Assessing Visual Landscape Sensitivity towards Wind Turbines with a Distance Decay Effect: An Exploration of Different GIS Approaches

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Abstract: The German energy transition has come to a halt in terms of on-shore wind turbine deployment. This is to a large extent due to public opposition. Sensitive siting of wind farm locations in the landscape early in the planning process might help to overcome this problem. In our paper, we investigate different methods for visual landscape sensitivity analysis towards wind turbines that can be used as one input into spatial planning at the federal state or regional level, where strategic decisions for wind farm locations are mainly taken. Statistically comparing different methodological approaches, different distance decay effects with different distance weights and different GIS algorithms, we conclude that (a) large-area visual sensitivity analyses are possible, (b) the distance decay effect has a negligible influence on the spatial distribution of visual sensitivity and (c) that there are more methodological questions that should be empirically investigated in order to base strategic wind farm siting decisions on a valid information basis.

Keywords: Visual landscape sensitivity, wind turbines, assessment, GIS, distance decay effect

1 Introduction

An increasing share for renewable energy sources is not only a target of the European 2030 Climate and Energy Framework (EUROPEAN COMMISSION n.d.) but also of the German Climate Protection Program (BMU 2019). In order to realize the targets, existing potentials need to be utilized with solar and wind power being the most important ones in Germany (BFN 2019). Therefore, German spatial planning authorities have the legal task to designate areas for possible wind energy use in a substantial share of their administrative area (FA WIND 2016). After a continuously rising number of newly installed wind turbines since the early 2000s, wind power deployment came to a halt in Germany in 2017 (FA WIND 2020).

Despite the set political goals, selecting concrete sites for wind power development and ensuring public acceptance for these new landscape elements remains a major difficulty in spatial planning. Residents often perceive the process of change critically. Wind turbines in particular change the visual landscape by their sheer dominance. This happens due to their height (200 m and above), their technical design and the moving blades (BREUER 2001). LIMA et al. (2013) briefly summarize additional imposed impacts of wind turbines. The subsequent landscape transformation might even lead to a shift from a (more or less) traditional cultural landscape into an energy landscape. Consequently, wind turbines impair visual landscape functions like the scenic landscape quality or the recreation potential (NOHL 1993).

Yet, the impact on landscape aesthetics is not uniform. Perception varies depending on the landscape configuration and personal attitude (ZUBE et al. 1982, NOHL 2001). It is commonly accepted that the perceived visual impact caused by a wind turbine decreases with distance

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from the observer (e. g. BREUER 2001, BISHOP & MILLER 2007, DE VRIES et al. 2012, MOLNAROVA et al. 2012, BETAKOVA et al. 2015). This is called distance decay effect.

The visual impact is inter alia characterized by visual sensitivity (BACHFISCHER 1978). Visual sensitivity is less often investigated and has no universal definition. For example, STORE et al. (2015) took visibility, potential users and visual landscape quality into account. While GERHARDS (2003: 97) found landscape character to be important for visual sensitivity as well, he also pointed to visual vulnerability/visibility to be important especially for regional planning.

We understand visual landscape sensitivity as an indicator that describes the potentially impacted area if a project is realized at a certain location. This indicator is – at first – independent of specific locations of viewers, the landscape quality and character in the area and existing impacts from other structures. Nevertheless, in a complete visual impact assessment our sensitivity indicator can – and should be – combined with the three mentioned other aspects. We focused our study on visual sensitivity solely on visibility: Visual vulnerability can be analyzed using visibility analyses. We investigated five different approaches to calculate a visibility index as a proxy for visual landscape sensitivity. Low visual landscape sensitivity is the ability of a landscape to cloak negatively affecting objects (ROTH & BRUNS 2016: 52f.).

Of particular interest is how the distance decay effect affects visual landscape sensitivity. Distant wind turbines are perceived as less intrusive as close ones. However, little research has been done to assess how the generally accepted distance decay effect of visual impacts influences sensitivity results.

BRUGHMANS et al. (2018) and HILDEBRANDT (2015) differentiate three approaches to work with distance weights for the inclusion of the distance decay effect in sensitivity analyses:

- No distance weight (no distance decay effect)
- Stepwise discrete distance weights (zonal distance decay effect)
- Continuous distance weight (continuous distance decay effect)

Figure 1 visualizes the distance decay effect for these approaches. A uniform distance weight corresponds to no distance decay effect and no distance weights. A stepwise approach uses distance zones (bands) as visual impact thresholds with specific distance weights. Lastly, with a continuous distance decay effect the distance weight changes continuously.

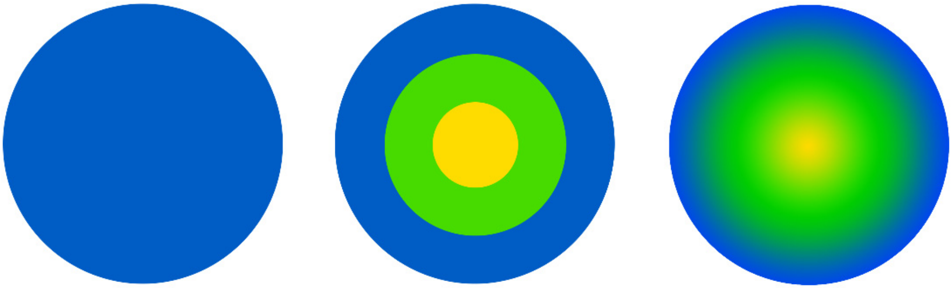

Fig. 1: Visual representation of approaches to model the distance decay effect; adapted from BRUGHMANS et al. (2018, 16)

Even though a theoretic basis exists, there is no large-scale application for visual landscape sensitivity assessments with a distance weight. Distance weights were only integrated into a few methods with purposes other than visual landscape sensitivity (e. g. WAGTENDONK & VERMAAT 2014, GIBBONS 2015, BRUGHMANS et al. 2018). Our aim is to close this gap by investigating the implementation of a distance weight into large-area sensitivity calculations for wind turbines. Specifically, our objectives are (a) to develop Geographic Information System (GIS) procedures to cover each of the three approaches of a distance decay effect, (b) to compare the resulting visual sensitivity and (c) to suggest the most efficient methodology based on performance. For the explorative study of visual landscape sensitivity with a distance weight, we used parts of the federal German state of Thuringia.

Knowledge of visual landscape sensitivity prior to specific wind energy projects is essential to inform spatial planning authorities. Consequently, different sites for wind power development are identifiable and comparable. This allows the inclusion of landscape aspects into earlier stages of planning, when specific locations for wind turbines are not yet determined. Well-founded, responsible siting decisions help to avoid or minimize negative visual impacts of wind turbines and to protect sensitive areas. This could also contribute to higher public acceptance of well-sited new energy infrastructure.

2 Methods

Our main research aim was to develop GIS procedures to include a distance weight into visual landscape sensitivity assessment for wind turbines. These should be applicable for large-area analyses. We also wanted to know, how visual landscape sensitivity differs between these approaches and the corresponding implications. We solely focused on visibility and therefore used different modifications of visibility analyses.

It is important to recognize the difference between visibility and viewshed analyses. Using a GIS for viewshed analyses is state of the art to quantify a project's visual impact (e. g. PAUL et al. 2004, MÖLLER 2006, WRÓŻYŃSKI et al. 2016). In this case, location and dimension of a turbine are known. The field of view is calculated from the turbine tip while a potential viewer is placed on each cell to quantify the impact. However, the deployment for visibility analyses to quantify visual sensitivity is also possible (e. g. FISCHER & ROTH 2020). Therefore, the setting of the viewshed analysis is inversed. We do not look from a wind turbine at viewers but from viewers to a wind turbine. The visibility analysis assesses the visual landscape sensitivity against potential wind turbines' impacts. Here the location of the wind turbine is not known. Hypothetical observer points (persons) are placed in a landscape. The visibility analysis places a potential turbine tip over each raster cell and calculates the number of observer points from which the tip is visible. Using this approach it is possible to compare the visual sensitivity of different areas to potential energy infrastructure development.

We hypothesized that using a uniform distance weight is the fastest and simplest approach. Furthermore, we believed that visual landscape sensitivity to wind turbines differs depending on applied coefficients and thresholds.

We used five GIS procedures to assess visual sensitivity to potential wind turbines with 200 m tip height. Table 1 summarizes the approaches. We gave meaningful names to all approaches to indicate the main concept of each method. They cover all distance decay approaches and calculate a visibility index.

We integrated understandings of NOHL (1993) and BREUER (2001) into the method by FISCHER & ROTH (2020). Both primarily focused on offering a method to calculate the necessary area of compensation measures for impacted landscape aesthetics. Even though NOHL's (1993) approach is almost 30 years old, the method itself or modifications are still part of German planning practice. Our integration of a continuous distance decay effect for visibility analyses is new in the field of landscape planning. All results were reclassified using seven levels of sensitivity and a quantile distribution. This simplifies spatial comparison.

Table 1: Methodologies to integrate a distance weight and GIS procedure

	Approach of distance weight integration		
	Uniform distance decay effect	**Stepwise distance decay effect**	**Continuous distance decay effect**
Underlying methodology	1. Uniform analysis (3 km) after BREUER (2001) 2. Uniform analysis (10 km) after FISCHER & ROTH (2020)	Stepwise analysis after NOHL (1993)	1. Observer viewshed 2. QGIS Interpolation
GIS procedure	1. Adapted from FISCHER & ROTH (2020) 2. Adopted from FISCHER & ROTH (2020)	Adapted from FISCHER & ROTH (2020)	1. Summarized viewshed based on hypothetical observers 2. Lines of sight and interpolation

We conducted the analyses for a 20 × 20 km tile of the German federal state of Thuringia (shown in Figure 2). The state is in the heart of Germany, which prevents boundary effects due to abrupt end of data. Furthermore, it contains diverse landscapes with gradients in relief, anthropogenic dominance and a varied land use. Additionally, FISCHER & ROTH (2020) developed their original method for this state and their results are available for comparisons.

We used ArcMap (Version 10.6.1) and its "Viewshed 1" to calculate the visibility indices for all selected methodologies except the QGIS interpolation. We deployed QGIS (Version 3.10.1) for the QGIS interpolation and R (R CORE TEAM 2020) for further statistical analyses. We calculated Pearson's correlation coefficients to compare the resulting visibility indices.

National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.

Fig. 2: Location of the investigation area within Germany.
The map shows the federal state of Thuringia (red contour; ATKIS, © GDI-Th, Date: 30.06.2020) and the 20 × 20 km tile of the investigation.

2.1 General Assumptions of Visibility Analyses

Visibility analyses calculate for each cell how many hypothetical observers (persons) within a fixed distance are able to see the tip of a potential wind turbine if the tip is located above the center of the raster cell. In our case, the obtained frequency quantifies the visibility of a 200 m high wind turbine when erected on a cell based on set observer points. This frequency value equals the visibility index and is our proxy for the visual landscape sensitivity. A higher value equals a higher sensitivity. Assigning a decreasing distance weight to each observer reflects the declining visual impact with distance.

Observer points, representing fictive persons with an average German eye height of 1.57 m (JÜRGENS 2004), are the basis for a visibility analysis. They are spread in a regular grid (500 × 500 m) throughout the study area. Points that are located within land use types with a vertical extent permanently higher than eye height (namely forest and settlement) are excluded from the visibility analyses, as their field of vision is restricted. Additionally earth curvature correction was always applied. A Digital Surface Model with a resolution of 10 m (based on DSM2 © GDI-Th: 2010-2013, adjusted by FISCHER & ROTH 2020) was the basis for all methods. It determined the resulting sensitivity resolution. We used the data in all methodologies. Figure 3 shows the topographic characteristics of the investigated area.

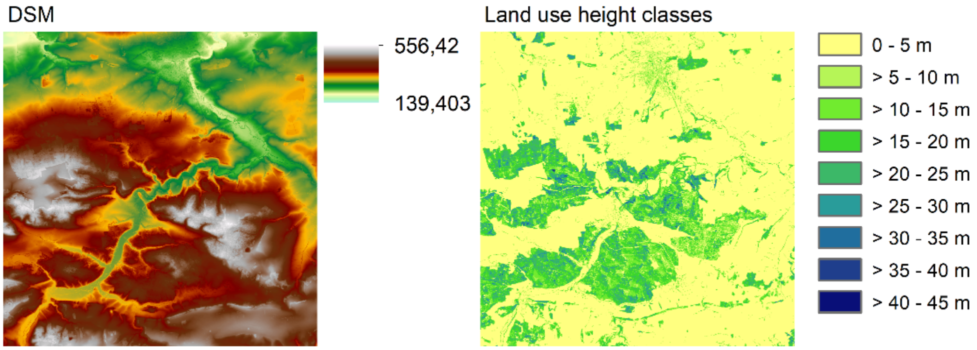

Fig. 3: Digital Surface Model and land use height classes of the investigated area

Another important parameter for visibility analyses is the maximum analysis distance. This corresponds to the maximum viewing distance. Visibility is examined only within this boundary. After this threshold, the assumption of a visual impact caused by a wind turbine is neglected. A visibility range of 10 km is typically applied in Germany (TÄUBER & ROTH 2011) and is used within all methodologies except in the uniform analysis (3 km). The maximum viewing distance also acts as a buffer enlarging the analyzed area to exclude boundary effects. Otherwise, visual sensitivity is underestimated closer to the border, as less observers exist. The area with results, the 20 × 20 km tile respectively, remains the same for all approaches.

Furthermore, the application of the distance decay effect needs to be set. The selected methodologies correspond to different distance decay effects and apply diverging distance weights as shown in Table 2 and Figure 4. The latter allows for a visual comparison of the applied distance weights for each distance from the turbine to the observer. The continuous distance decay effect is modelled with a linear decrease in distance weight from 1 (observer close to turbine) to 0 (observer at maximum viewing distance).

Table 2: Applied distance weights per visual zone

	Method	**Zone**	**Distance weight (coefficient)**
Uniform distance decay effect	Uniform analysis (3 km) after BREUER (2001)	0 – 3,000 m	1
	Uniform analysis (10 km) after FISCHER & ROTH (2020)	0 – 10,000 m	1
Stepwise distance decay effect	Stepwise analysis after NOHL (1993)	0 – 200 m	0.6
		200 – 1,500	0.3
		1,500 – 10,000 m	0.04
Continuous distance decay effect	Observer viewshed	0 – 10,000 m	Linear decrease from 1 to 0
	QGIS Interpolation	0 – 10,000 m	Linear decrease from 1 to 0

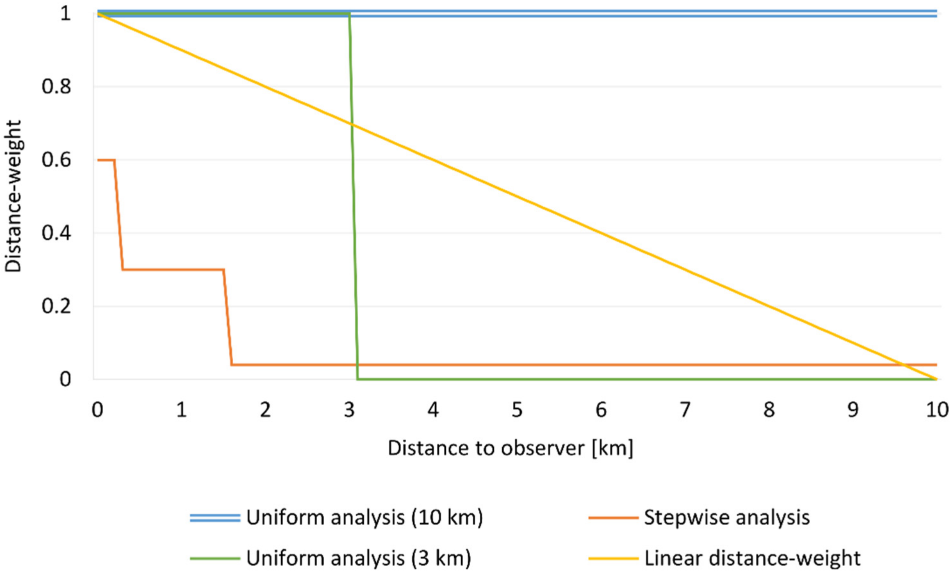

Fig. 4: Visualization of the applied distance weights; adapted from HILDEBRANDT (2015, 67), modified

The uniform analysis (3 km) as well as the uniform analysis (10 km) follow an all-or-nothing approach with no distance decay effect (uniform). Here every observer, who is able to see the turbine tip, is weighted equally. The stepwise analysis differentiates between three zones of distance between an observer and a turbine. For each zone, NOHL (1993) selected a distance weight to classify the strength of the visual impact as integrated in the stepwise analysis.

2.2 GIS Procedures in the Uniform Analysis (10 km) after FISCHER & ROTH (2020)

FISCHER & ROTH (2020) developed a workflow to assess visual landscape sensitivity for large areas using a visibility analysis. The methodology and the results are our baseline within the uniform analysis (10 km). We explain their GIS procedure below. The authors calculated a visibility index with high resolution. They developed the workflow around the ArcMap tool “viewshed 1” which allows several specifications as summarized in Table 3.

Table 3: Parameter settings used by FISCHER & ROTH (2020) and within the uniform analysis (10 km)

Parameter name	Representation of	Value [m]
OFFSETA	Hypothetical observer / person eye height	1.57
OFFSETB	Height of potential turbine	200
RADIUS2	Maximum viewing distance	10,000

The tool "Viewshed 1" adds the OFFSETB value to every cell of the DSM. This leads to errors if a cell has a permanent land use height (forest and settlement) as the sum implies higher turbines. To cope with this problem, FISCHER & ROTH (2020) classified land use height in classes with 5 m intervals (see Figure 3). The value of each land use height class is subtracted from the 200 m original turbine height. For each of the resulting heights (adjusted OFFSETB) visibility analyses covering the investigated area completely were conducted. The final visibility index is the combination of the interim-results, where the value corresponds to the land use height class of each cell.

2.3 Adaptations for the Uniform Analysis (3 km) after BREUER (2001)

To obtain visual landscape sensitivity for the constant effect within the uniform 3 km analysis, we adjusted the uniform analysis (10 km) to the understanding of the maximum viewing distance by BREUER (2001). He believes that a considerable visual impact only occurs within a radius 15-times the turbine height. The maximum viewing distance was thus reduced to 3,000 m. This value acted as the visual threshold for the visibility analysis. All other parameter settings match the ones of the uniform analysis (10 km) to calculate the visibility index.

2.4 Adaptations for the Stepwise Analysis after NOHL (1993)

For integrating the stepwise distance decay effect, we calculated the visibility index per distance zone. NOHL (1993) defined the thresholds. We selected the zones by using a minimum (RADIUS1) and a maximum distance (RADIUS2) as corresponding thresholds. As a result, the frequency of observers within the specific zones who are able to see the potential wind turbine was calculated. We integrated the distance weights by NOHL (1993) by multiplying the frequency per zone with the corresponding distance weight coefficient. Then, all results were summed up.

Since the first zone ends at 200 m distance from the observer but observers are arranged with 500 m between them, no values were calculated for some cells. However, tests showed that observers are able to see a wind turbine within a 200 m radius with almost no exception. We consequently assumed that an observer in this zone would always see a wind turbine and consequently set the interim-result to one. With this setting, we were able to work with area-wide values. In areas with a land use height, visibility was assumed to be nil.

2.5 GIS Procedures Based on Methodology Observer Viewshed

For the representation of a continuous distance decay effect, we developed a new workflow using the ArcMap ModelBuilder. It is a summarized viewshed analysis of all primarily selected observer points (see Section 2.1). Within the model, each observer is selected separately. Then a viewshed analysis (tool "Viewshed 1") integrating the DSM starts. The settings match the ones made in the uniform analysis (10 km) in Table 3. The results show all cells where a potentially installed turbine tip is visible for this one observer. Additionally, the Euclidean distance is calculated with a radius of 10,000 m (matching maximum viewing distance) starting from the selected observer (hypothetical person) and a resolution of 10 m (matching DSM resolution). These values are inversed and normalized to values from zero (far from the observer) to one (close to the observer) to represent distance weights with a continuous distance decay effect. Next, we intersected the area of visibility and the inversed Euclidean distance. Only areas, which are visible from the observer, maintain their weight value. All other cells are set to zero. Subsequently, all distance weighted raster datasets are summed up to create the visibility index for one fixed height.

As the same parameters as used in the uniform analysis (10 km) are applied, errors as described in Section 2.2 occur likewise from only using one fixed height as OFFSETB. Consequently, the previously described procedure was repeated for all adjusted heights (OFFSETB) used in the uniform analysis (10 km). Finally, the visibility index of each cell is selected by taking the calculated value following the land use height class of the cell.

2.6 GIS Procedures Based on Methodology QGIS Interpolation

We developed an additional GIS approach independent of ArcGIS and a viewshed tool. Instead, we used the tool "Intervisibility network" by CUCKOVIC (2016) in QGIS. The tool creates lines of sight between two sets of points. One set acts as the observers and one as the targets. This calculation is based on the DSM.

The previously described methods calculate the visual landscape sensitivity for each cell of the DSM. This is not possible using the tool "Intervisibility network". Instead, we created a point-feature class arranged uniformly in a grid with 100 m distance between points. These points represent the wind turbines that are potentially placed on the cells. As their height value is also added to the land use height, we subtracted the land use height class from the 200 m object height to receive the right height. This dataset worked as source dataset in the tool. The tool draws lines of sight to each point of our observer dataset that lies within maximum viewing distance of 10,000 m and is visible.

Each resulting line characterizes a visual relation between a potential turbine and an observer. We calculated the length of the line. After inversing and normalizing, a distance weight was obtained. Next, we summed up all distance weights (originating from lines) per source point (representing a turbine). Thereby, the distance weighted frequency of observers who were able to see the tip of the potential wind turbine (visibility index) resulted. These values were interpolated (Natural Neighbor) to create an area-wide grid with 10 m resolution.

3 Results

Table 4 summarizes the needed computing time to calculate the visibility index in the investigated area for each selected methodology using one workstation. Time needed to prepare the relevant datasets, as well as additional steps like the conversion into a sensitivity assessment are not included.

Table 4: Time for calculation of visibility frequency in the investigated area using one workstation

Method	Time (hh:mm:ss)
Stepwise analysis	Ca. 40:00:00
Uniform analysis (3 km)	Ca. 12:00:00
Uniform analysis (10 km)	Ca. 28:00:00
Observer viewshed	Ca. 177:00:00 (> 7 days)
QGIS Interpolation	Ca. 13:00:00

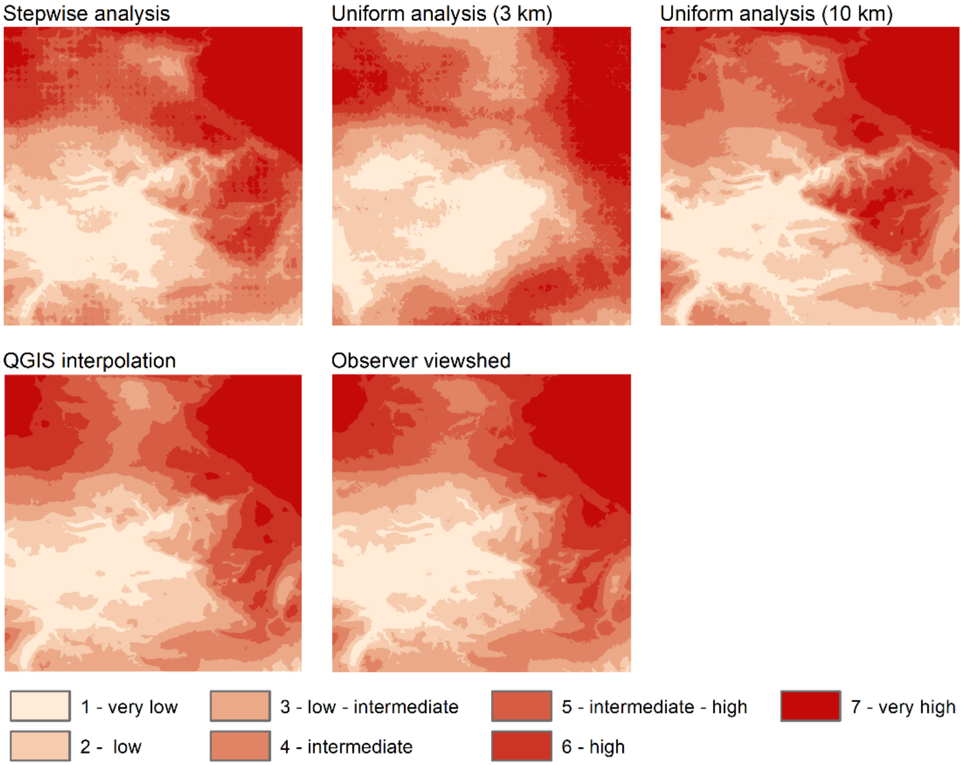

Fig. 5: Spatial comparison of the visual sensitivity as predicted by all approaches using a quantile distribution

Absolute values of the visibility indices differ substantially. However, values based on the observer viewshed and the QGIS interpolation are very similar. The visual sensitivity is comparable using classes based on a quantile distribution as illustrated in Figure 5.

The results based on the stepwise and uniform analyses 10 km, as well as the ones based on the QGIS interpolation and the observer viewshed, are particularly similar and spatially comparable with slight deviations. These four partly resemble the topography. Open areas with less undulating terrain tend to higher sensitivity. Meanwhile valleys and mountainous regions possess a lower visual sensitivity.

Results based on the stepwise analysis are coarser. Sensitivity, after the uniform analysis (3 km), differs from all others with contrasting sensitivity especially in the east and southeast. This result also seems to be stronger influenced by land use height classes with larger areas of the lowest height class having high sensitivity.

Table 5 summarizes the calculated correlation coefficients for all pairwise comparisons. All pairs correlated positively and statistically highly significant. The visibility index based on the uniform analysis (10 km) correlated strongly with all other values except the one based on the uniform analysis (3 km). Here correlation was moderate. All other pairs show strong correlations. The results by the observer viewshed and the QGIS interpolation correlated almost perfectly.

Table 5: Pearson's correlation coefficients of the visibility indices

	Stepwise analysis	**Uniform analysis (3 km)**	**QGIS interpolation**	**Observer viewshed**
Uniform analysis (10 km)	r = 0.97 $p \leq 0.001$	r = 0.67 $p \leq 0.001$	r = 0.94 $p \leq 0.001$	r = 0.95 $p \leq 0.001$
Stepwise analysis		r = 0.80 $p \leq 0.001$	r = 0.97 $p \leq 0.001$	r = 0.97 $p \leq 0.001$
Uniform analysis (3 km)			r = 0.84 $p \leq 0.001$	r = 0.84 $p \leq 0.001$
QGIS interpolation				r = 0.99 $p \leq 0.001$

4 Discussion

This study investigated different approaches to integrate the distance decay effect into visual sensitivity assessment towards wind turbines. Therefore, we conducted a variety of visibility analyses with distance weights. The innovative part was the development of new GIS-based models to assess the continuous distance decay effect. We expected to find diverse results.

We showed that it is possible to model a stepwise and a continuous distance decay effect into visual landscape sensitivity assessments for wind turbines: A uniform distance decay effect as well as stepwise one can be calculated by adopting the methodology by FISCHER & ROTH (2020). Both of our new GIS approaches are suitable to model a continuous distance decay effect.

The absolute values of the visibility indices are a direct consequence of hypothetical observer density and the applied maximum viewing distance. The latter determines the number of hypothetical observers included in the analysis. Consequently, the mere visibility index has little meaning. The main aim of a visual sensitivity analysis is to identify areas that are not as sensitive towards wind turbines compared to others. This is true for mountainous regions. For once observer density is lower as the land use type often is forest. Moreover, while far views are possible from the edge of mountainous regions, the relief restricts the view within. Often one can see only to the next mountain. This is amplified in valleys. Consequently, visual landscape sensitivity is low there.

We found that the visual sensitivity results differ stronger between varying maximum viewing distances than between different distance decay effects. Spatial areas of different visual landscape sensitivity (classified by a quantile distribution) match mostly between methods as long as the maximum viewing distance is the same. Changes in the applied maximum viewing distance lead to broader deviations in sensitivity assessment. This is due to the very different number of included observers. The reasoning, that maximum viewing distance is more influential than the distance decay effect is also supported by the very strong correlation between all approaches with 10,000 m maximum viewing distance.

Our results suggest that the distance decay effect has a negligible influence on the spatial distribution of visual sensitivity. Hence, applying a uniform distance decay effect while setting the maximum viewing distance to 10,000 m (uniform analysis (10 km)) is adequate to assess visual landscape sensitivity to wind turbines. This is the simplest approach with a moderate calculation time and a simultaneously high accuracy. The even faster QGIS interpolation does not assess every cell uniquely but interpolates values. This saves time but is not as accurate. The observer viewshed took a vast amount of time as viewshed analyses were conducted for each observer point. This procedure is repeated nine times with nine adjusted height values. Nevertheless, as correlation values of the stepwise analysis are high in comparison to the approaches for the uniform and the continuous distance decay effect alike, an analysis with distance zones may contribute to results that match the real perception even more. We conclude that the uniform analysis (10 km) is the most efficient methodology to assess visual sensitivity.

Our explorative approach focused on an investigation area measuring 20 × 20 km. Nevertheless, all investigated GIS approaches are transferrable to large areas by deploying a parallel calculating computer network. FISCHER & ROTH (2020) already demonstrated that for the whole federal state of Thuringia.

Visibility analyses offer a valid quantitative approach to assess visual landscape sensitivity towards wind turbines or other structures. Our results contribute to the prevention of extensive visual impacts, as different sites for wind power development and their sensitivity are comparable. This supports siting decisions concerning wind turbines, as aesthetic impacts are included into the decision-making, which in turn might increase public acceptance. Still additional aspects like political interest, other environmental impacts for example on species and economic feasibility need to be included as well.

However, sensitivity of the landscape as predicted by visibility analyses can only be approximated. Still, maximum viewing distance and the distance weights influence the results strongly. Which of the five investigated understandings of the distance decay effect and the predicted visual impact is the most fitting one in reality is not part of this study and needs investigation by a ground-truthing approach. An online survey based on photographs of existing wind parks would be meaningful to obtain empirical results. Knowledge on the realistic perception of visual landscape sensitivity could found a generally accepted method.

Even though the usually applied maximum viewing distance for viewshed analyses is set at 10 km in Germany (TÄUBER & ROTH 2011), ROTH & GRUEHN (2014) believe that 10 km is a minimum threshold. The 10 km value was chosen for turbines with a maximum height of 100 m in the 1990s and early 2000s (e. g. NOHL 1993, BISHOP 2002 as cited in BETAKOVA et al. 2015). This threshold still has not been changed with current turbine heights of 200 m and above. It also varies depending on the method (brief overview given by IOANNIDIS & KOUTSOYIANNIS 2020). So far, no scientifically proven visual threshold for wind turbines exists (BETAKOVA et al. 2015). At the same time, the SCOTTISH NATURAL HERITAGE (2017) stated in its guidance document for the siting of wind farms that generic distances are no longer suitable. This is justified by varying viewing distances due to turbine design, site aspects and weather conditions. Still, one threshold, which is valid for the German landscape configuration and atmospheric composition, would be desirable. Reinvestigation into this topic is overdue. HILDEBRANDT (2015) suggests a range of 15-16 km with significant visual impacts, based on studies from other countries (e. g. SULLIVAN et al. 2012). Whether the situations of these studies are comparable to German landscapes has to be further examined.

Another topic that needs to be challenged is the zoning of visual thresholds to model a stepwise distance decay effect. BETAKOVA et al. (2015) found thresholds at comparable distances as NOHL (1993). A perceived impact reduction occurred at thresholds of 1,500 m, 7,500 m and 10,000 m distance from the observer (150 m wind turbine height). However, several thresholds were preliminary fixed in their study. It is furthermore unclear, how NOHL (1993) drew the distance weights. Their validity is thus questionable. If there are thresholds with differing visual sensitivity and which values are appropriate in reality is uncertain and a task for future research.

Additionally, landscape aesthetic quality influences landscape sensitivity (GERHARDS 2003: 97, BETAKOVA et al. 2015, STORE et al. 2015). As the visual impact is stronger in highly aesthetic landscapes so is the perception of the decreasing impact with distance. Simultaneously, the distance decay effect is not as pronounced in landscapes with a lower aesthetic quality (BETAKOVA et al. 2015). How this is applicable in practice needs investigation.

We modelled the continuous distance decay effect as a linear function. However, other types of mathematical functions may be useful. Alternatives include a fraction (WAGTENDONK & VERMAAT 2014), the logarithmic function or the exponential function (e. g. SHANG & BISHOP 2000). As long as no empirical study enables a deeper understanding of the distance decay effect for 200 m and above turbines, all functions are equally suitable.

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