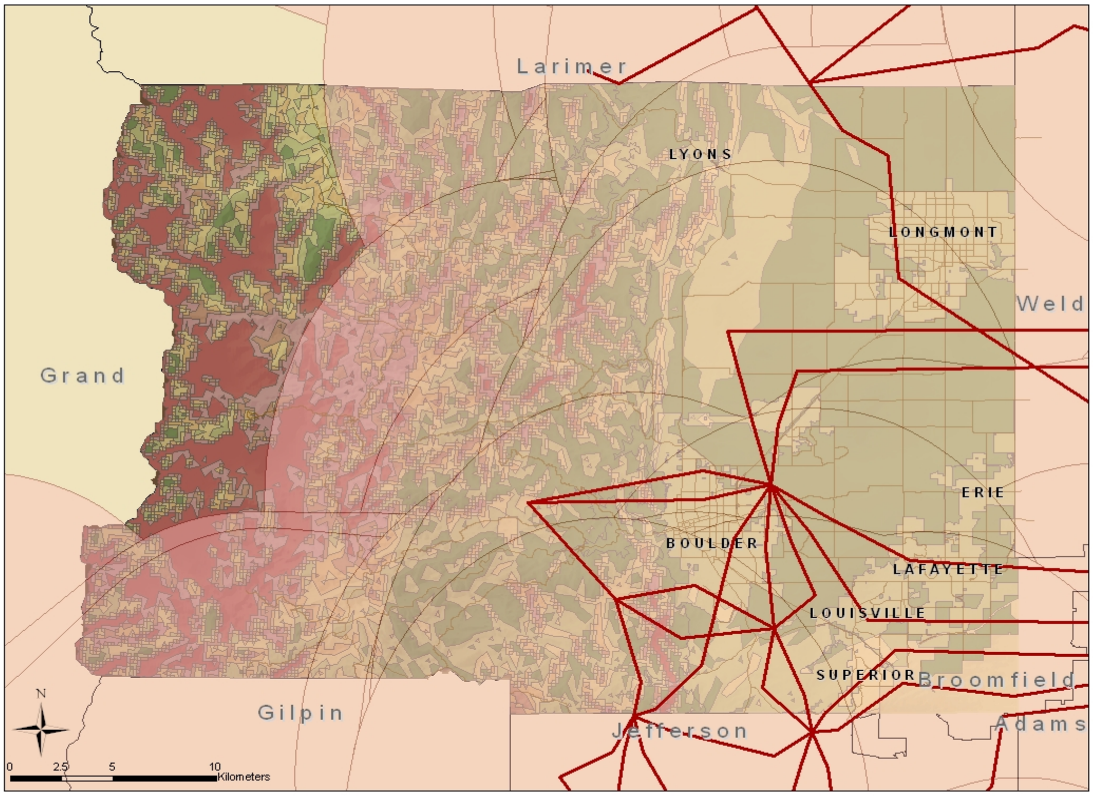

Figure 12. Energy Grid 20KM Buffer, (http://www.spatialinsights.com, http://www.bouldercounty.org, Coventry 2010)

3.3 Alternative Wind Energy Views Using ArcToolBox

There are several ways to illustrate data within a GIS to help support a research topic. The method this research project chose was to utilize the ArcToolBox in ArcGIS. ArcToolBox is a location to search and manage geoprocessing tools. The GIS end user may have different tools available depending on which version of GIS they're using. This research project utilized the Kernel Density and 3D Analyst tools.

Kernel Density

An alternative way to illustrate the distribution of high WPC's within the study area is to employ the Kernel Density tool in GIS. This tool calculates the density per unit area to illustrate 'hot spots' of high density points or line features. Since the BOCO WPC file is currently in a shapefile format, it was required to convert the data to a point feature in order to employ the Kernel Density tool. To proceed with this step, the Feature to Point tool within the Data Management Tool was employed. Using the Feature to Point tool converted the BOCO WPC shapefile to a point layer by maintaining the attributes from the input feature and representing the wind data in a point. Once the point layer was created, the data was then added to the Kernel Density tool for analysis. The following is the output for the entire Boulder County Project area:

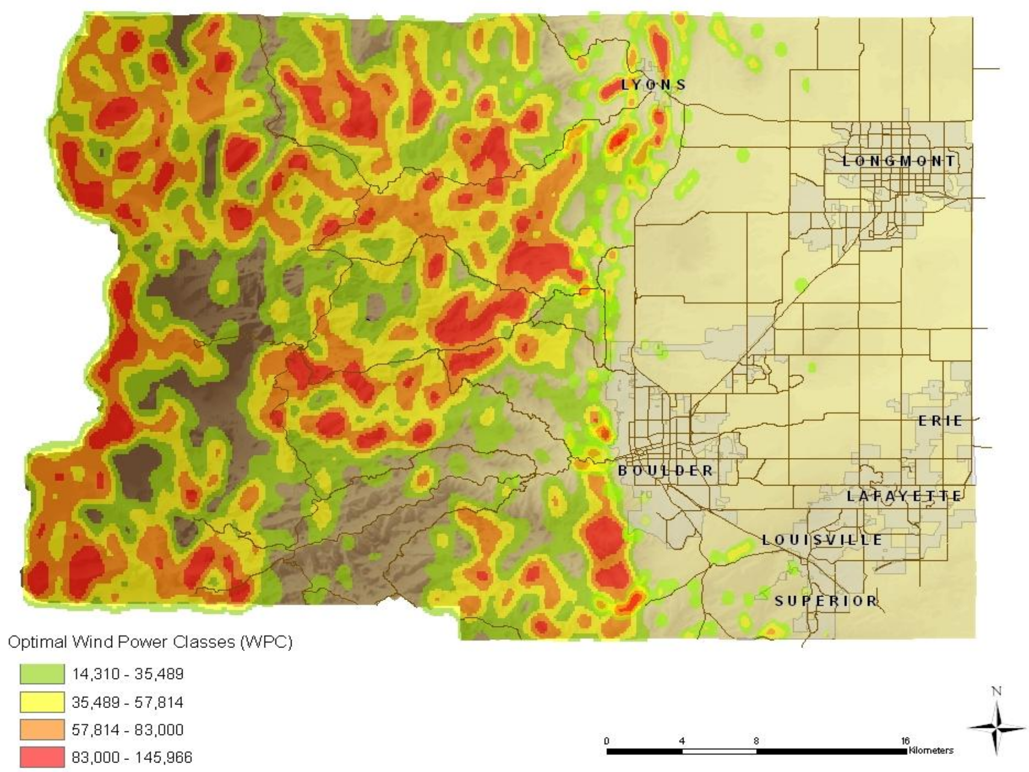

Figure 13. Kernel Density, (http://www.spatialinsights.com, http://www.bouldercounty.org, Coventry 2010)

3D Analyst

Another alternative way to illustrate the BOCO WPC shapefile is to use the 3D Analyst tools and display the shapefile in ArcScene. Employing this method allowed for multiple viewpoints of the WPC data to give a realistic perspective of the imaging. The ArcGIS 3D Analyst tools allows 3D modeling and analysis and brings a 2-dimensional shapefile to life. To create this 3-dimensional view, the Boulder County DEM was added to ArcScene. Base heights were calculated opening the Properties of the raster and selecting "Obtain heights from the surface layer". Once these heights were established, the BOCO WPC shapefile was added. By opening the Properties, an option enabled the shapefile to match the base heights of the Boulder County DEM as illustrated in Figure 14.

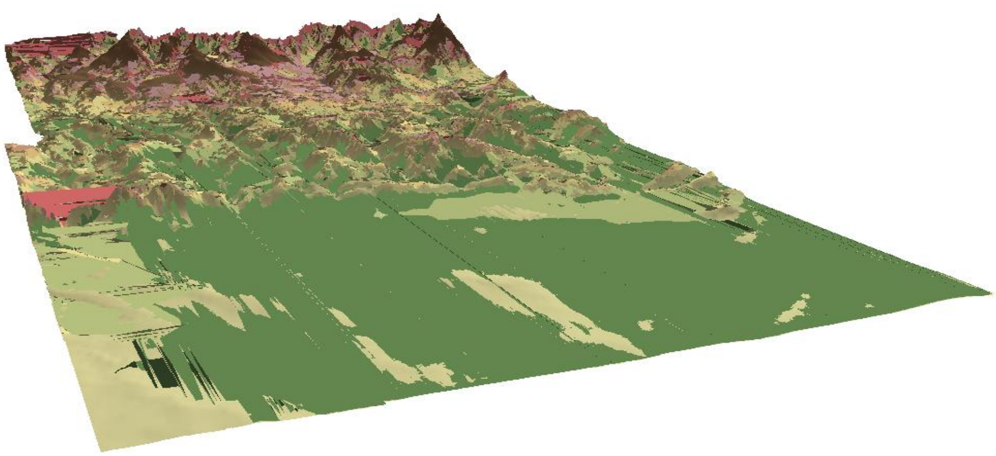

Figure 14. 3D Analyst, (http://www.spatialinsights.com, http://www.bouldercounty.org, Coventry 2010)

Chapter 4
Data Analysis and Interpretation of Results

4.1 Mountain Region

The Mountain Region is the most diverse and complex region in this study area. The terrain contains jagged peaks reaching 14,252 feet AMSL and steep canyon walls descending down 6,233 feet AMSL. To illustrate the WPC's for the Mountain Region, a clip of the BOCO WPC shapefile with the Mountain Region shapefile resulted in an a new shapefile containing Mountain Region's WPC's. Figures 14 and 15 illustrate the WPC and the geographic areas they encompass.

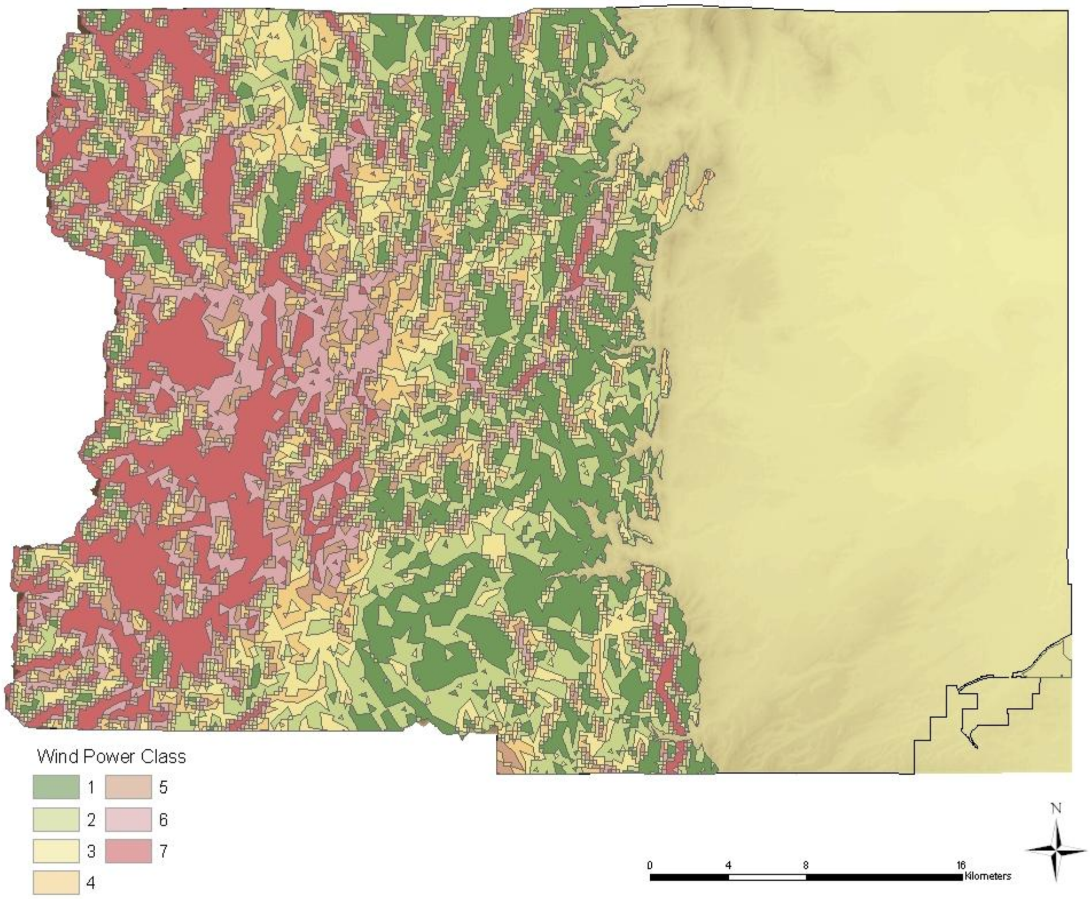

Figure 15. Mountain Region Wind Potential, (http://www.spatialinsights.com, http://www.bouldercounty.org, Coventry 2010)

Exporting the Mountain Region's BOCO WPC shapefile attribute table to Excel determined the total acreage according to WPC as illustrated in Figure 16.

Mountains
Wind Power Class by Acreage

WPC	Acres
1	51,973
2	51,575
3	42,201
4	32,015
5	23,535
6	32,423
7	43,746
Total	277,468

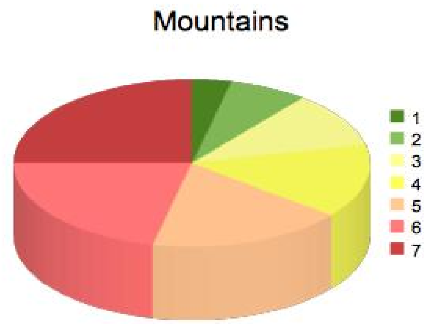

Figure 16. Mountain Region Wind Power Class by Acreage, (Coventry 2010)

4.1.2 City Region

The City Region has the least amount of diverse WPC in this research paper's project area as illustrated in Figures 17. The City Region is primarily flat with elevations ranging from a high 6,437 feet AMSL to a low 4,918 feet AMSL. To illustrate the WPC's for the City Region, a clip of the BOCO WPC shapefile with the City Region shapefile resulted in an a new shapefile containing City Region's WPC's. Figures 17 and 18 illustrates the WPC's and the geographic areas they encompass.

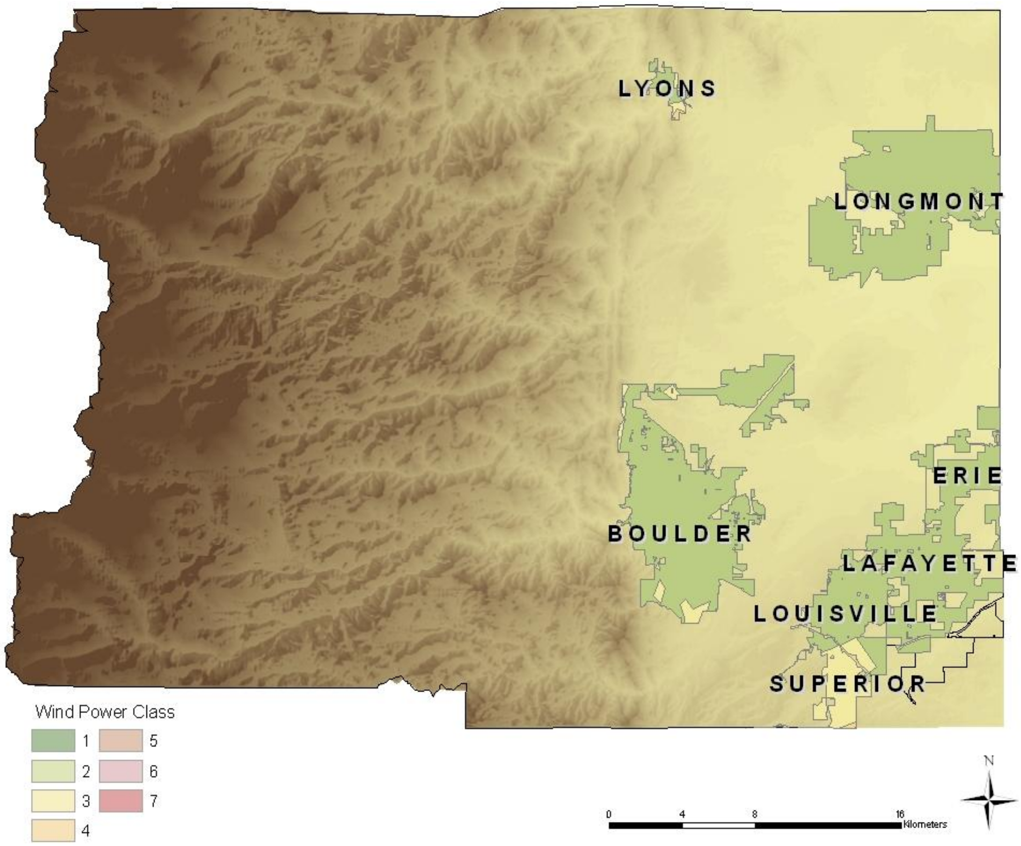

Figure 17. City Region Wind Potential (http://www.spatialinsights.com, http://www.bouldercounty.org, Coventry 2010)

To determine the total number of acreage affected by each WPC, exporting the attribute table from the BOCO WPC shapefile to Excel determined the following in Figure 18.

City
Wind Power Class by Acreage

Region	WPC	Acres
City	1	45,203
City	2	3,360
City	3	113
City	4	10
	Total	48,686

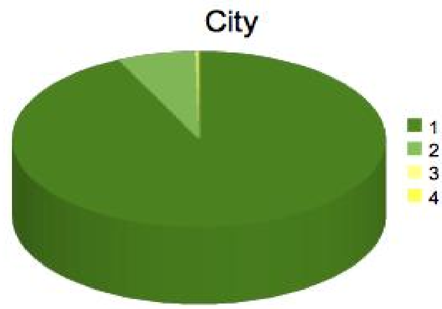

Figure 18. City Region Wind Power Class by Acreage, (Coventry 2010)

4.1.3 Plains Region

The Plains Region has similar terrain as the City Region with elevations ranging from a high 6,680 feet AMSL to a low 4,918 feet AMSL. To illustrate the WPC's for the Plains Region, a clip of the BOCO WPC shapefile with the Plains Region shapefile resulted in an a new shapefile containing City Region's WPC's. Figures 19 and 20 illustrates the WPC's and the geographic areas they encompass.

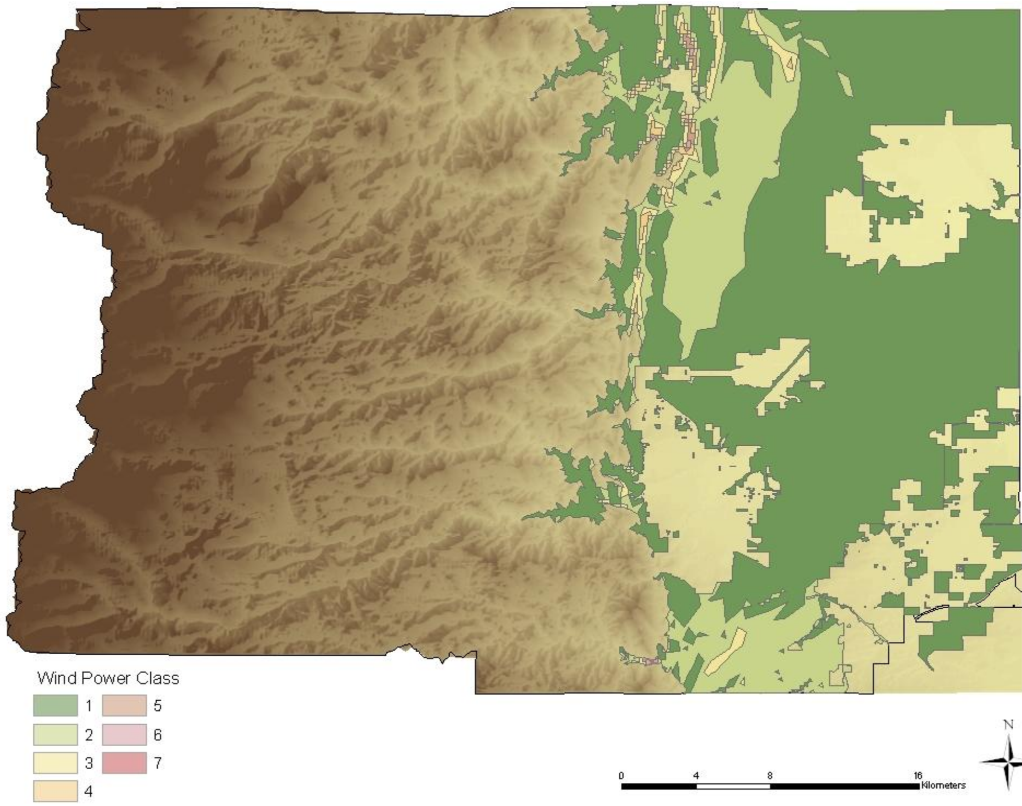

Figure 19.Plains Region Wind Potential, (http://www.spatialinsights.com, http://www.bouldercounty.org, Coventry 2010)

To determine the total number of acreage affected by each WPC in the Plains Region, an export of the shapefile's attribute table to Excel determined the following breakdown in Figure 20.

Plains
Wind Power Class by Acreage

Region	WPC	Acres
Plains	1	113,830
Plains	2	29,910
Plains	3	3,270
Plains	4	743
Plains	5	254
Plains	6	68
Plains	7	20
	Total	148,095

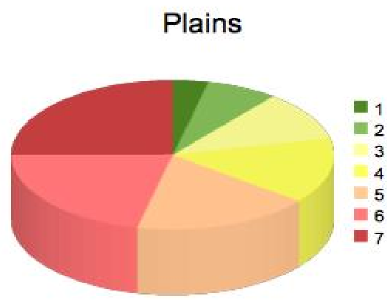

Figure 20. Plains Region Wind Power Class by Acreage, (Coventry 2010)

<u>4.2 Determining Wind Power</u>

The factors that influence the size and use of a wind turbine are the amount of energy needed, the amount of wind energy available, and the height of the turbine tower. Through literature review and research, this research paper has not found a standard wind turbine size and height for use in regions such as the mountains, plains, and cities (Chiras 2009; Edwards 2003). The size of the wind turbine is dependent on the developer and the amount of energy needed. Turbine height is a component that influences the amount of potential wind energy harvested. Winds move more slowly at ground level due to ground drag, and wind speed increases with height above ground, due to a reduction in ground drag (Chiras 2009). The rule of thumb is that the entire rotor should be at least 9.144 meters (30 feet) above the tallest obstacles within a radius of 152.4 meters (500 feet) (Chiras 2009). The Wind Profiler Law (Table 7) illustrates the relationship between wind speeds at various heights.

Class	10 m (33 ft)		30 m (98 ft)		50 m (164 ft)	
	Wind power density (W/m^2)	Speed m/s (mph)	Wind power density (W/m^2)	Speed m/s (mph)	Wind power density (W/m^2)	Speed m/s (mph)
1	0 - 100	0 - 4.4 (0 - 9.8)	0 - 160	0 - 5.1 (0 - 11.4)	0 - 200	0 - 5.6 (0 - 12.5)
2	100 - 150	4.4 - 5.1 (9.8 - 11.5)	160 - 240	5.1 - 5.9 (11.4 - 13.2)	200 - 300	5.6 - 6.4 (12.5 - 14.3)
3	150 - 200	5.1 - 5.6 (11.5 - 12.5)	240 - 320	5.9 - 6.5 (13.2 - 14.6)	300 - 400	6.4 - 7.0 (14.3 - 15.7)
4	200 - 250	5.6 - 6.0 (12.5 - 13.4)	320 - 400	6.5 - 7.0 (14.6 - 15.7)	400 - 500	7.0 - 7.5 (15.7 - 16.8)
5	250 - 300	6.0 - 6.4 (13.4 - 14.3)	400 - 480	7.0 - 7.4 (15.7 - 16.6)	500 - 600	7.5 - 8.0 (16.8 - 17.9)
6	300 - 400	6.4 - 7.0 (14.3 - 15.7)	480 - 640	7.4 - 8.2 (16.6 - 18.3)	600 - 800	8.0 - 8.8 (17.9 - 19.7)
7	400 - 1000	7.0 - 9.4 (15.7 - 21.1)	640 - 1600	8.2 - 11.0 (18.3 - 24.7)	800 - 2000	8.8 - 11.9 (19.7 - 26.6)

Table 7. Wind Profiler Law,
(http://en.wikipedia.org/wiki/Wind_profile_power_law, Coventry 2010)

The following formula determined the amount of energy (watts) wind power can generate. This formula and research project does not assume wind turbine height.

Power in the wind(Watts) = 1/2 * rho * A * V^3

Where:

rho = air density (cubic meters)

A = swept area in square meters. Power available from a wind turbine is related to the *square* of the blade diameter.

V^3 = velocity (wind speed, in meters per second).

Air density needed to be determined as a part of the equation. Using Table. 8, a benchmark of 70 degrees Fahrenheit was an arbitrary temperature determined and applied for all geographic regions in this project. A mean elevation of 2247.06 meters (7,372.04 feet AMSL) was determined by analyzing the Boulder County DEM histogram in GIS (Figure 21). To correspond to Table 8, the elevation as rounded down to 7,000 feel AMSL. The resulting air density correction factor used is 1.30

AIR DENSITY CORRECTION FACTORS

Air Temp. °F	Elevation (Feet Above Sea Level)															
	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000	12000	13000	14000	15000
0	0.87	0.90	0.94	0.97	1.01	1.05	1.08	1.13	1.17	1.22	1.26	1.31	1.37	1.43	1.48	1.54
50	0.96	1.00	1.04	1.08	1.11	1.15	1.20	1.24	1.30	1.34	1.40	1.45	1.51	1.57	1.63	1.70
70	1.00	1.04	1.08	1.12	1.16	1.22	1.25	1.30	1.35	1.40	1.45	1.51	1.57	1.64	1.70	1.77
100	1.06	1.10	1.14	1.18	1.22	1.27	1.32	1.37	1.42	1.48	1.54	1.60	1.66	1.74	1.80	1.88
150	1.15	1.19	1.24	1.30	1.33	1.38	1.44	1.49	1.55	1.61	1.67	1.74	1.81	1.89	1.96	2.04
200	1.25	1.29	1.34	1.40	1.44	1.50	1.56	1.61	1.68	1.75	1.81	1.89	1.96	2.05	2.13	2.21
250	1.34	1.39	1.44	1.50	1.55	1.61	1.67	1.74	1.80	1.88	1.95	2.02	2.10	2.20	2.28	2.37
300	1.43	1.49	1.54	1.60	1.66	1.72	1.79	1.86	1.93	2.01	2.08	2.16	2.25	2.35	2.43	2.53
350	1.53	1.58	1.64	1.71	1.77	1.84	1.91	1.98	2.06	2.14	2.22	2.31	2.40	2.51	2.60	2.71
400	1.62	1.68	1.75	1.81	1.88	1.94	2.03	2.09	2.19	2.27	2.37	2.46	2.54	2.66	2.75	2.87
500	1.81	1.88	1.95	2.02	2.10	2.18	2.26	2.35	2.44	2.54	2.63	2.73	2.84	2.97	3.08	3.20
600	2.00	2.07	2.15	2.23	2.31	2.40	2.50	2.59	2.69	2.84	2.91	3.02	3.14	3.28	3.40	3.54
700	2.19	2.27	2.35	2.44	2.53	2.63	2.73	2.83	2.94	3.07	3.17	3.31	3.44	3.59	3.72	3.88
800	2.38	2.48	2.57	2.67	2.76	2.86	2.98	3.09	3.21	3.33	3.45	3.59	3.74	3.90	4.05	4.21
900	2.56	2.66	2.76	2.87	2.97	3.07	3.20	3.33	3.46	3.58	3.71	3.87	4.02	4.20	4.35	4.53
1000	2.76	2.87	2.99	3.09	3.20	3.31	3.45	3.59	3.73	3.86	4.00	4.17	4.33	4.53	4.69	4.89

Note: It's acceptable to interpolate when exact temperatures or elevations are not shown in chart.

Table 8. Air Density Correction Factors,
(www.rlcraigco.com/Temperature.htm, Coventry 2010)

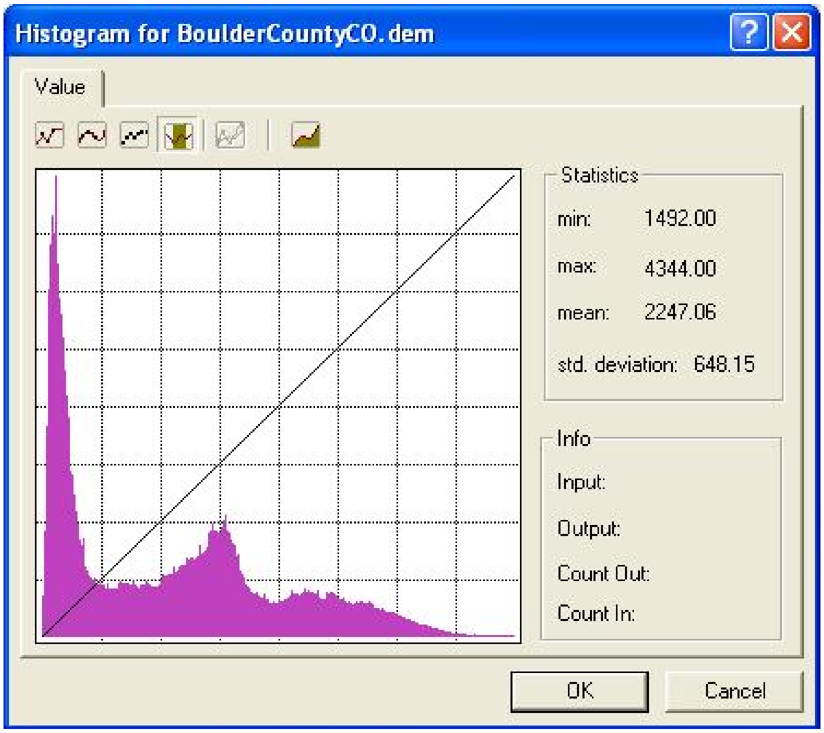

Figure 21. Histogram for Boulder County DEM, (Coventry 2010)

4.3 Boulder County's Current Energy Assessments

To determine Boulder County's current energy assessments, this project investigated utility companies currently providing energy use to the County. These utility companies are identified in the Table 9, identifying the usage in kilowatt hours during the years 2006, 2007 and 2008. Data provided in Table 9 was gathered by the Boulder County Commissioner's Office and presented to be by Ann Livingston, the County's Sustainability Coordinator. To determine the amount of offsetting wind energy harvested, the analysis used data in Table 9 and represented concluding results in Table 10.

Community	2006 usage (kWh)	2007 usage (kWh)	2008 usage (kWh)
Boulder (Xcel)			
Residential	241,672,453	253,704,408	247,853,273
Commercial	625,629,273	656,204,578	650,450,371
Industrial	379,151,654	380,074,064	382,065,022
Street Lighting	5,409,958	5,646,591	5,854,884
TOTAL	**1,251,863,338**	**1,295,629,641**	**1,286,223,550**
Longmont (Xcel)			
Residential	19,031	19,979	19,518
Commercial	58,973	61,855	61,312
Industrial	-	-	-
Street Lighting	16,007	16,707	17,323
Longmont Power & Communications			
Residential	295,031,222	308,208,553	298,992,768
Commercial	306,903,774	313,329,573	325,349,787
Industrial	176,313,601	177,183,280	162,559,040
Street Lighting	22,902,950	23,006,217	22,530,379
TOTAL	**801,245,558**	**821,826,164**	**809,530,127**
Louisville (Xcel)			
Residential	58,938,567	61,872,895	60,445,932
Commercial	114,803,032	120,413,604	199,357,706
Industrial	138,108,045	138,444,038	139,169,255
Street Lighting	850,964	888,186	920,949
TOTAL	**312,700,608**	**321,618,723**	**399,893,842**
Lafayette (Xcel)			
Residential	78,849,732	82,775,361	80,866,329
Commercial	63,213,744	66,303,081	65,721,675
Industrial	-	-	-
Street Lighting	672,251	701,655	727,538
TOTAL	**142,735,727**	**149,780,097**	**147,315,542**

Community	2006 usage (kWh)	2007 usage (kWh)	2008 usage (kWh)
Lyons (NMPP)			
Residential	6,844,817	7,201,162	7,957,118
Commercial	4,194,071	4,528,879	4,469,290
Industrial	-	-	-
Street Lighting	-	-	-
TOTAL	**11,038,888**	**11,730,041**	**12,426,408**
Nederland (Xcel)			
Residential	5,258,260	5,520,049	5,392,742
Commercial	3,799,798	3,985,499	3,950,551
Industrial	-	-	-
Street Lighting	8,876	9,264	9,606
TOTAL	**9,066,934**	**9,514,812**	**9,352,899**
Superior (Xcel)			
Residential	48,680,915	51,104,554	49,925,939
Commercial	27,515,458	28,860,174	28,607,101
Industrial	-	-	-
Street Lighting	289,374	302,031	313,173
TOTAL	**76,485,747**	**80,266,759**	**78,846,213**
Unincorporated/Other (Xcel, United Power)			
Residential	194,064,041	203,725,754	199,027,267
Commercial	110,565,721	115,969,209	114,952,284
Industrial	6,822,300	6,838,898	6,874,722
Street Lighting	388,570	405,566	420,526
TOTAL	**311,840,632**	**326,939,427**	**321,274,799**
Pouder Valley (PVREA)			
Residential	118,920,945	118,920,945	118,920,945
Commercial	-	-	-
Industrial	-	-	
Street Lighting	-	-	
TOTAL	**118,920,945**	**118,920,945**	**118,920,945**
Boulder County Totals	**3,035,898,377**	**3,136,226,609**	**3,183,784,325**

Table 9. Boulder County Energy Usage, (Boulder County Commissioner's Office; Coventry 2010)

4.4 Proposed Wind Turbine Assessments and Offsetting Energy

UNINCORPORATED REGION

Wind Turbine Size				Wind Speeds (Low/High WPC)	Wind Energy		Current Energy Use	
Typical Power Rating*	Rotor (meters)	Swept Area (meters)	Tower Height (meters)	Wind Speed (meters per second)	Watts	Kilowatts	Total kWh	Number of Wind Turbines
1kW	2.5	19.63	19	5.9	2,479.97	2.48	118,920,945.00	47,952,651.22
				9.3	9,703.18	9.70		12,255,877.52
5kW	6.4	128.61	24	5.9	16,252.71	16.25		7,316,993.90
				9.3	63,590.74	63.59		1,870,098.50
10kW	8	200.96	24	5.9	25,394.85	25.39		4,682,876.10
				9.3	99,360.53	99.36		1,196,863.04
20kW	12.4	482.81	24	5.9	61,011.13	61.01		1,949,167.99
				9.3	238,713.67	238.71		498,174.00
50kW	15	706.5	30	5.9	89,278.78	89.28		1,332,018.09
				9.3	349,314.36	349.31		340,441.04

*Power rating based on estimates from SolarEstimates.org

CITY REGION

Wind Turbine Size				Wind Speeds (Low/High WPC)	Wind Energy		Current Energy Use	
Typical Power Rating*	Rotor (meters)	Swept Area (meters)	Tower Height (meters)	Wind Speed (meters per second)	Watts	Kilowatts	Total kWh	Number of Wind Turbines
1kW	2.5	19.63	19	5.9	2,479.97	2.48	2,853,156,627.00	1,150,482,150.98
				7.91	5,979.21	5.98		477,179,612.08
5kW	6.4	128.61	24	5.9	16,252.71	16.25		175,549,644.62
				7.91	39,185.34	39.19		72,811,830.46
10kW	8	200.96	24	5.9	25,394.85	25.39		112,351,772.56
				7.91	61,227.10	61.23		46,599,571.49
20kW	12.4	482.81	24	5.9	61,011.13	61.01		46,764,525.52
				7.91	147,098.11	147.10		19,396,283.66
50kW	15	706.5	30	5.9	89,278.78	89.28		31,957,837.53
				7.91	215,251.52	215.25		13,254,989.22

*Power rating based on estimates from SolarEstimates.org

MOUNTAIN COMMUNITY REGION

Wind Turbine Size				Wind Speeds (Low/High WPC)	Wind Energy		Current Energy Use	
Typical Power Rating*	Rotor (meters)	Swept Area (meters)	Tower Height (meters)	Wind Speed (meters per second)	Watts	Kilowatts	Total kWh	Number of Wind Turbines
1kW	2.5	19.63	19	5.9	2,479.97	2.48	9,352,899.00	3,771,381.93
				9.3	9,703.18	9.70		963,900.72
5kW	6.4	128.61	24	5.9	16,252.71	16.25		575,467.21
				9.3	63,590.74	63.59		147,079.58
10kW	8	200.96	24	5.9	25,394.85	25.39		368,299.02
				9.3	99,360.53	99.36		94,130.93
20kW	12.4	482.81	24	5.9	61,011.13	61.01		153,298.24
				9.3	238,713.67	238.71		39,180.41
50kW	15	706.5	30	5.9	89,278.78	89.28		104,760.61
				9.3	349,314.36	349.31		26,775.02

*Power rating based on estimates from SolarEstimates.org

Table 10. Offsetting Energy, (Coventry 2010)

The concluding results in Table 10 identifies Wind Turbine Size, Wind Speeds, Wind Energy, and Current Energy Use. The geographic regions and related data identified in Table 9 were summarized into three regions in Table 10: Unincorporated, City, and Mountain Region. The wind turbine size, height, and power rating were consistently used in all three geographic regions to provide a range of scenarios determined by developers and decision makers. Wind speeds identified in Table 10 provide a range of the low and high WPC in the region. The wind speed data range identifies the potential wind energy in the region. Calculating the wind speed by the turbine swept area determines the amount of wind energy in watts. Summarizing the current 2008 energy use by region and dividing the amount of potential wind energy determines the number of turbines to offset the energy usage.

Chapter 5
Final Considerations

5.1 Conclusion

This research project met the following goals:

1) Used GIS to determine optimal wind harvesting locations within Boulder County illustrated in Figure 22.

2) Identified Boulder County's current energy assessments.

3) Determined that harvesting wind energy helps offset Boulder County's

current energy usage in efforts to become a more sustainable County.

This project detailed the necessary steps of gathering wind potential and project area related spatial data from several reliable sources via the Internet. The project illustrated the geoprocessing steps taken to modify the spatial data so that analysis could be made within the Boulder County project area. Analysis was conducted to identify areas of optimum wind potential and the possible environmental effects. A final comparison of Boulder County's current energy with proposed wind turbine assessments determined potential offsetting energy. This research project serves as a basis for further analysis beyond the topics discussed. The amount of offsetting wind will should be determined by developers and decision makers to determine the number of wind turbines and appropriate size.

5.2 Limitations and Recommendations

This research project relied solely on NREL's Wind Potential shapefile data for wind data. Since NREL's Wind Potential shapefile is based on a 2003 survey of wind in the state of Colorado at 50 meters above ground, there are limitation for further research. Analysis of wind potential at any other height AMSL is not possible with this data. There are no other wind data provided by NREL based on any other year than 2003. Further research would not allow comparisons between years to determine whether or not there is a consistent wind potential within specific geographic regions in this study area.

An alternative wind data resource is available through the state of

Colorado Energy Office. The state offers an Anemometer Loan Program (ALP) that loans anemometers to land owners to determine wind potential in their regions. The data collected from anemometer is collected and available for public use. Such data will assist in further research beyond the scope of this research project.

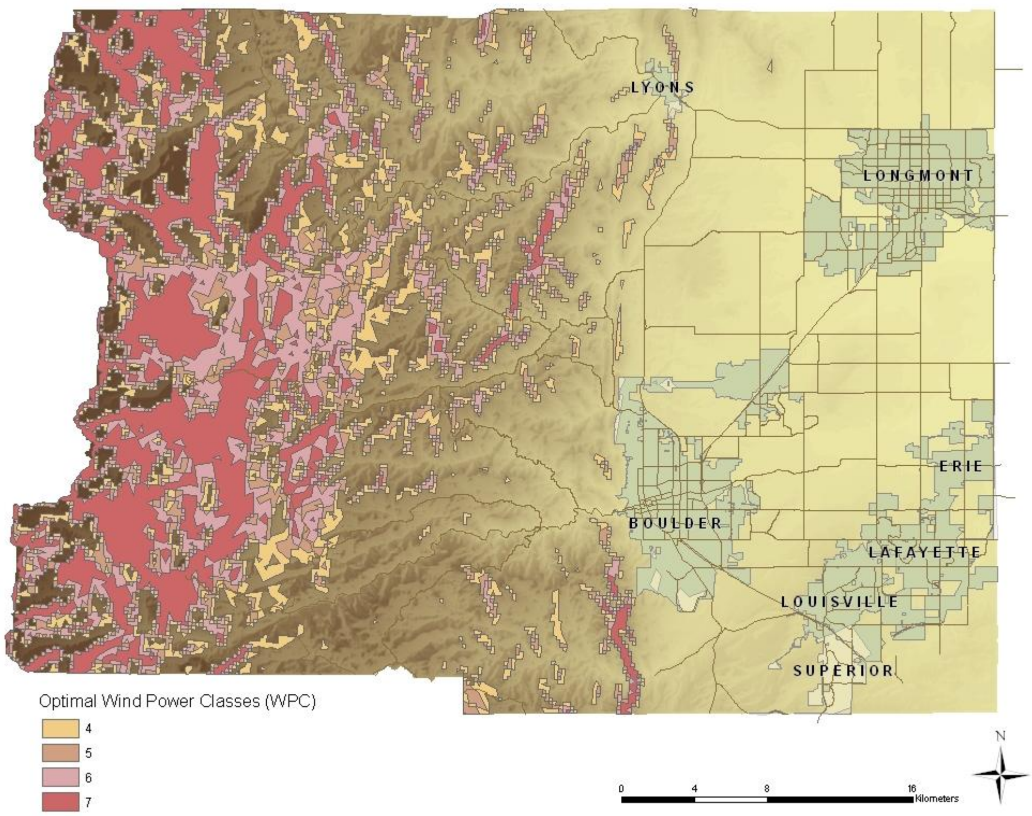

Figure 22. Optimal WPC, (http://www.spatialinsights.com, http://www.bouldercounty.org, Coventry 2010)

Glossary

2D – 2 dimensional

3D – 3 dimensional

ALP - Anemometer Loan Program

AMSL – Above Mean Sea Level

BOCO – Boulder County

BOCO WPC – Boulder County Wind Power Class

DCVZ - Denver Convergence Vorticity Zone

GIS – Geographic Information System

NREL – National Renewable Energy Laboratory

WPC – Wind Power Class

Work Cited

American Wind Energy Association. 2010. *Facts About Wind Energy & Birds.* http://www.awea.org/pubs/factsheets/avianfs.pdf (accessed April 24, 2010).

AWS True Wind. 2010. *US Wind Potential Estimates.* http://www.awstruewind.com/windpotential.cfm (accessed April 10, 2010).

Chiras, Dan. 2009. *Power from the Wind Achieving Energy Independence*. Gabriola Island, BC: New Society Publishers

Dempsey, Caitlin. 2000. *The Power of Mapping*. March 30, 2010. http://gislounge.com/the-power-of-mapping/

Department of Energy. 2010. *Wind and Water Program – Information Resources*. March 23, 2010.

http://www1.eere.energy.gov/windandhydro/faqs.html

Eckhart, Michael. 2006. RENEWABLES Looking Toward Inexhaustible Energy. *eJournal USA*. 7

Edwards, Peter D. 2003. The Potential of Wind Energy as a Farm Diversification. *Royal Agricultural Society of England*. 164
ESRI. 2010. *What is GIS?* March 30, 2010.
http://www.esri.com/what-is-gis/index.html

Greene, Richard P. and James B. Pick, 2006. *Exploring The Urban Community, A GIS Approach*. Upper Saddle River: Pearson Education, Inc.

Nastu, Paul. 2008. US Companies Embrace Green Technology. *eJournal USA.* 4

Nelson, Mike. 2007. *Colorado Weather Almanac.* Boulder: Johnson Books

Panjaitan, Togar Wiliater Soaloon. 2005. Assessment of Renewable Energy Technologies (Solar Thermal and Windmils). *Journal Technical Industrial*. 7

Rosenbloom, Eric. 2006. "A Problem With Wind Power." *AWEO*. 7-8

Scott, Ralph C. 1992. *Physical Geography* 2nd ed. St. Paul: West Publishing Company

Solar Guide. 2010. Wind Energy History. February 16, 2010.
http://www.thesolarguide.com/wind-power/history.aspx

University of Washington. 2009. 3D Analysis and Surface Modeling
http://courses.washington.edu/esrm590/lessons/3d/index.html

Williams, Scott. 2009. Wind Turbines Complicate Weather Monitoring. *The Journal Sentinel*. April 11, 2009.

Wind Industry. 2010. *About Wind Industry*. February 26, 2010.
http://www.windustry.org/about-windustry/about-windustry

Yang, George. 2009. A Conceptual Study of Negative Impact of Wind Farms to the Environment. *Technology Interface Journal*. Fall 2009