Appendix B – Shadow Flicker Assessment: Blazing Star Wind Farm 2

Final Report
Blazing Star 2 Wind Farm
Shadow Flicker Study
Hendricks, MN

August 31,

2017

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Revision History

Revision No.	Revision Purpose	Date	Revised By
0	Original	8/08/2017	J. Haley
1	Added Tables 4 & 5, Included BS 1 turbines	8/29/2017	J. Haley

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Executive Summary

EAPC was hired by Merjent to provide estimates of the shadow flicker potential for a proposed wind turbine layout, using four different turbine models, for the Blazing Star 2 Wind Energy project in southern Minnesota. Locations of area dwellings and a wind turbine layout were provided to EAPC by the client. A windPRO model was built combining digital elevation data with the information supplied to generate a shadow flicker model for the site. The resulting model was then used to perform shadow flicker calculations for the area. Based on the shadow flicker calculation, a site-wide realistic shadow flicker map was produced and an evaluation of the shadow flicker at all 455 area dwellings within one mile of any proposed turbine location or project boundary was performed.

The 455 dwellings were represented in the model by omni-directional shadow receptors that simulate a 1 m x 1 m window 1 m above ground level. Reductions based on turbine operational time, turbine operational direction, and sunshine probabilities were used to calculate a realistic number of hours of shadow flicker to be expected at each shadow receptor. No obstacles were used so that shadow flicker reductions due to interference from trees and structures were not included.

The evaluation of the four separate arrays using different turbine models resulted in varying results based on the individual turbine hub heights and rotor sizes. The number of occupied residences registering more than 30 hours per year ranged from 11 to 15 for the four different arrays with the number of hours ranging from 30 hours to 80 hours and 27 minutes.

1. INTRODUCTION

Merjent hired EAPC to conduct a shadow flicker analysis for the four potential wind turbine layouts located in southern Minnesota near the town of Hendricks. Four separate turbine arrays were assessed using four different turbine models:

- GE 2.5-116-94 m hub height,
- Vestas V110-80 m hub height
- Gamesa G126-84 m hub height
- Acciona AW132-84 m hub height

Coordinates for 455 dwellings which could potentially experience shadow flicker from the proposed wind farm were also supplied by the client.

2. BACKGROUND

Shadow flicker from wind turbines occurs when rotating wind turbine blades move between the sun and the observer. Shadow flicker is generally experienced in areas near wind turbines where the distance between the observer and wind turbine blade is short enough that sunlight has not been significantly diffused by the atmosphere. When the blades rotate, this shadow creates a pulsating effect, known as shadow flicker. If the blade's shadow is passing over the window of a building, it will have the effect of increasing and decreasing the light intensity in the room at a low frequency in the range of 0.5 to 1.2 Hz, hence the term "flicker". This flickering effect can also be experienced outdoors, but the effect is typically less intense, and becomes less intense when farther from the wind turbine causing the flicker. The moving shadow of a wind turbine blade on the ground is similar to the effect one experiences when driving on a road when there are shadows cast across the road by an adjacent row of trees.

This flickering effect is most noticeable within approximately 1,000 meters of the turbine, and becomes more and more diffused as the distance increases. There are no uniform standards defining what distance from the turbine is regarded as an acceptable limit beyond which, the shadow flicker is considered to be insignificant. The same applies to the number of hours of flickering that is deemed to be acceptable.

Shadow flicker is typically greatest in the winter months when the angle of the sun is lower and casts longer shadows. The effect is also more pronounced around sunrise and sunset when the sun is near the horizon and the shadows are longer. A number of factors influence the amount of shadow flicker on the shadow receptors (simulated windows). One consideration is the environment around the shadow receptor. Obstacles such as terrain, trees or buildings between the wind turbine and the receptor can significantly reduce or eliminate shadow flicker effects. Deciduous trees may block the shadow flickering effect to some degree, depending on the tree density, species present and time of year. Deciduous trees can lead to a reduction of shadow flicker during the summer when the trees are bearing leaves. However, during the winter months, these trees are

without their leaves and their impact on shadow flicker is not as significant. Coniferous trees tend to provide shading year round. For this study, no credit was taken for any potential shading effects from any type of trees or other obstacles that would reduce the number of shadow flickering hours at the structures.

Another consideration is the time of day when shadow flicker occurs. For example, a factory or office building would not be significantly affected if all the shadow flicker impact occurred before or after business hours whereas, it may be more acceptable for private homes to experience the shadow flickering during working hours when family members may be at work or school.

The climate also needs be considered when assessing shadow flicker. In areas with a significant amount of overcast weather, there would be less shadow flicker. Also, if the wind is not blowing, the turbines would not be operational and therefore not creating shadow flickering.

3. *STUDY METHODOLOGY*

This shadow flicker analysis was performed utilizing windPRO[1], a sophisticated wind modeling software program. windPRO has the ability to calculate detailed shadow flicker maps across an entire area of interest or at site-specific locations using shadow receptors.

Shadow maps which indicate where the shadows will be cast and for how long, are generated using windPRO, calculating the shadow flicker in varying user-defined resolutions. Standard resolution was used for this study and represents shadow flicker being calculated every three minutes of every day over the period of an entire year over a grid with a 20 m by 20 m resolution.

In addition to generating a shadow flicker map, the amount of shadow flicker that may occur at a specific point can be calculated more precisely by placing a shadow receptor at the location of interest and essentially "recording" the shadow flicker that occurs as the relative sunrise to sunset motion of the sun is simulated throughout an entire year.

The point-specific shadow flicker calculation is run at a higher resolution as compared to the shadow flicker map calculation to include the highest precision possible within windPRO. Shadow flicker at each shadow receptor location is calculated every minute of every day for an entire year. Shadow receptors can be configured to represent an omni-directional window of a specific size at a specific point (greenhouse mode) or a window facing a single direction of a specific size at a specific point (single direction mode). The shadow receptors used in this analysis were configured as greenhouse-mode receptors

[1] windPRO is the world's leading software tool for wind farm design including shadow flicker analysis.

representing a 1 m x 1 m window located 1 m above ground level. This represents more of a "worst-case" scenario and thus will produce more conservative results.

As a part of the calculation method, windPRO must determine whether or not a turbine will be visible at the receptor locations. It does this by performing a preliminary Zones of Visual Influence (ZVI) calculation, utilizing 10 m grid spacing. If a particular turbine is not visible within the 10 m x 10 m area that the shadow receptor is contained within, then that turbine is not included in the shadow flicker calculation for that receptor.

The maximum distance limit for which shadow flicker should be counted was set to 1,500 meters. Any shadow flicker contributions from turbines within this distance limit are added to the total for each receptor.

The inputs for the windPRO shadow flicker calculation include the following:

- Turbine Coordinates
- Turbine Specifications
- Shadow Receptor Coordinates
- Monthly Sunshine Probabilities
- Joint Wind Speed and Direction Frequency Distribution
- USGS Digital Elevation Model (DEM) (height contour data)
- Existing Turbines

A description of each input variable and how they affect the shadow flicker calculation are included below.

Turbine Coordinates: The location of a wind turbine in relation to a shadow receptor is one of the most important factors in determining shadow flicker impacts. A line-of-site is required for shadow flicker to occur. The intensity of the shadow flicker is dependent upon the distance from the wind turbine and weather conditions.

Turbine Specifications: A wind turbines total height and rotor diameter will be included in the windPRO shadow flicker model. The taller the wind turbine, the more likely shadow flicker could have an impact on local shadow receptors as the ability to clear obstacles (such as hills or trees) is greater. The larger the rotor diameter is, the wider the area where shadows will be cast. Also included with the turbine specifications are the cut-in and cut-out wind speeds within which the wind turbine is operational. If the wind speed is below the cut-in threshold or above the cut-out threshold, the turbine rotor will not be spinning and thus shadow flicker will not occur. The specifications of the three wind turbine models used in this study are included in Table 1 below.

Table 1: Blazing Star 2 Wind Turbine Specifications.

Blazing Star 2 Wind - Shadow Modeled Turbine Specifications					
Manufacturer	**Model**	**Hub Height (m)**	**Rotor Diameter (m)**	**Cut-In Wind Speed (m/s)**	**Cut-Out Wind Speed (m/s)**
General Electric (GE)	GE 2.5-116	94	116	3	25
Vestas	V110	80	110	3	20
Gamesa	G126	84	126	3	25
Acciona	AW132	84	132	3	25

Shadow Receptor Coordinates: As with the wind turbine coordinates, the elevation, distance and orientation of a shadow receptor in relation to the wind turbines and the sun are the main factors in determining the impact of shadow flicker. EAPC was provided with coordinates for 455 structures found to be located within one mile of the proposed wind turbine locations.

Monthly Sunshine Probabilities: windPRO calculates sunrise and sunset times to determine the total annual hours of daylight for the modeled area. To further refine the shadow flicker calculations, the monthly probability of sunshine is included to account for cloud cover. The greater the probability of cloud cover, the less of an impact from shadow flicker. The monthly sunshine probabilities for many of the larger cities across the United States are available from the National Climatic Data Center (NCDC). For this study, 18 years' worth of monthly sunshine probability data were retrieved for Minneapolis, MN, which was the closest, most representative station, to create the long-term representative monthly sunshine probabilities. The long-term representative monthly average sunshine probabilities are presented in Table 2.

Table 2: Minneapolis, MN monthly sunshine probabilities.

Minneapolis, MN Monthly Sunshine Probabilities (1965-1983)												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sunshine %	53%	59%	57%	56%	62%	67%	74%	69%	62%	51%	37%	38%
retrieved from: http:// http://www1.ncdc.noaa.gov/pub/data/ccd-data/pctpos15.dat												

Joint Wind Speed and Direction Frequency Distribution: A set of long-term corrected wind distributions generated from an on-site meteorological mast was provided by the client to represent the annual wind speed and direction distribution for the project site for the three proposed turbine hub heights. This data was used to estimate the probable number of operational hours for the wind turbines from each of the 12 wind direction sectors. During operation, the wind turbine rotors will always be assumed to face into the wind and automatically orient themselves as the wind direction changes. Shadow flicker can only occur when the blades are turning and the wind turbine rotor is between the sun and the receptor. Shadow flicker is most significant when the rotor is facing the sun.

USGS Digital Elevation Model (DEM) (height contour data): For this study, 10 m USGS National Elevation Database (NED) DEM's were used to construct 10-foot interval height contour lines for the windPRO shadow flicker model. The height contour information is important to the shadow flicker calculation since it allows the model to place the wind turbines and the shadow receptors at the correct elevations. The height contour lines also allow the model to include the topography of the site when calculating the zones of visual influence surrounding the wind turbine and shadow receptor locations.

The actual calculation of potential shadow flicker at a given shadow receptor is carried out by simulating the environment near the wind turbines and the shadow receptors. The position of the sun relative to the turbine rotor disk and the resulting shadow is calculated in time steps of one minute throughout an entire year. If the shadow of the rotor disk (which in the calculation is assumed solid) at any time casts a shadow on a receptor window, then this step will be registered as one minute of shadow flicker. The calculation also requires that the sun must be at least 3.0° above the horizon in order to register shadow flicker.

The sun's path with respect to each wind turbine location is calculated by the software to determine the paths of cast shadows for every minute of every day over a full year. The turbine runtime and direction are calculated from the site's long-term wind speed and direction distribution. Finally, the effects of cloud cover are calculated using long-term reference data (monthly sunshine probability) to arrive at the projected annual flicker time at each receptor.

4. SITE OVERVIEW

The area of interest is located in Lincoln County near the town of Hendricks in southern Minnesota. It is located on the just off of the Buffalo Ridge along the eastern slope of the Coteau des Prairies which is a long expanse of rolling hills running northwest to southeast through the southwest corner of Minnesota. The surrounding terrain has a change in elevation across the project site ranging from 465 meters to 580 meters (1,525 feet to 1,900 feet). The regions vegetation is comprised primarily of agricultural land. The area also has a number of existing wind energy projects currently in operation, primarily to the south of the Blazing Star 2 project along the Buffalo Ridge.

5. RESULTS OF ANALYSIS

The term "realistic " as used in this report means that turbine operational hours and direction as well as local sunshine probabilities have been factored in, but no blocking or shading effects due to trees or structures have been accounted for. This means that the "realistic" estimates are still inherently conservative values. The realistic shadow flicker hours predicted by windPRO assumes an availability factor of 100% which is very unlikely to be the case. The realistic shadow flicker hours predicted by windPRO were reduced by 4.2% to account for wind turbine downtime attributable to an assumed realistic availability factor of 95.8%

A total of 455 residential structures within project vicinity were analyzed and standard resolution realistic shadow flicker maps and individual maps were generated for each turbine array.

The 455 shadow receptors were then modeled as greenhouse-mode receptors and the estimated shadow flicker was calculated for each array using a 1,500 meter distance limit. The percentage of the 455 receptors that registered no shadow flicker hours for the respective turbine arrays is as follows:

- 68% - GE 2.5-116-80 m hub height
- 67% - Vestas V110-80 m hub height
- 72% - Gamesa G126-84 m hub height
- 75% - Acciona AW132-84 m hub height

Table 3 contains the shadow flicker distribution of the 455 residential structures within one mile of any turbine location along with a breakdown of how many are non-participating.

Table 3: Residential structures realistic shadow flicker distribution

Realistic Shadow Flicker (hrs/year)	GE 2.5-116-94		Vestas V110-80		Gamesa G126-84		Acciona AW132-84	
	# structures	# non-part	# structures	# non-part	# structures	# non-part	# structures	# non-part
0	309	249	304	244	323	258	336	269
0 to 5	65	35	66	40	50	24	45	19
5 to 10	31	19	26	16	39	24	23	11
10 to 15	13	4	18	4	6	2	17	9
15 to 20	17	3	10	3	16	3	12	2
20 to 25	7	1	12	4	5	0	6	1
25 to 30	2	0	5	0	2	0	1	0
30+	11	0	14	0	14	0	15	0

Tables 4 and 5 below provide a breakdown of the maximum and average number of shadow flicker hours that are projected for each of the four turbine models at participating and non-participating residences for both the worst and realistic cases.

Table 4: Summary of shadow flicker hours per year at participating residences

Participating Residences				
Statistic	**GE**	**Vestas**	**Gamesa**	**Acciona**
Max - Worst Case	196:22	175:15	195:12	215:18
Avg - Worst Case	45:50	50:31	49:19	51:38
Max - Real Case	64:14	55:24	72:55	80:27
Avg - Real Case	14:36	16:14	16:29	17:03

Table 5: Summary of shadow flicker hours per year at non-participating residences

Non-Participating Residences				
Statistic	**GE**	**Vestas**	**Gamesa**	**Acciona**
Max - Worst Case	85:21	73:21	57:23	92:53
Avg - Worst Case	18:40	19:18	18:35	21:48
Max - Real Case	22:21	24:41	18:48	21:43
Avg - Real Case	5:51	6:13	5:57	6:54

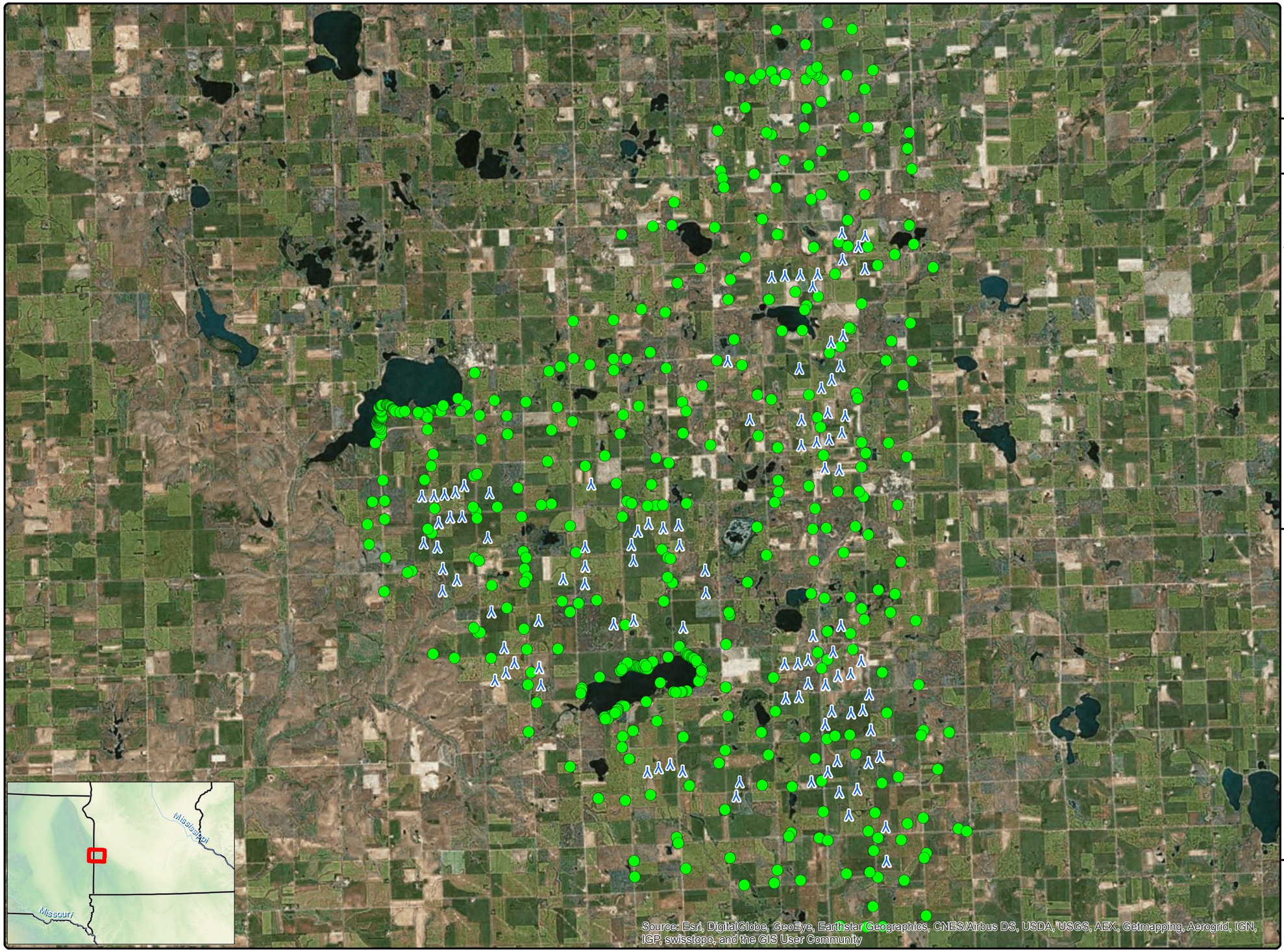
6. *CONCLUSIONS*

The conservative results of this study indicate that, of the four wind turbine model scenarios and 455 receptors modeled for each scenario, 15 measured more than 30 hours per year at participating landowners' occupied residences with none measuring over 30 hours or more per year of realistic shadow flicker at a non-participating landowner's occupied residence. The shadow flicker impact on the receptors was calculated from turbines within 1 mile with reductions due to turbine operational time, turbine operational direction and sunshine probabilities included. This shadow flicker analysis is based on a number of conservative assumptions including:

- No credit was taken for the blocking effects of trees or buildings.
- The receptors were omni-directional rather than modeling specific facades of buildings.

The overall effect of using these conservative assumptions indicate that realistically, the number of hours of shadow flicker that would be observed will be less than those predicted by this study.

APPENDIX A: BLAZING STAR 2 WIND ENERGY PROJECT SITE OVERVIEW



0 0.75 1.5 3 Mile

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Blazing Star 2 Wind Farm
Project Overview

Client

Merjent

Project Description

Primary wind turbine layout with occupied structures within one mile of proposed wind turbines or project boundary.

Location: Hendricks, MN

Project #: 20163620

Issue Dates

#	Description	Date
1	Original	2017.08.30

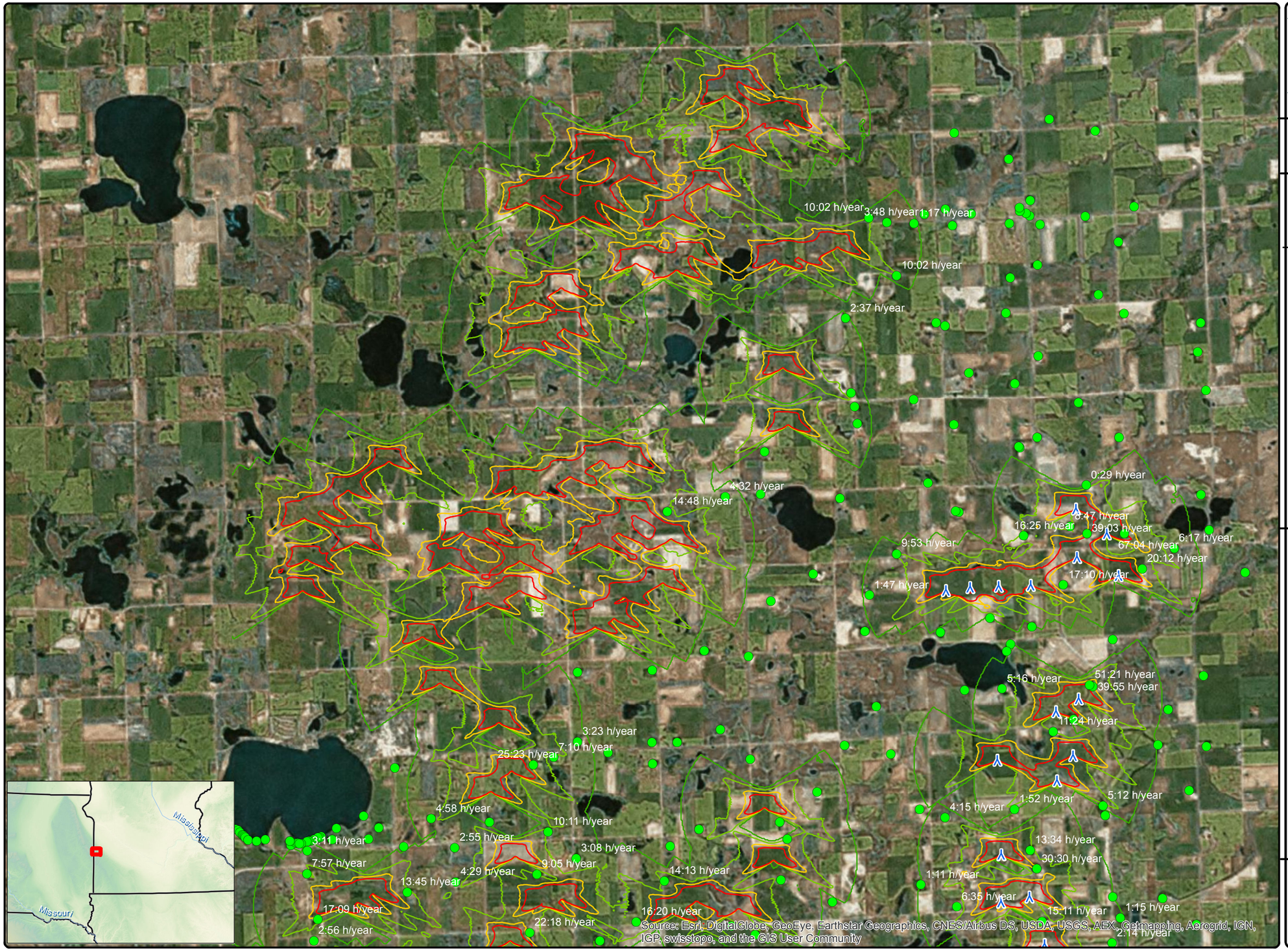
Drawn By: JH *Checked By: JH*

Legend

- Blazing Star 2 Turbines
- Blazing Star 2 Occ. Residences

N W E S

APPENDIX B: GE 2.5-116-94 LAYOUT STANDARD RESOLUTION SHADOW FLICKER MAP



0 0.5 1 2 Mile

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Blazing Star 2 Shadow Flicker Realistic Case (North Half) General Electric GE 116-94 m HH

Client

Merjent

Project Description

Shadow Flicker for GE 2.5-116 94m HH WTGs. Realistic shadow flicker map and data at receptors (hrs/yr) within at least 1 mile of turbines. Assumes statistical reduction due to sunshine probability, turbine orientation and operation probability. Sensors in "greenhouse" mode. No obstacles assumed.

Location: Hendricks, MN

Project #: 20163620

Issue Dates

#	Description	Date
1	Original	2017.08.30

Drawn By: JH *Checked By: JH*

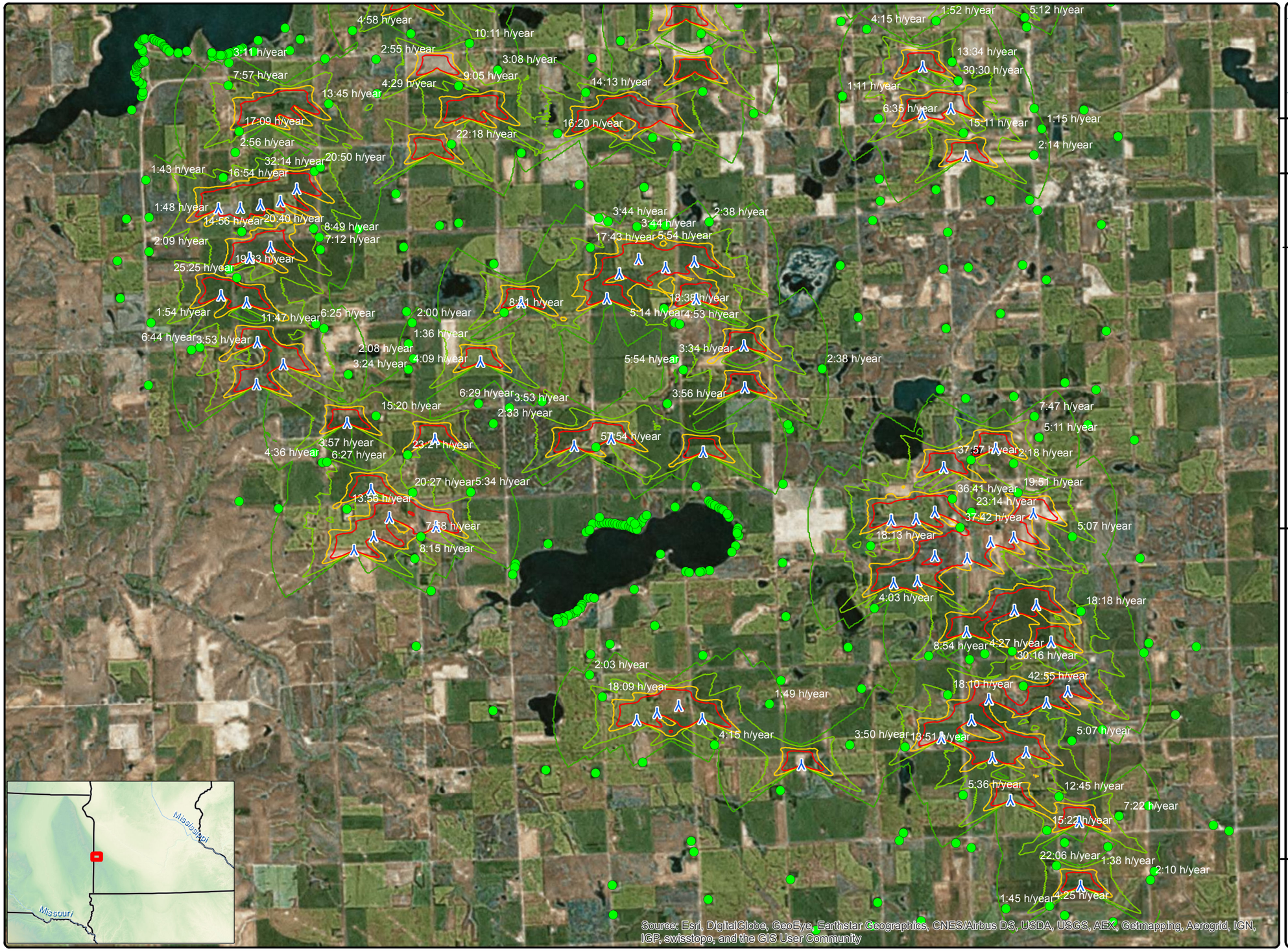
Legend

- BS2 GE-116-94
- Occupied Residences

RESULT (hrs/yr)

- 0
- 10
- 20
- 30
- 40
- 50

N W E S



0 0.5 1 2 Mile

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Blazing Star 2 Shadow Flicker Realistic Case (South Half) General Electric GE 116-94 m HH

Client

Merjent

Project Description

Shadow Flicker for GE 116 94m HH WTGs. Realistic shadow flicker map and data at receptors (hrs/yr) within at least 1 mile of turbines. Assumes statistical reduction due to sunshine probability, turbine orientation and operation probability. Sensors in "greenhouse" mode. No obstacles assumed.

Location: Hendricks, MN

Project #: 20163620

Issue Dates

#	Description	Date
1	Original	2017.08.30

Drawn By: JH *Checked By: JH*

Legend

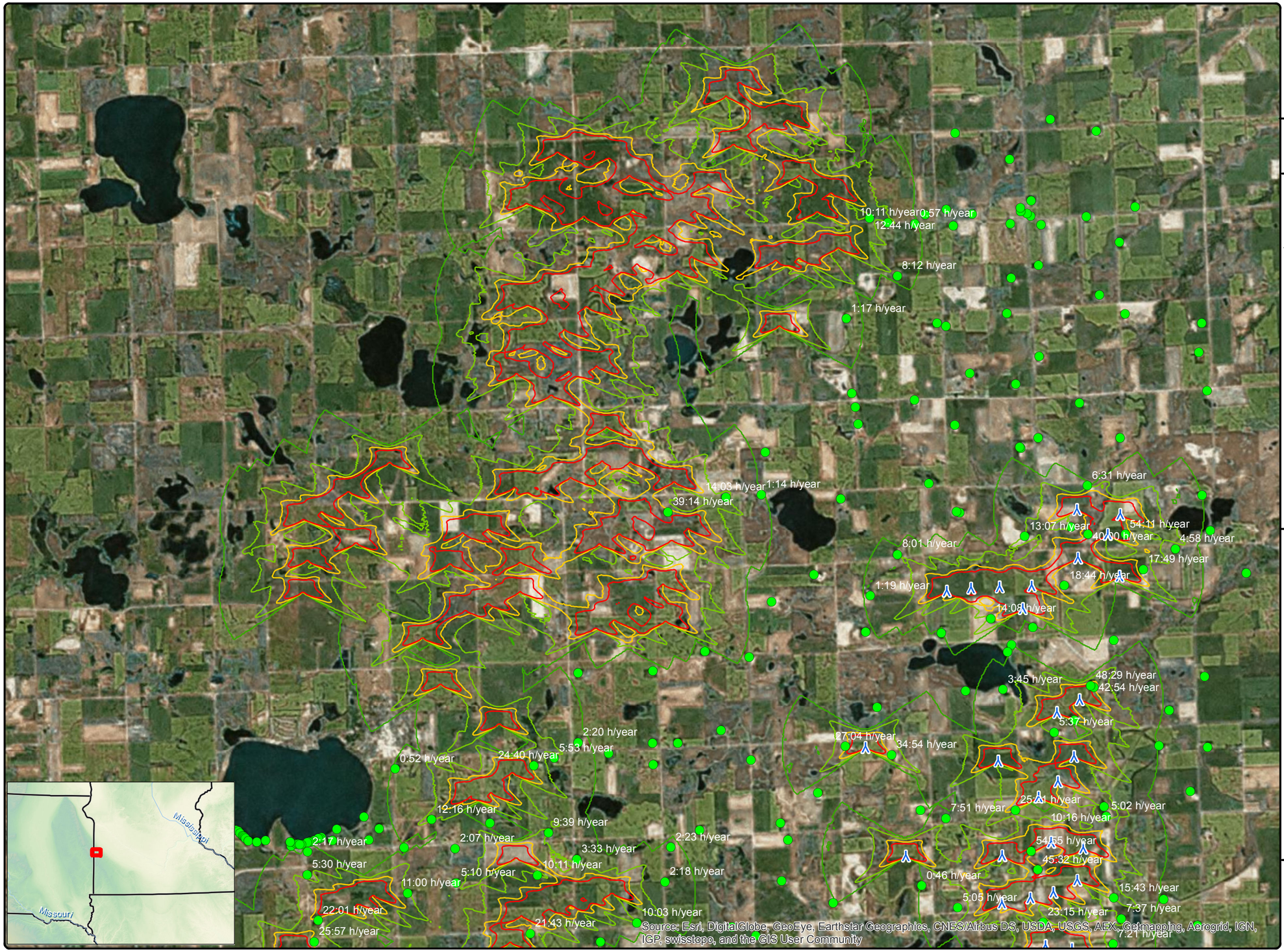
- BS2 GE-116-94
- Occupied Residences

RESULT (hrs/yr)

- 0
- 10
- 20
- 30
- 40
- 50

N W E S

APPENDIX C: VESTAS V110-80 LAYOUT STANDARD RESOLUTION SHADOW FLICKER MAP



0 0.5 1 2 Mile

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Blazing Star 2 Shadow Flicker Realistic Case (North Half) Vestas V110-80 m HH

Client

Merjent

Project Description

Shadow Flicker for Vestas V110 80m HH WTGs. Realistic shadow flicker map and data at receptors (hrs/yr) within at least 1 mile of turbines. Assumes statistical reduction due to sunshine probability, turbine orientation and operation probability. Sensors in "greenhouse" mode. No obstacles assumed.

Location: Hendricks, MN

Project #: 20163620

Issue Dates

#	Description	Date
1	Original	2017.08.30

Drawn By: JH | Checked By: JH

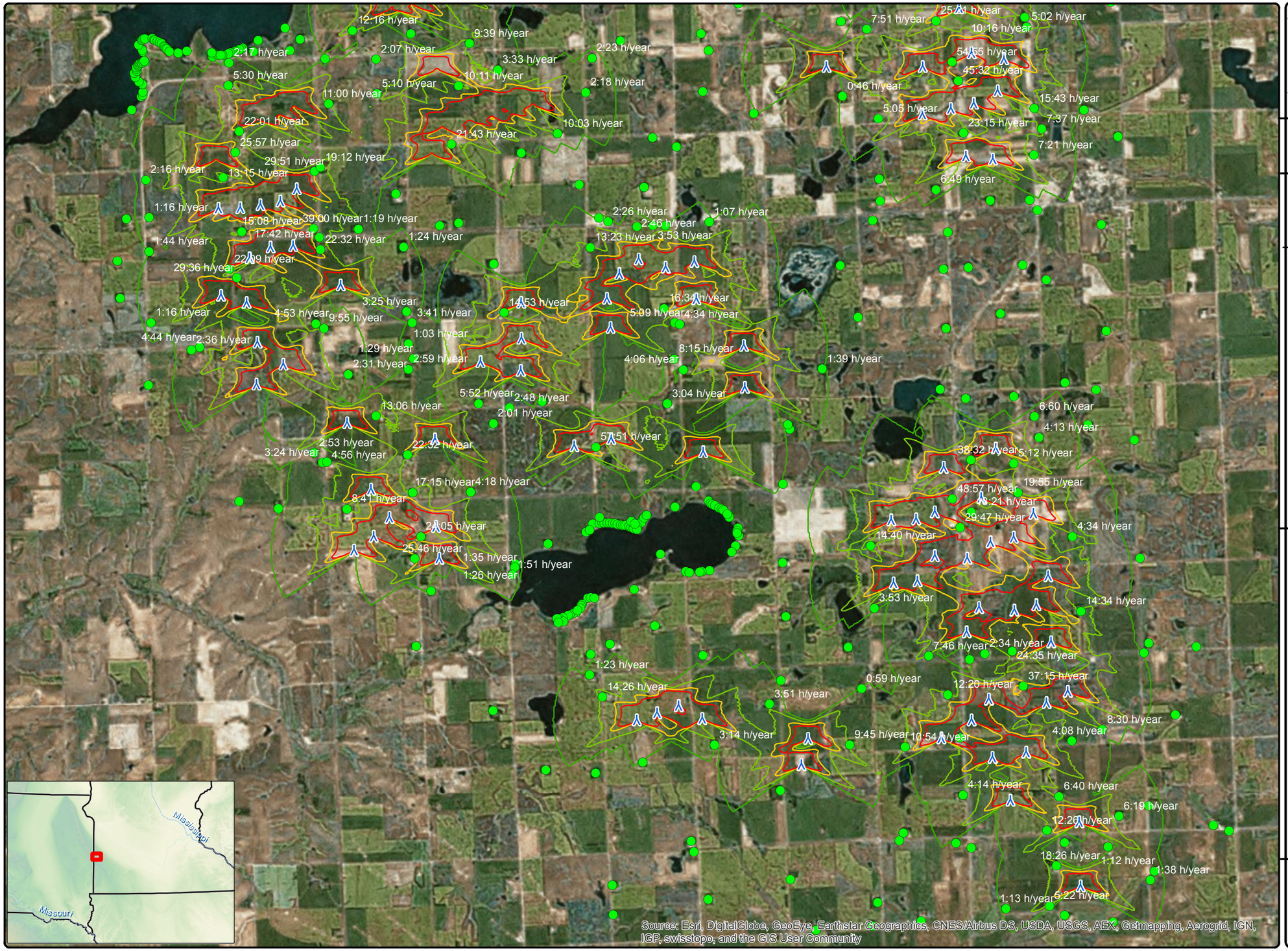
Legend

- BS2_V110-80
- Occupied Residences

RESULT (hrs/yr)

- 0
- 10
- 20
- 30
- 40
- 50

N W E S



0 0.5 1 2 Mile

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Blazing Star 2 Shadow Flicker Realistic Case (South Half) Vestas V110-80 m HH

Client

Merjent

Project Description

Shadow Flicker for Vestas V110 80m HH WTGs. Realistic shadow flicker map and data at receptors (hrs/yr) within at least 1 mile of turbines. Assumes statistical reduction due to sunshine probability, turbine orientation and operation probability. Sensors in "greenhouse" mode. No obstacles assumed.

Location: Hendricks, MN

Project #: 20163620

Issue Dates

#	Description	Date
1	Original	2017.08.30

Drawn By: JH *Checked By: JH*

Legend

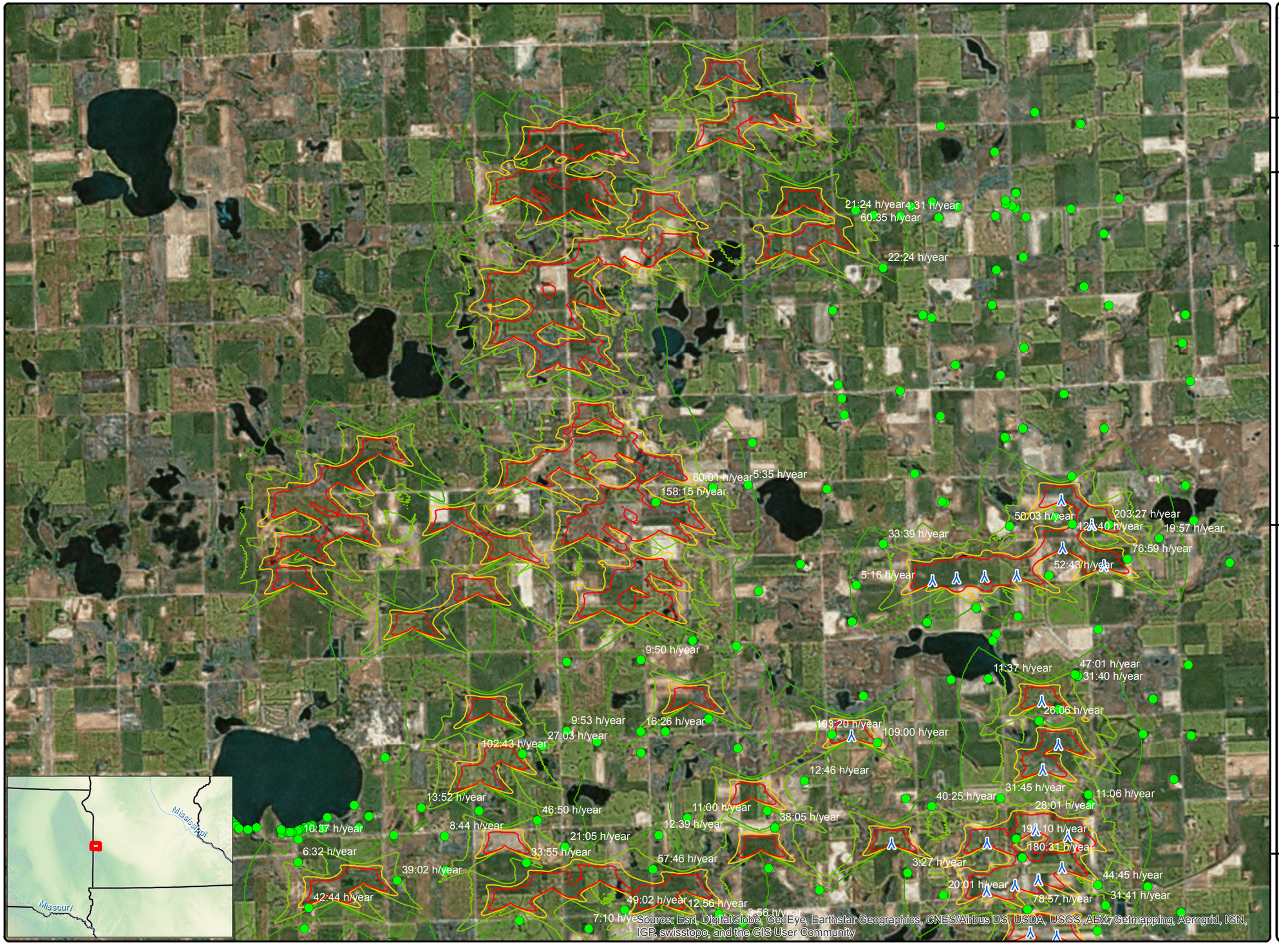
- BS2_V110-80
- Occupied Residences

RESULT (hrs/yr)

- 0
- 10
- 20
- 30
- 40
- 50

N W E S

APPENDIX D: GAMESA G126-84 LAYOUT STANDARD RESOLUTION SHADOW FLICKER MAP



0 0.5 1 2 Mile

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Blazing Star 2 Shadow Flicker Realistic Case (North Half) Gamesa G126-84 m HH

Client

Merjent

Project Description

Shadow Flicker for G126 84m HH WTGs. Realistic shadow flicker map and data at receptors (hrs/yr) within at least 1 mile of turbines. Assumes statistical reduction due to sunshine probability, turbine orientation and operation probability. Sensors in "greenhouse" mode. No obstacles assumed.

Location: Hendricks, MN

Project #: 20163620

Issue Dates

#	Description	Date
1	Original	2017.08.30

Drawn By: JH *Checked By: JH*

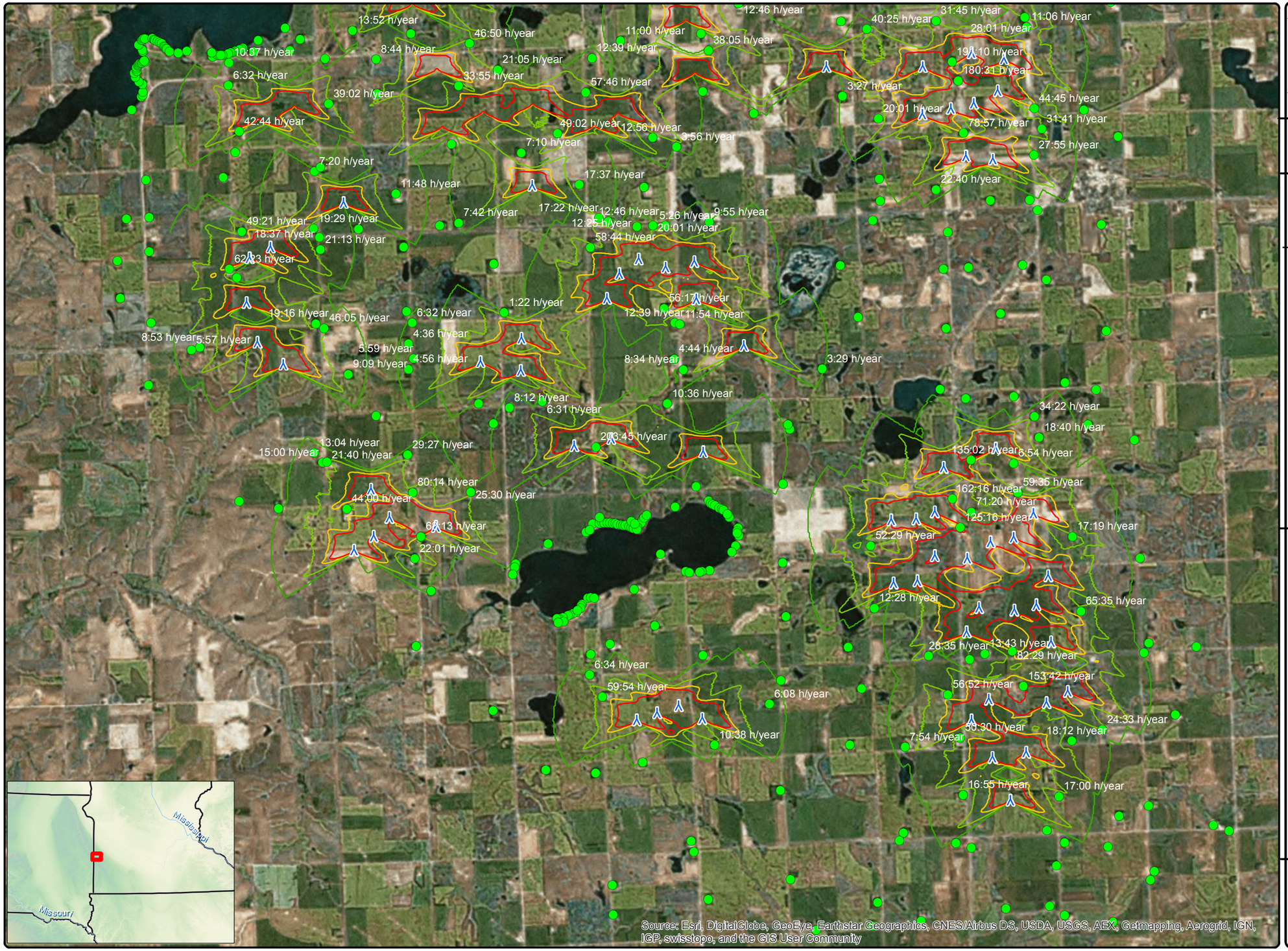
Legend

- Occupied Residences
- BS2 G126-84

RESULT (hrs/yr)

- 0
- 10
- 20
- 30
- 40
- 50

N W E S



0 0.5 1 2 Mile

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Blazing Star 2 Shadow Flicker Realistic Case (South Half) Gamesa G126-84 m HH

Client

Merjent

Project Description

Shadow Flicker for G126 84m HH WTGs. Realistic shadow flicker map and data at receptors (hrs/yr) within at least 1 mile of turbines. Assumes statistical reduction due to sunshine probability, turbine orientation and operation probability. Sensors in "greenhouse" mode. No obstacles assumed.

Location: Hendricks, MN

Project #: 20163620

Issue Dates

#	Description	Date
1	Original	2017.08.30

Drawn By: JH *Checked By: JH*

Legend

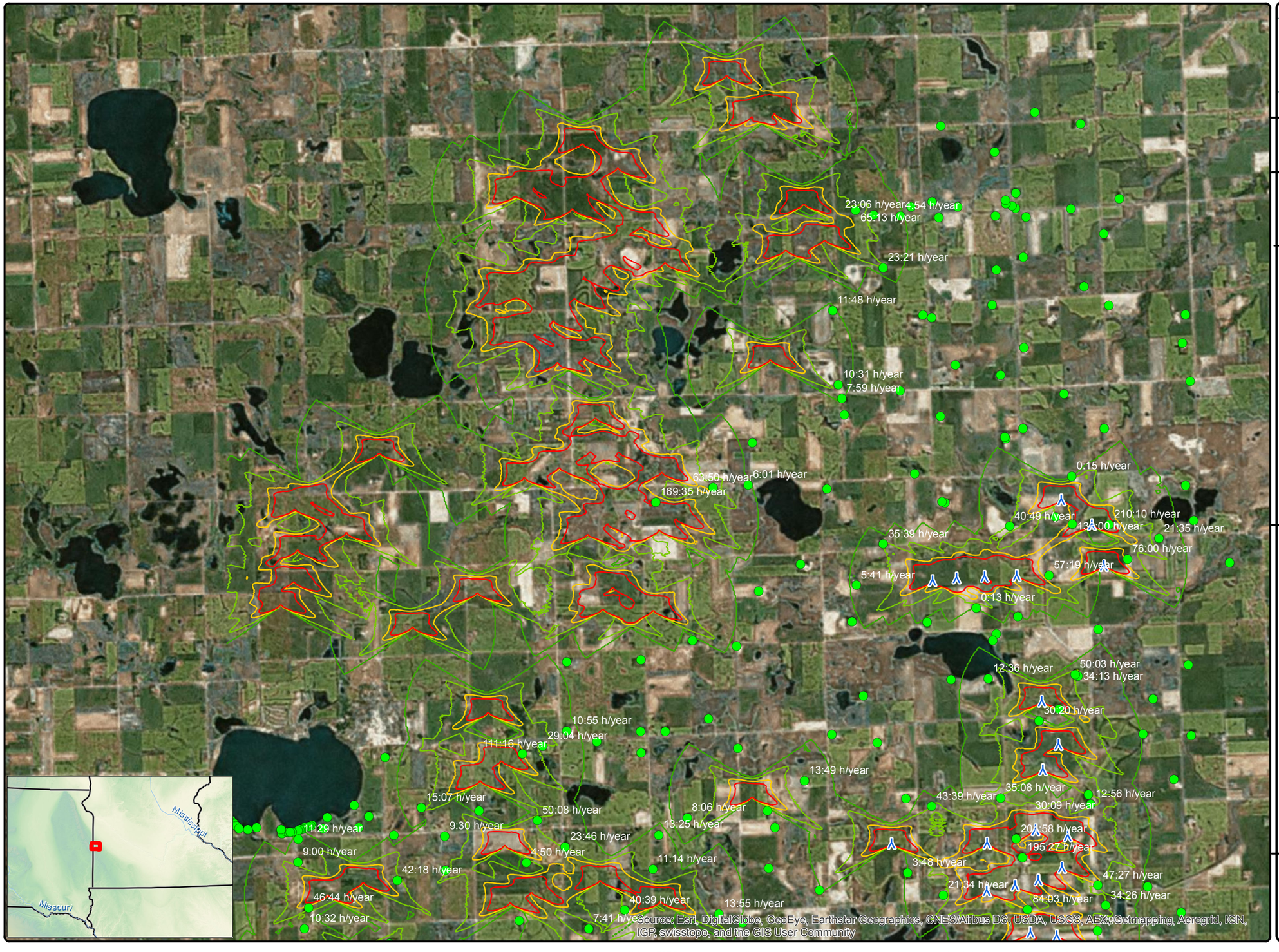
- Occupied Residences
- BS2 G126-84

RESULT (hrs/yr)

- 0
- 10
- 20
- 30
- 40
- 50

N W E S

APPENDIX E: ACCIONA AW132-84 LAYOUT STANDARD RESOLUTION SHADOW FLICKER MAP



0 0.5 1 2 Mile

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Blazing Star 2 Shadow Flicker Realistic Case (North Half) Acciona AW132-84 m HH

Client

Merjent

Project Description

Shadow Flicker for AW132 84m HH WTGs. Realistic shadow flicker map and data at receptors (hrs/yr) within at least 1 mile of turbines. Assumes statistical reduction due to sunshine probability, turbine orientation and operation probability. Sensors in "greenhouse" mode. No obstacles assumed.

Location: Hendricks, MN

Project #: 20163620

Issue Dates

#	Description	Date
1	Original	2017.08.30

Drawn By: JH *Checked By: JH*

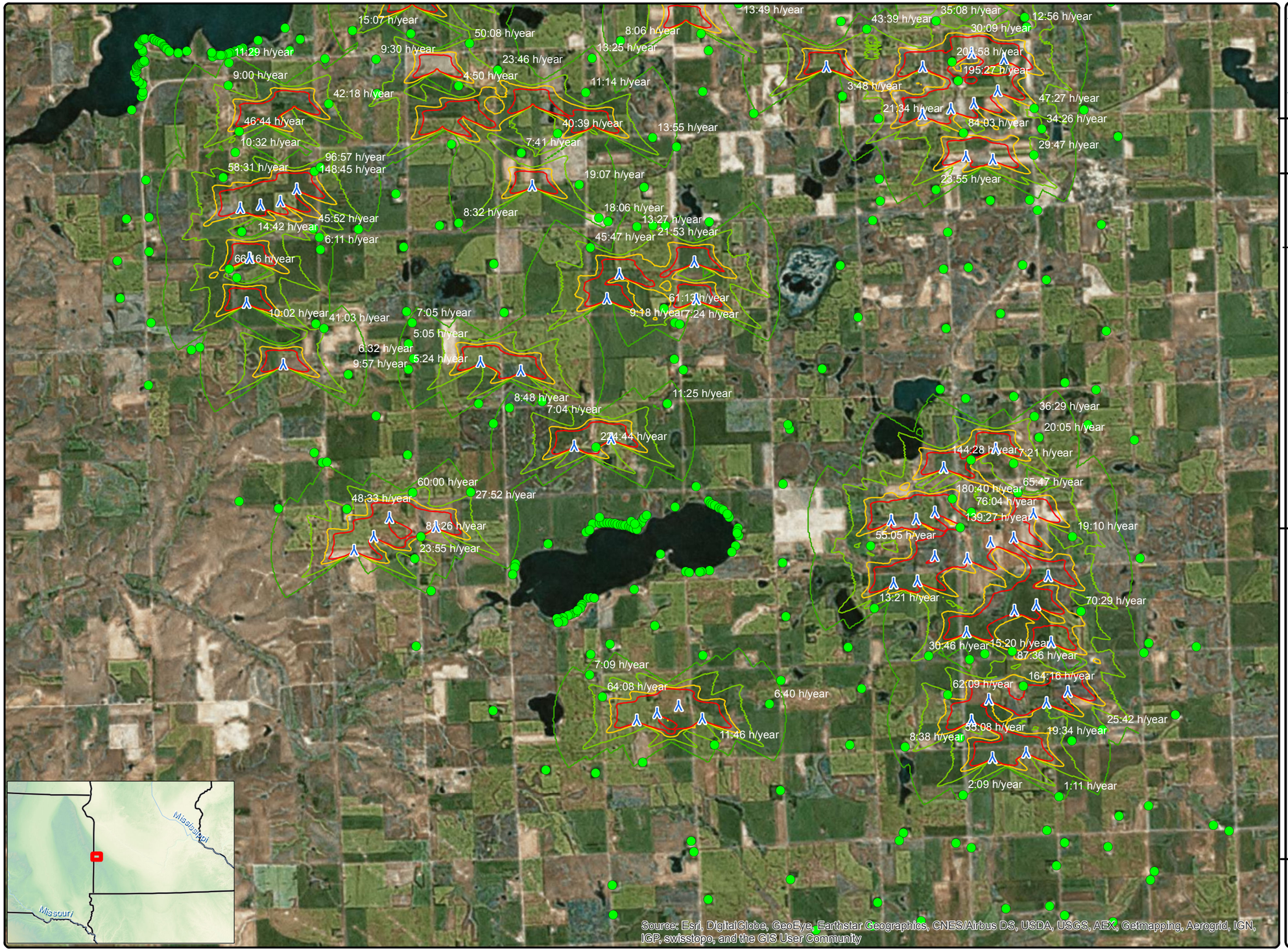
Legend

- Occupied Residences
- BS2 AW132-84

RESULT (hrs/yr)

- 0
- 10
- 20
- 30
- 40
- 50

N W E S



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Blazing Star 2 Shadow Flicker Realistic Case (South Half) Acciona AW132-84 m HH

Client

Merjent

Project Description

Shadow Flicker for AW132 84m HH WTGs. Realistic shadow flicker map and data at receptors (hrs/yr) within at least 1 mile of turbines. Assumes statistical reduction due to sunshine probability, turbine orientation and operation probability. Sensors in "greenhouse" mode. No obstacles assumed.

Location: Hendricks, MN

Project #: 20163620

Issue Dates

#	Description	Date
1	Original	2017.08.30

Drawn By: JH *Checked By: JH*

Legend

- Occupied Residences
- BS2 AW132-84

RESULT (hrs/yr)

- 0
- 10
- 20
- 30
- 40
- 50

N W E S

0 0.5 1 2 Mile