

Exploring the usability and suitability of different techniques for visualising uncertainty in 3D maps for regional level wind farm planning

by

Yvette Bevis

Submitted in fulfilment for the requirements of the degree

Magister Scientiae (Geoinformatics)

in the Faculty of Natural & Agricultural Sciences

University of Pretoria

Pretoria

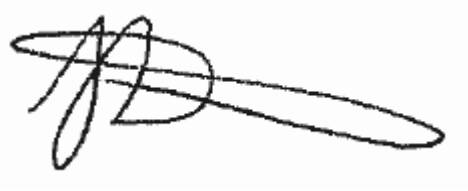
December 2017

Abstract

All geospatial data contains uncertainty and ignoring it can lead to negative or unforeseen consequences for spatial analysis and decision-making. It has been suggested that communicating uncertainty through visualisation can increase trust in the results and can support analysis and decision-making. To date, most studies on uncertainty visualisations have focused on 2D representations. The increasing popularity of 3D maps present new opportunities for the visualisation of uncertainty. Wind energy is a prominent form of renewable energy and much research has been done on the different aspects of using geospatial data to support the utilization of wind for power production. The goal of this research is to explore the suitability and usability of different techniques for visualising uncertainty in 3D maps in order to aid in regional level planning of wind farms. To achieve this goal, different 3D maps that visualise uncertainty were developed. To understand the usability and suitability of different visualisation techniques for representing uncertainty in 3D maps, semi – structured qualitative expert interviews were conducted. The results from nine expert interviews provide valuable insights for suitability and usability of various techniques for visualising uncertainty in 3D maps. The research results can be used to guide the design of controlled user studies to further investigate the visualisation of uncertainty in 3D maps and can contribute to the development of guidelines for the design and use of techniques for visualising uncertainty in 3D maps in wind energy projects.

Declaration

I, Yvette Bevis, declare that the dissertation which I hereby submit for the degree Magister Scientiae (Geoinformatics) at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.



01 December 2017

Signature

Date

Acknowledgements

First and foremost, I would like to acknowledge and thank my supervisors Prof. Serena Coetzee and Dr. Victoria Rautenbach for their unwavering support and guidance throughout the course of my Masters. Your commitment and dedication to the field of Geoinformatics is inspiring.

Secondly, I would like to thank Prof. Gertrud Schaab from the Karlsruhe University of Applied Sciences for her support and guidance during my time in Germany. Your input to this dissertation is greatly appreciated.

I would like to thank Sybil Adams for providing climate data in a readily readable data format, Cristina Balmuş for the suitability model output, and Ingrid Booysen for assisting me with the creation of some of the figures. I would also like to acknowledge the Baden-Württemberg-STIPENDIUM for University Students – BWS plus funded exchange program between the Karlsruhe University of Applied Sciences in Germany and the University of Pretoria in South Africa.

To my family and friends who have supported me on this journey: Thank you! Special thanks must be given to my Mom, Sean Cullen, Nadia Oosthuizen, and my team members at Esri South Africa for encouraging and pushing me towards the finish line. I dedicate this work to Stephen Muller, who although not with us anymore, provided me with the wise words of motivation that I relied on often during the final stages of writing.

Lastly, my sincere gratitude to Esri South Africa for allowing me the flexibility needed to complete this Masters degree.

Table of Contents

Chapter 1: Introduction	1
1.1. Overview	1
1.2. Problem statement	2
1.3. Objectives.....	2
1.4. Methodology.....	3
1.5. Significance	3
1.6. Publications from this research	4
Chapter 2: Background and related work.....	5
2.1. Overview	5
2.2. Current use of maps in regional level planning of wind farms.....	5
2.3. Uncertainty	11
2.3.1. Defining uncertainty	11
2.3.2. Domains of uncertainty research	13
2.3.3. Types of uncertainty maps.....	14
2.3.4. Techniques for representing uncertainty	18
2.3.5. Visualising uncertainty in wind farm planning	31
2.4. 3D maps	33
2.4.1. Overview	33
2.4.2. Advantages.....	34
2.4.3. Challenges.....	35
2.4.4. Applications of 3D maps	36
2.5. 3D maps in wind farm planning	40
Chapter 3: Design and development of 3D maps.....	43
3.1. Introduction	43
3.2. Wind farm planning and uncertainty.....	43
3.3. Study area	44
3.4. Data.....	44
3.4.1. Quantification of uncertainty	46

3.5. 3D maps	46
3.5.1. Prism map	47
3.5.2. Pin map	51
3.5.3. Texture map	53
3.5.4. Trivariate map	56
Chapter 4: Study design	58
4.1 Introduction	58
4.2 First set of interviews in Germany	58
4.2.1 Overview	58
4.2.2 Materials	58
4.2.3 Procedure	59
4.2.4 Semi-structured interview questions	60
4.2.5 Participants	61
4.2.6 Domains of uncertainty research covered	62
4.3 Second set of interviews in South Africa	64
4.3.1 Overview	64
4.3.2 Materials	64
4.3.3 Semi-structured expert interview questions	65
4.3.4 Participants	66
4.3.5 Domains of uncertainty research covered	67
Chapter 5: German expert opinions on using the third dimension to visualise wind speed uncertainty in wind farm planning	69
5.1 Abstract	69
5.2 Introduction	69
5.3 Study design	71
5.3.1 Overview	71
5.3.2 Materials	72
5.3.3 Interviewees	79
5.4 Results and discussion	80
5.5 Conclusions	84
Chapter 6: South African expert opinions on techniques to visualise wind speed uncertainty in 3D maps for wind farm planning	86

6.1 Introduction	86
6.2 Qualitative analysis of the results.....	86
6.2.1 Results and discussion	86
6.3 Conclusion.....	115
Chapter 7: Discussion and conclusions.....	118
7.1 Introduction	118
7.2 Discussion.....	118
7.3 Main results from dissertation	120
7.4 Recommendations for further research	124
References	125
Annex A. Acronyms and abbreviations	133
Annex B. Ethical approval	134

List of Tables

Table 1: Sub categories of visualisation techniques as defined by Mason et al. (2016)	13
Table 2: Summary of research studies focusing on the use of 2D techniques for representing uncertainty.....	20
Table 3: Summary of research studies focusing on the use of 3D techniques for representing uncertainty.....	26
Table 4: The five downscaled RCMs used in this research and their developing organizations	45
Table 5: Characteristics of uncertainty visualisations. The characteristics used in this research are indicated in red.	46
Table 6: The characteristics of the prism map in relation to other characteristics of uncertainty visualisations	48
Table 7: The wind speed categories as defined in the mean wind speed renderer.....	49
Table 8: The characteristics of the pin map.....	52
Table 9: The characteristics of the texture map	54
Table 10: The interview questions for the first set of interviews.....	61
Table 11: Overview of the background of the interviewees who participated in the first set of interviewees.....	62
Table 12: The visual summary (Figure 42) explained	64
Table 13: The interview questions for the second set of interviews	66
Table 14: Overview of the background of the interviewees	67
Table 15: The visual summary (Figure 43) explained	68
Table 16: Overview of the interview questions.....	72
Table 17: Summary of the background of each interviewee.....	80
Table 18: Reason for user preference for texture map over prism map.....	82
Table 19: Summary of user opinions on the usefulness of 3D maps	83
Table 20: The interview questions developed for the second set of interviews	87
Table 21: Purposes for which 3D models are used by interviewees	90
Table 22: Summary of technique preference. Where interviewees specified the trivariate map it was interpreted that they preferred the prism technique.....	102
Table 23: Summary of the drawbacks of the 3D maps as identified by the interviewees	107

List of Figures

Figure 1: An example of a regional planning map used to determine the priority and suitability areas for wind power (Source: Ohl & Eichhorn (2010))	5
Figure 2: An energy output for the West Saxony Planning Region (Source: Ohl & Eichhorn (2010)).....	6
Figure 3: A wind probability map used in the study by Azzelino et al. (2013)	7
Figure 4: Map showing ship traffic, which is one of the factors considered in offshore wind farm planning. Source: Azzelino et al. (2013)	7
Figure 5: As part of the suitability analysis, wind speed was interpolated at 100m above ground level. This map shows the interpolation (Baseer et al. (2017))	8
Figure 6: A suitability map for the Kingdom of Saudi Arabia indicating suitable areas for wind farms (Baseer et al. (2017))	9
Figure 7: A thematic map of the wind velocity over Greece (Vasileiou et al. (2017)).....	10
Figure 8: Unsuitable areas for the deployment of Hybrid Wind and Wave Energy Systems in Greece (Vasileiou et al. (2017))	11
Figure 9: The complete visual summary developed by Mason et al. (2016) to portray domains of geospatial uncertainty visualisations addressed in research studies.	14
Figure 10: The vertical bars used by Slocum et al. (2003) to depict uncertainty in a water balance model.....	27
Figure 11: Local areas of uncertainty represented by cone glyphs (Newman & Lee 2004)....	29
Figure 12: Point displacement representing uncertainty in 3D tumour data (Grigoryan & Rheingans 2004).....	30
Figure 13: Point displacement used in combination with transparency to portray uncertainty (Grigoryan & Rheingans 2004).....	31
Figure 14: Uncertainty in the distribution of wind speed and wind direction presented in a graph format (Messac, et al. (2012)	32
Figure 15: Normalised uncertainty in the power curve to normalised wind speed at hub height. Source: Afanasyeva et al. (2016)	33
Figure 16: The 3D map Kwan (2000) developed to model human activity travel patterns	36
Figure 17: A closer view of Kwan's (2000) 3D map.....	37
Figure 18: A 3D map from the study by Kwan & Kotsev (2014) showing an individual's commute times. The two peaks indicate the individuals waiting time for transport.	37
Figure 19: A 3D map from the study by Kwan & Kotsev (2014) showing the travel time for the women participants	38
Figure 20: A 3D map from the study by Lu & Fang (2014) showing an individual's air quality index and space time path.....	38

Figure 21: A 3D map from the study by Lu & Fang (2014) showing an individual’s personal air pollution danger zone and space time path	39
Figure 22:A space time density map for a bird (Demšar et al. 2015)	40
Figure 23: The visual impact assessment inside the virtual reality environment. Source: Bishop & Stock (2010).....	41
Figure 24: The 3D map used in the public participation survey in the study by Berry et al. (2011).....	42
Figure 25: A 3D scene used for visual impact analysis of a proposed wind farm. Source: Wróżyński et al. (2016)	42
Figure 26: Map of the study area.....	44
Figure 27: Workflow followed for the creation of the prism 3D map.....	48
Figure 28: An aerial view of the prism geovisualisation	49
Figure 29: A zoomed in view of the prism map	50
Figure 30: The legend for the prism map	50
Figure 31: A small section of the pin map	52
Figure 32: The legend for the pin map	53
Figure 33: A zoomed in portion of the texture map.....	55
Figure 34: The texture map from a different angle. The 3D basemap is obvious in this screenshot.....	55
Figure 35: The legend for the texture map.....	56
Figure 36: A zoomed in portion of the trivariate map. The thick black squares are a proportional.....	57
Figure 37: The legend for the trivariate map.....	57
Figure 38: The prism map	59
Figure 39: <i>The texture map</i>	59
Figure 40: The pin map	59
Figure 41: The trivariate map	59
Figure 42: A visual summary of the domains of uncertainty visualisation research covered by the expert interviews in the first experiment. Adopted from Mason et al. (2016).	63
Figure 43: A visual summary of the domains of uncertainty visualisation research covered by the expert interviews in the second experiment. Adopted from Mason et al. (2016).	67
Figure 44: The study area (delimited by the red rectangle) in Southern Europe.....	73
Figure 45: A part of the prism showing the uncertainty of the wind speed.	74
Figure 46: The prism map legend	74

Figure 47: The pin map. The position of a disc on the pin represents the mean wind speed of a specific climate model. The hollow ring indicates the average wind speed of all the model outputs.....75

Figure 48: The pin map legend.76

Figure 49: A zoomed in section of the texture map. The pattern of the diagonal lines indicates the degree of uncertainty. Thin lines that are close together indicate areas of low uncertainty.77

Figure 50: The texture map legend.....77

Figure 51: A zoomed in part of the trivariate map. Three variables are being represented: the wind speed (colour), the uncertainty of the wind speed (height of the prism) and the percentage of the cell that is highly suitable for renewable energy.78

Figure 52: The trivariate map legend.....79

Figure 53: The prism map88

Figure 54: The texture map.....88

Figure 55: The pin map88

Figure 56: The trivariate map88

Figure 57: The general workflow applicable to wind farm projects as described by the interviewees in the interview88

Figure 58: The four steps of decisions analysis for regional energy planning (Mourmouris & Potolias (2013)).....89

Figure 59: The workflow implemented by Tsoutsos et al. (2015) for regional wind farm planning89

Figure 60: Atlas.ti network of responses on uncertainty representation91

Figure 61: An example of uncertainty representation related to wind farm performance (Messaac, 2011).....92

Figure 62: A graph showing uncertainty in wind speed for a specific wind farm (Messaac, 2011)92

Figure 63: The Atlas.ti network of the responses to the question on preference of technique for acquiring an initial overview of the study area.....95

Figure 64: The Atlas.ti network of the responses to the question on preference of technique for comparing uncertainty98

Figure 65: The Atlas.ti network of the responses to the question on overall preference of technique101

Figure 66: The Atlas.ti network of the responses to the question on which maps would be useful in their current workflow103

Figure 67: The Atlas.ti network of the responses to the question on interviewee's opinion on representing uncertainty statistically vs visually106

Figure 68: The Atlas.ti network of the responses to the question on the drawbacks of the 3D maps.....109

Figure 69: The Atlas.ti network of the responses to the question on the interviewee's opinion on representing uncertainty in the third dimension111

Figure 70: The Atlas.ti network of the responses to the question on whether the interviewee's would recommend 3D maps that visualise uncertainty112

Figure 71: The Atlas.ti network of the responses to the question on suggestions for other planning scenarios113

Figure 72: The Atlas.ti network of the responses to the question on additional variables for inclusion114

Chapter 1: Introduction

1.1. Overview

In most scientific studies, statements of accuracy are required (MacEachren et al. 2005). Error is a calculated value and is the statement of inaccuracy, but when the error is not known, uncertainty applies (Hunter & Goodchild 1993; MacEachren et al. 2005). All geospatial data contains uncertainty and ignoring it can lead to negative or unforeseen consequences for spatial analysis and decision making (Zhang & Goodchild 2002; Newman & Lee 2004; Kinkeldey, MacEachren, et al. 2014). It has been suggested that communicating uncertainty through visualisation can increase trust in the results and can support analysis and decision making (Deitrick & Edsall 2006; Hope & Hunter 2007; Fisher et al. 2012). Including uncertainty as a variable to visualise in maps is a challenging task as it difficult to adequately express the complexity of the uncertainty (Potter et al. 2012). Numerous studies have been conducted on visualising uncertainty in geographical information science (GIScience) and other related fields (MacEachren et al. 2005) but many of them have focused on two - dimensional (2D) representations and did not make use of the third dimension.

The increasing popularity of virtual environments (e.g., Google Earth) has contributed to a wider acceptance of the third dimension in many fields (Bandrova et al. 2012). Most people prefer realistic 3D representations of environments as they are more intuitive (van Lammeren et al. 2010). 3D maps are thought to allow better understanding of spatial relationships and vertical dimensions (Bos et al. 1998; van Lammeren et al. 2010), especially if the 3D map is dynamic and the user can navigate themselves through the environment (Bleisch et al. 2008; Mülder et al. 2007). Although there are many documented advantages of 3D maps there are some documented challenges such as information overload resulting in poor spatial knowledge acquisition (Liao et al. 2016). Existing 3D techniques for representing uncertainty make it possible to visualise uncertainty in 3D maps but this concept has not been fully explored in the literature.

Most of the maps used in regional level planning of wind farms are in support of spatial analysis for the optimal siting of wind farms. Many of these maps are 2D but there are cases where 3D maps are used to explore the terrain or to realistically model proposed, or existing, wind farms. 3D maps may be more beneficial than 2D maps in regional level planning of wind

farms as they can result in improved understanding of information and can lead to better informed decisions being made (Brasebin et al. 2012). Using 3D maps to visualise uncertainty in regional level planning of wind farms has not been explored in the literature.

The main aim of this dissertation is to explore the usability and suitability of different techniques for visualising uncertainty in 3D maps for regional level wind farm planning in Southern Europe.

1.2. Problem statement

Previous work has mostly been limited to the visualisation of uncertainty in 2D maps with few researchers in the fields of climate modelling and GIS having addressed uncertainty in 3D maps. To the best of the author's knowledge, expert perceptions of the usability and suitability of 3D uncertainty maps for regional level planning of wind farms have not been investigated.

A challenge to the use of 3D maps for visualising uncertainty in regional level wind farm planning is a lack of definite design guidelines stemming from a gap in knowledge regarding expert preference. Proof of this gap is given by the lack of scientific literature addressing the topic.

1.3. Objectives

The main goal of this research is to explore the usability and suitability of different techniques for visualising uncertainty in 3D maps for regional level wind farm planning in Southern Europe. The following secondary objectives support the achievement of the main goal:

- 1) Perform an on-going literature review of existing theory and related work.
- 2) Design and produce 3D maps to visualise uncertainty and design semi-structured expert interviews to explore perceptions regarding such maps
- 3) Conduct expert interviews to ascertain expert preferences and perceptions regarding the use of 3D maps to visualise uncertainty
- 4) Use the results from the expert interviews to draw conclusions

1.4. Methodology

To achieve the main goal and objectives set out in this dissertation, the following methodology was applied.

A literature review (**chapter 2**) was conducted on existing theory and related work in order to provide the necessary background knowledge on the different aspects of uncertainty visualisations, 3D maps and geovisualisations, and wind farm planning. This literature review achieves **objective 1**.

In order to achieve **objective 2**, four interactive 3D maps of wind speed and related uncertainty were designed and produced. Different techniques identified in the literature were adapted in order to represent uncertainty.

To achieve **objective 3**, semi-structured expert interviews were conducted in Germany and in South Africa. The questions asked in the expert interviews were designed to elicit answers that enable a better understanding of expert perception on the usability and suitability of different techniques for visualising uncertainty in 3D maps in regional wind farm planning. The design of the interviews is presented in **chapter 3**. The results and discussion of the interviews are presented in **chapters 4 and 5**.

The results of the literature review and the expert interviews are combined to draw conclusions on the suitability and usability of different techniques for visualising uncertainty in 3D maps for regional level planning of wind farms. These conclusions are presented in **chapter 6**.

1.5. Significance

Wind energy is one of the fastest growing forms of renewable energy in the world (Mytilinou et al. 2015) due to increasing concerns over climate change, energy security, and the rising cost of fossil fuel (Mentis et al. 2015). Globally, the wind energy market is expected to grow by six to ten percent annually (GWEC 2014).

In Europe, wind energy is a prominent renewable power (Jankowski 2010) which is central to meeting targets for renewable energy supply as defined in the Renewable Energy Sources Directive (2009/28/EC) (Scott & O'Neill 2013). The South African Constitution provides a mandate for a sustainable energy future of which wind energy is a critical component (DoE

2015). The South African Wind Energy Programme (SAWEP) was started in 2008 to contribute to national development objectives such as diversifying power generation in South Africa, setting up a wind energy industry to generate employment, and to promote sustainable development by making use of wind energy as a renewable source. As of 2015 there were 34 onshore wind projects in South Africa (DoE 2015).

There is a general consensus that spatial planning is an important component of the deployment of wind power (Cowell 2007; Jankowski 2010). Part of wind energy planning is to assess and map wind resources and reduce forecasting uncertainties of wind energy production (Jankowski 2010). Communicating uncertainty in regional wind farm planning is important because it is essential to effectively describe and represent uncertainty to reduce the misinterpretation and misuse of the data (Heuvelink & Burrough 2002). Effectively communicating uncertainty can result in better informed decisions.

3D maps that visualise uncertainty can be seen as a tool designed to meet the requirements of expert users in regional wind farm planning. These maps will enable data exploration in order facilitate knowledge creation regarding uncertainty. Understanding the uncertainty at regional levels is one of the first steps in effective decision-making.

The results of this research (outcomes of objectives 3 and 4) address the gap in knowledge regarding the suitability and usability of different techniques for visualising uncertainty in 3D maps in regional level wind farm planning. The research results can be used to guide the design of controlled user studies to further investigate the visualisation of uncertainty in 3D maps. The results can also ultimately contribute to the development of guidelines for the design and use of techniques for visualising uncertainty in 3D maps in wind energy projects. These guidelines could ensure the optimal design of 3D maps for visualising uncertainty in order to facilitate improved knowledge acquisition.

1.6. Publications from this research

Bevis, Y., Schaab, G., Rautenbach, V., and Coetzee, S., 2017: Expert opinions on using the third dimension to visualise wind speed uncertainty in wind farm planning, *International Journal of Cartography*, 3(1), 61-75, DOI: 10.1080/23729333.2017.1301349

Chapter 2: Background and related work

2.1. Overview

The aim of this chapter is to meet objective 1 which is to conduct a detailed literature review in order to understand all relevant concepts. This chapter discusses the theory of the following concepts: uncertainty, 3D maps, and the use of maps in regional level planning of wind farms.

2.2. Current use of maps in regional level planning of wind farms

Most of the maps used in regional level planning of wind farms are in support of spatial analysis for the optimal siting of wind farms. Many of these maps are presented in 2D but specific 3D examples can be found in section 2.5.

In a research paper by Ohl & Eichhorn (2010) regional planning maps used for wind farm planning in Germany were presented. These maps are presented in Figure 1 and Figure 2 below.

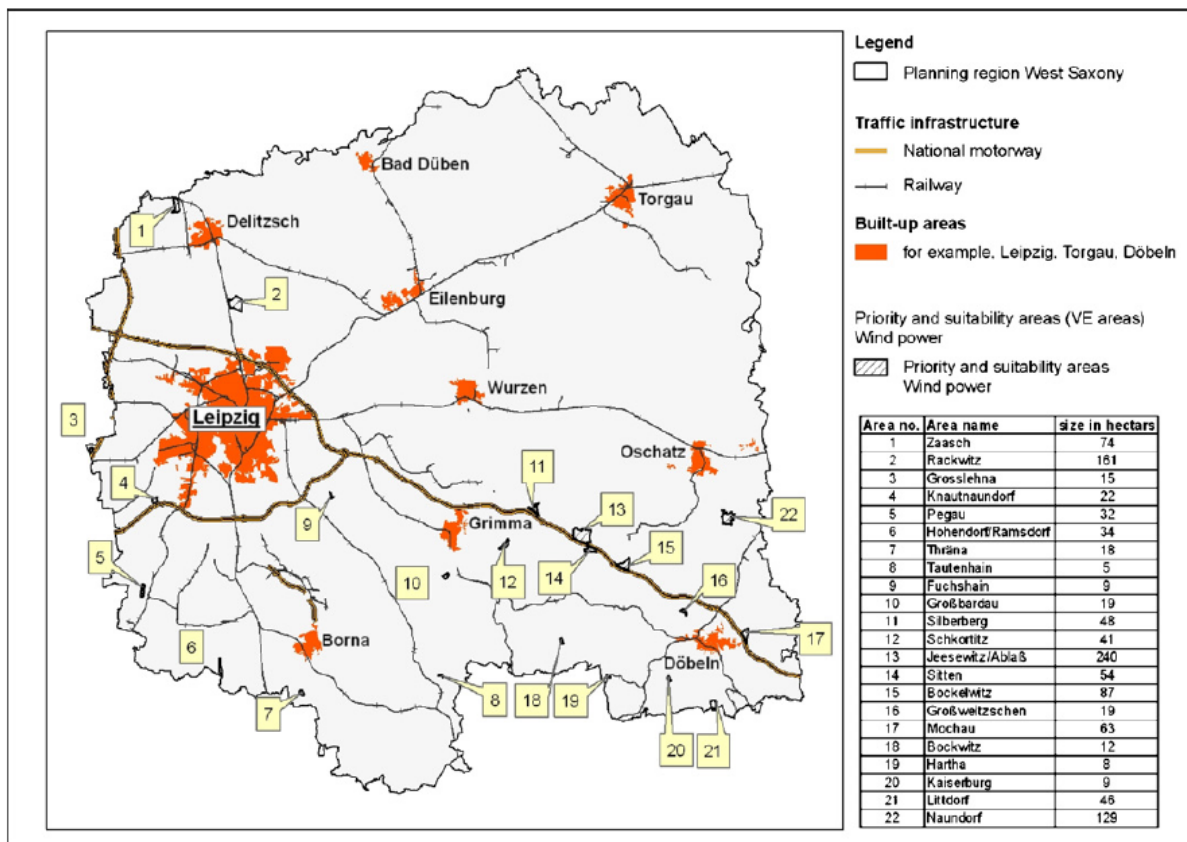


Figure 1: An example of a regional planning map used to determine the priority and suitability areas for wind power. Source: Ohl & Eichhorn (2010).

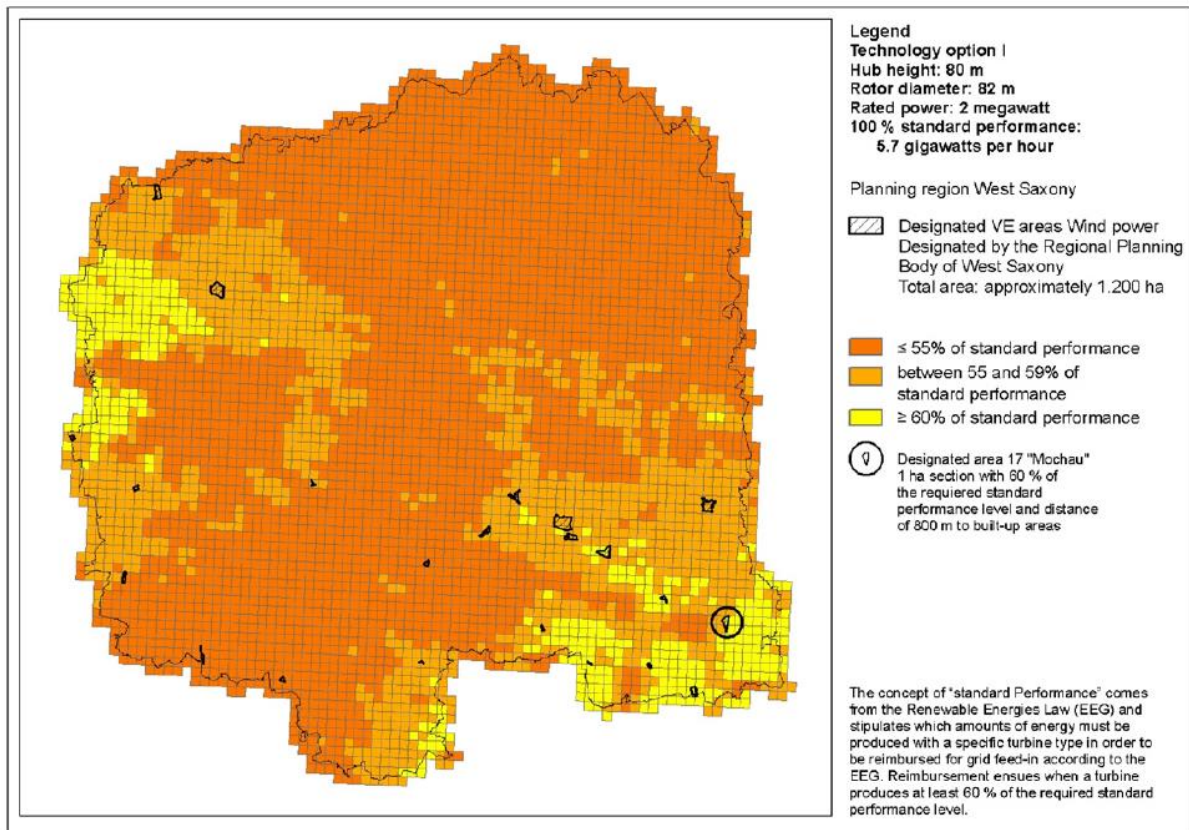


Figure 2: An energy output for the West Saxony Planning Region. Source: Ohl & Eichhorn (2010).

Azzelino et al. (2013) used a variety of maps in a marine spatial planning process for the optimal siting of offshore wind-power installations. The spatial analysis for this study was conducted in grid cells with dimensions of 22 x 12km. Figure 3 and Figure 4 show some of the maps used in the study by Azzelino et al. (2013).

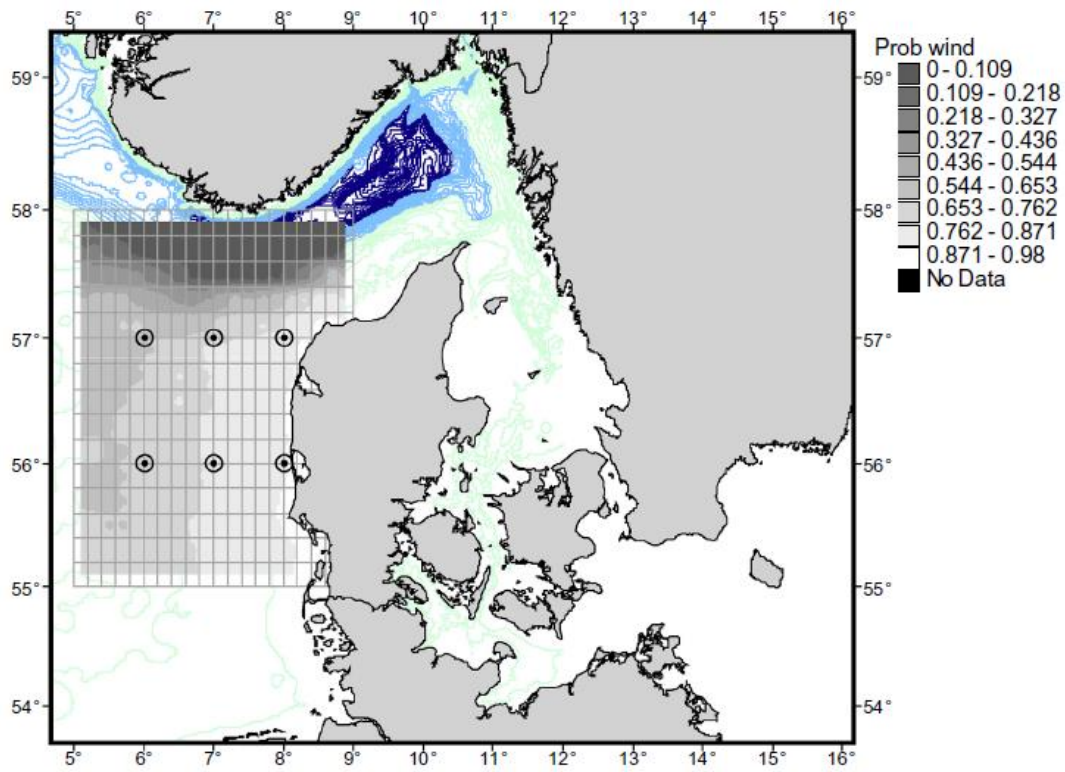


Figure 3: A wind probability map used in the study by Azzelino et al. (2013).

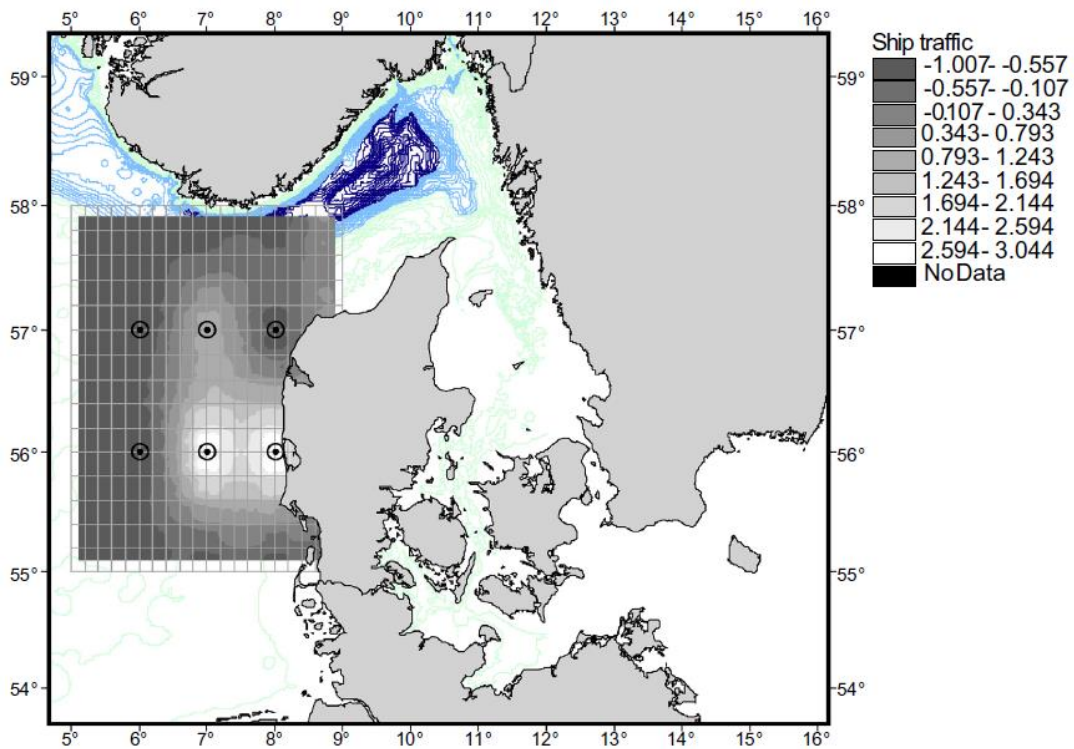


Figure 4: Map showing ship traffic, which is one of the factors considered in offshore wind farm planning. Source: Azzelino et al. (2013).

Baseer et al. (2017) presented a wind farm site suitability analysis which was applied to the entire Kingdom of Saudi Arabia. The resulting maps (Figure 5 and Figure 6) of this analysis were 2D maps that were used to communicate various results of the analysis.

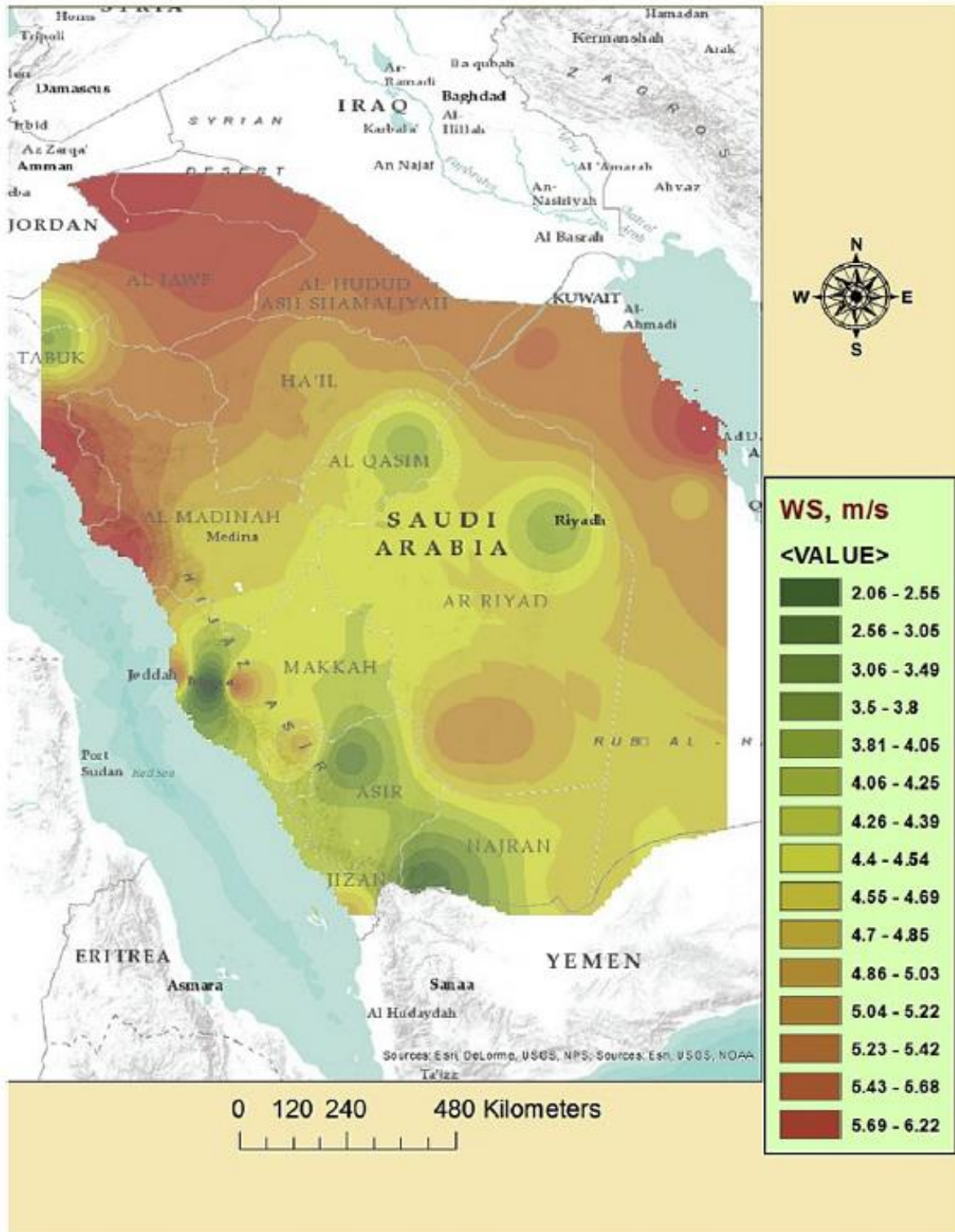


Figure 5: As part of the suitability analysis, wind speed was interpolated at 100m above ground level. This map shows the interpolation. Source: Baseer et al. (2017).

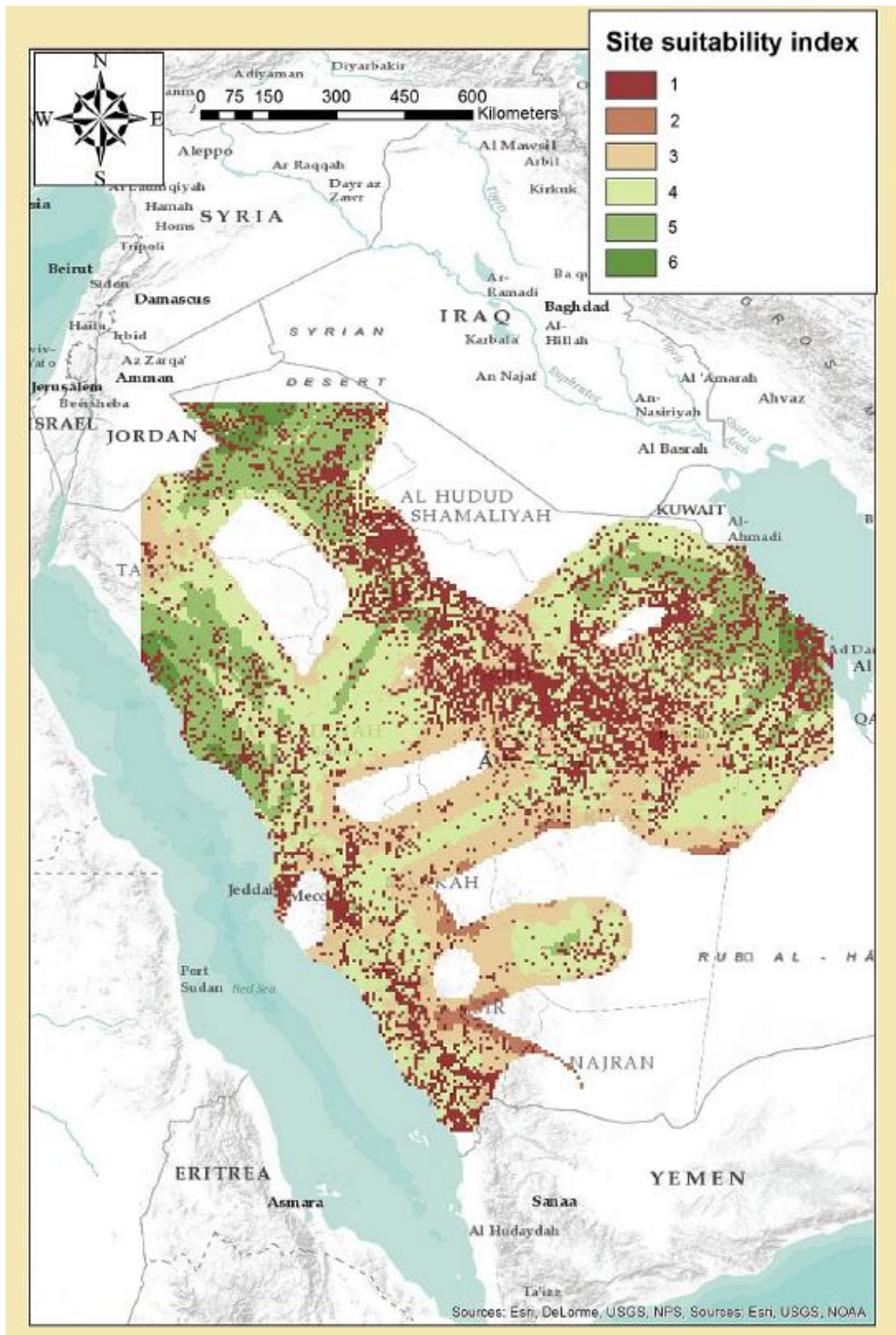


Figure 6: A suitability map for the Kingdom of Saudi Arabia indicating suitable areas for wind farms. Source: Baseer et al. (2017).

Vasileiou et al. (2017) presented a methodological framework for identifying the most suitable marine areas in Greece for the deployment of Hybrid Wind and Wave Energy Systems. As in the study by Baseer et al. (2017) 2D maps were used to communicate the results of the suitability analysis. Different thematic maps were produced to show exclusion zones, unsuitable areas and eligible areas. A selection of these maps are presented below in Figure 7 and Figure 8.

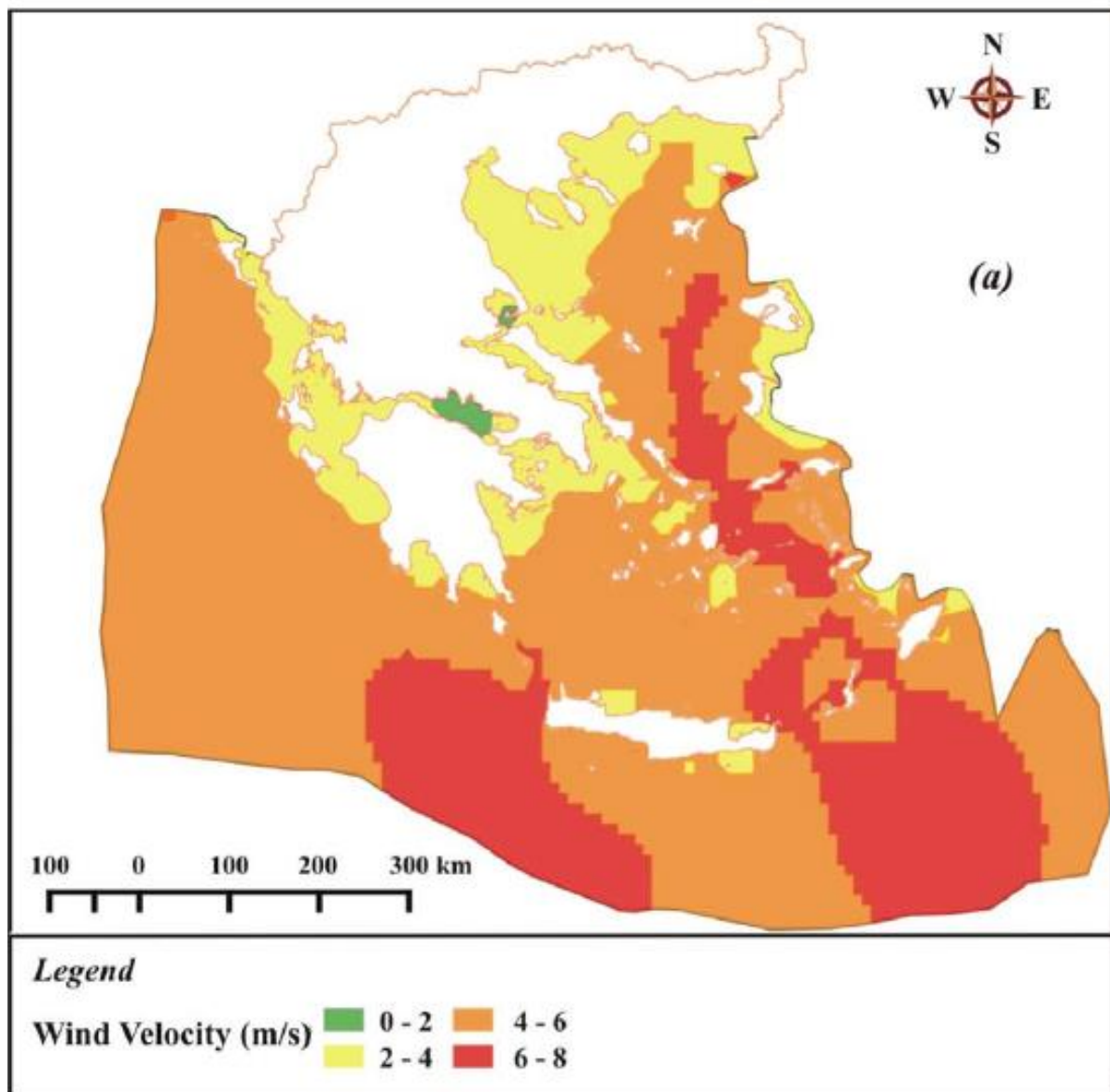


Figure 7: A thematic map of the wind velocity over Greece. Source: Vasileiou et al. (2017).

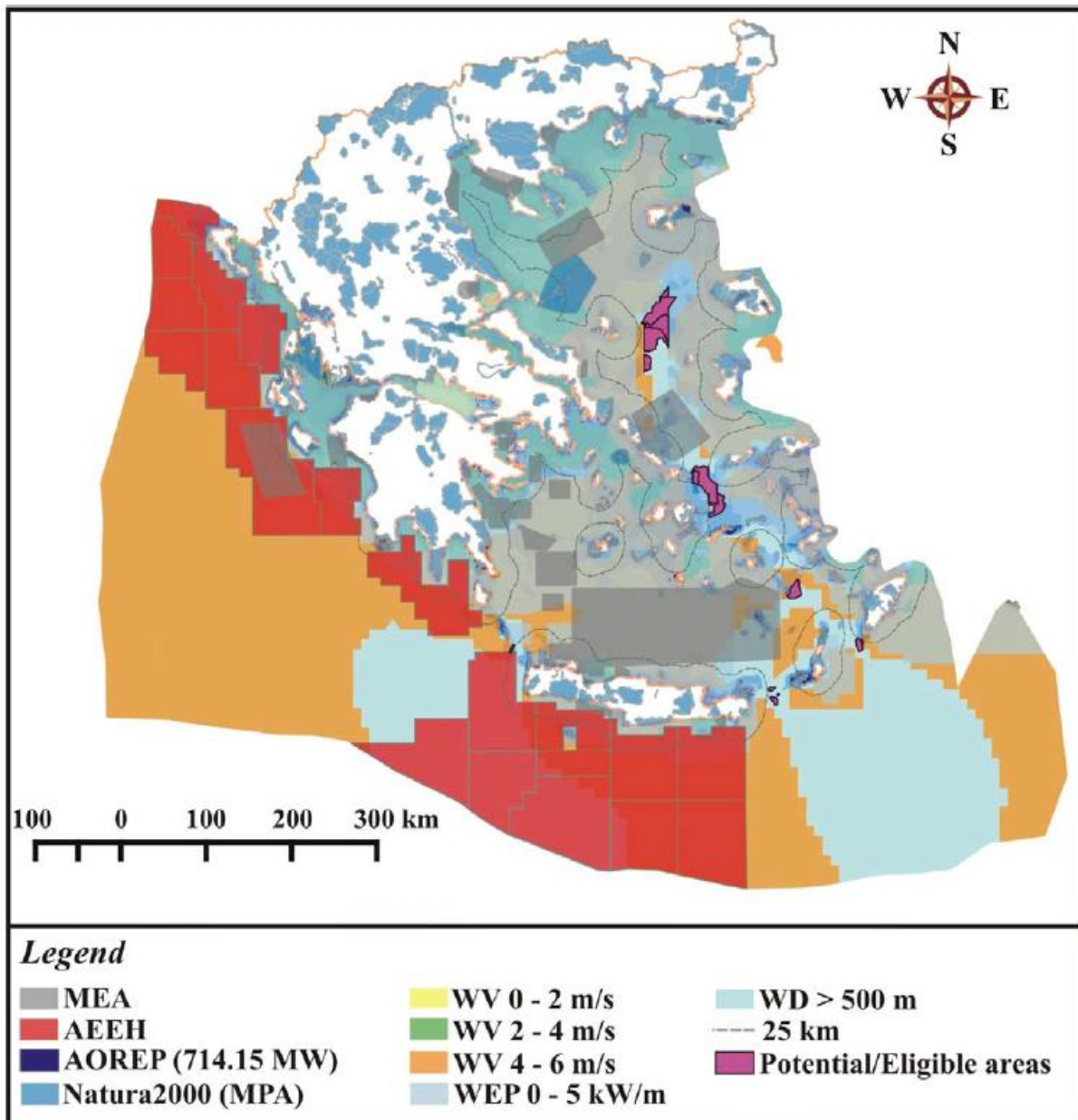


Figure 8: Unsuitable areas for the deployment of Hybrid Wind and Wave Energy Systems in Greece. Source: Vasileiou et al. (2017).

2.3. Uncertainty

2.3.1. Defining uncertainty

Uncertainty is a complex concept which is applicable to many knowledge domains (MacEachren et al. 2005). Uncertainty applies when it is known that values deviate from the true value but the exact amount of deviation is unknown (Davis & Keller 1997). In simple terms, uncertainty is a measure of what we do not know (O'Brien 2008; Uusitalo et al. 2015). Pang et al. (1997) define uncertainty to include statistical variance, errors, minimum – maximum ranges, as well as noisy or missing data. O'Brien (2008) similarly defines uncertainty

as a broad term which incorporates error, inaccuracy, imprecision, vagueness and lack of confidence in information. There are many definitions of uncertainty but essentially all definitions imply that uncertainty exists when a user does not have perfect knowledge about a dataset (Thomson et al. 2005).

There exists some degree of uncertainty in geographic data (Longley et al. 2005; Bektaş & Çöltekin 2011). There are many causes for uncertainty existing in a dataset. It could be due to imprecise measurement techniques, changes to data values during processing (e.g. during manipulation or classification), or due to the natural variability in the phenomena being measured (Davis & Keller 1997). Pang et al. (1997) also suggest that uncertainty can be introduced during the data acquisition phase as well as during the processing or transformation stage, but in addition, they suggest that uncertainty can also be introduced during the visualisation phase.

It is generally accepted that there are three broad categories of uncertainty, namely, positional, attribute and temporal uncertainty, with most research focusing on attribute (thematic) uncertainty (Davis & Keller 1997; MacEachren et al. 2005; Longley et al. 2005; Kinkeldey, MacEachren, et al. 2014). Positional uncertainty refers to a lack of knowledge regarding the exact location of a geographic feature. Attribute uncertainty refers to inexact values in the associated attributes of a geographic feature. Temporal uncertainty is inexact information regarding the time element of a geographic feature (Senaratne et al. 2012).

A variety of techniques exist for quantifying uncertainty such as fuzzy set theory (Jiang & Eastman 2000; Ducey 2001) and Bayesian Belief Networks (Krivoruchko & Gotway Crawford 2005; Dlamini 2010). Model ranges can also be a measure used to quantify uncertainty as shown by (Slocum et al., 2003). Slocum et al. (2003) investigated the visualisation of uncertainty in relation to a global water balance model. The global water balance model used the outputs of a global climate model as inputs. In order to quantify the uncertainty, the water balance model was repeatedly run using different global climate models. The range of outputs from the total number of runs provides a measure of the uncertainty. Uusitalo et al. (2015) confirmed this method of quantifying uncertainty when multiple models are used to predict the same scenario. If multiple models predict very similar results then it can be concluded that uncertainty is low (Uusitalo et al. 2015).

2.3.2. Domains of uncertainty research

Mason et al. (2016) developed a visual summary (Figure 9) to highlight categories of geospatial uncertainty visualisation. The visual summary is used to visually represent the important domains of uncertainty visualisation addressed in specific studies. There are three main categories of uncertainty visualisation research: Visualisation techniques, user effects, and stimulus effects. Visualisation techniques refer to how the different components of the visualisation are represented and consist of the sub categories described in Table 1.

Sub category	Description
Data type	The data type used to represent the uncertainty: point, line, polygon, network, field
Taxonomy	Overview or description of uncertainty through a formal or informal taxonomy
Representation	Visualisation of uncertainty through an intrinsic or extrinsic technique (see section 2.3.3)
Evaluation	Evaluation of an uncertainty visualisation technique
Interactivity	Whether the visualisation is interactive or not
Animation	Whether the visualisation is animated or static
Display	Whether the display is adjacent or coincident (see section 2.3.3)

Table 1: Sub categories of visualisation techniques as defined by Mason et al. (2016).

User effects refers to the user’s experience prior to viewing and interacting with the uncertainty visualisation. The user effects category has two sub categories: general individual differences (personality, abilities, and heuristics) and contextual individual differences (individual differences related to the context/phenomena being visualised). Stimulus effects describes the user interaction and state after viewing and interacting with the uncertainty visualisation. The stimulus effect category has three sub categories: user comprehension, affect, and decision-making. User comprehension refers to either map comprehension or data uncertainty comprehension. Affect measures whether the uncertainty visualisation elicits some type of emotional response. Decision-making is applicable to research that assesses the impact of the uncertainty visualisation on user decisions.

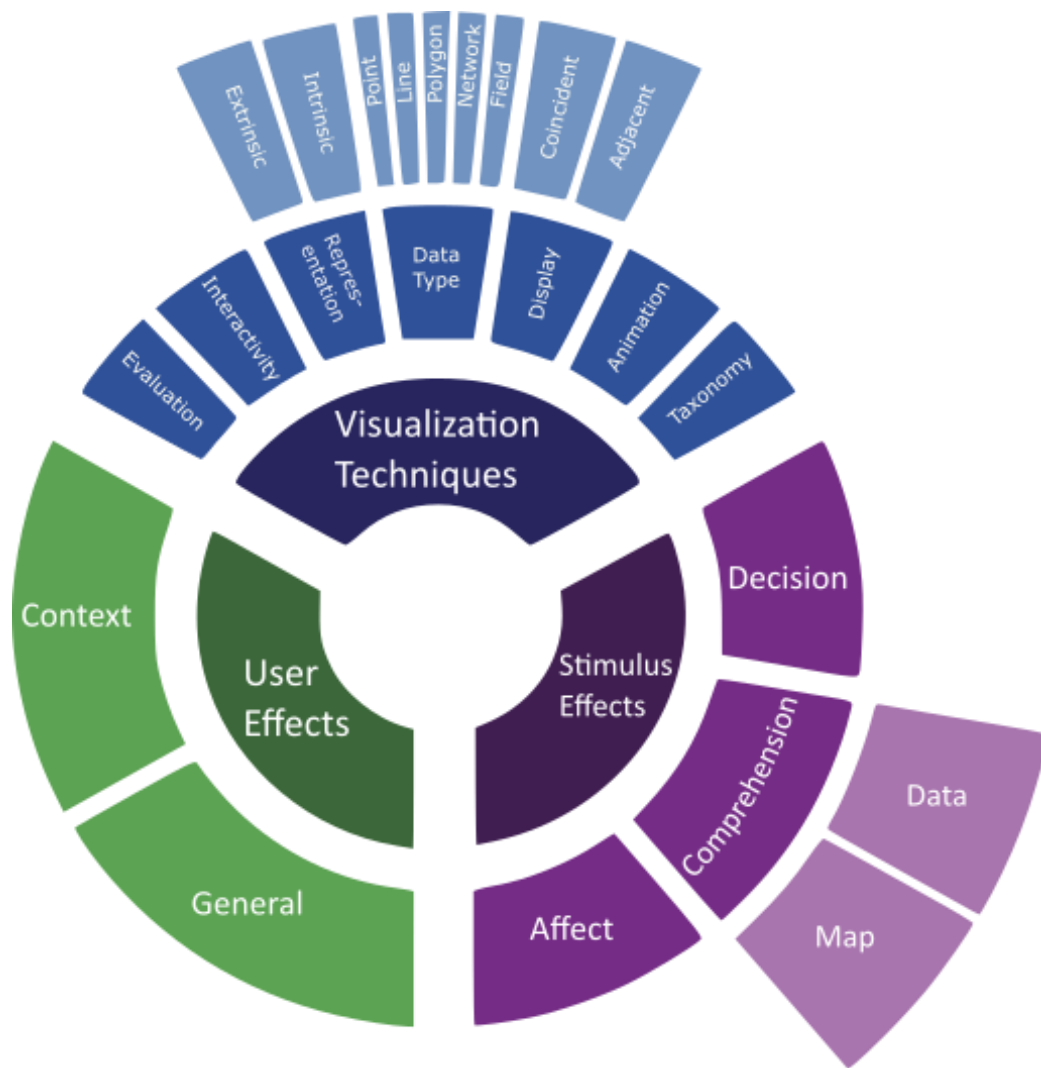


Figure 9: The complete visual summary developed by Mason et al. (2016) to portray domains of geospatial uncertainty visualisations addressed in research studies.

Robinson et al. (2017) presented a new cartographic research agenda relating to geospatial big data. One of the identified challenges is to develop new approaches for visualising the certainty of geospatial big data. It is envisioned that a future approach to highlighting uncertainty in big data is maps having an interactive component that reveals the extent of uncertainty.

2.3.3. Types of uncertainty maps

It is widely accepted in various research fields that there is a need to incorporate uncertainty into standard visualisations of data (Zuk & Carpendale 2006). Uncertainty can be visualised using a variety of methods (MacEachren et al. 2005). In its simplest form, uncertainty can be presented as average values in a table or on a graph, but in order to be meaningful it should be incorporated into one visualisation with the data of interest (Davis & Keller 1997).

Visualisation is the graphical representation of data in such a manner that the most important characteristics are made clear to the reader (Griethe & Schuhmann 2006). In an uncertainty visualisation both the data and the associated uncertainty are represented (Newman & Lee 2004). Although many experts agree that visualising uncertainty is beneficial, it is important to ensure that users are still able to decipher and interpret the underlying data (Sanyal et al. 2009). Uncertainty visualisations provide users with a more complete and accurate representation of information (Pang et al. 1997). There are different ways that uncertainty visualisations can be represented. Pang et al. (1997) suggested three different ways of displaying uncertainty visualisations: overloading, side-by-side comparison, and seamless integration. Overloading is when the uncertainty information is displayed graphically on top of the conventional visual representation of the data, side-by-side comparison is when the uncertainty visualisation is displayed next to the original visualisation, and seamless integration is when one representation is created by integrating the data, and the associated uncertainty in one visualisation.

It has been established that five distinguishable categories exist in terms of uncertainty visualisations (Kinkeldey et al. 2014):

1) Explicit/implicit

Uncertainty can either be depicted explicitly (directly) or implicitly (indirectly). An explicit depiction would be using symbols that directly represent the level of uncertainty at a specific point. Implicitly conveying uncertainty would involve, for example, showing numerous visualisations all highlighting different possible outcomes for a given scenario (Deitrick 2012). Explicit uncertainty visualisation is most commonly reported on in the literature (Kinkeldey et al. 2014).

2) Intrinsic/extrinsic

An intrinsic approach to uncertainty visualisation is to directly manipulate the different visual variables to signify uncertainty. Visual variables were proposed by Bertin (1983) as a means to communicating information visually. He defined seven basic visual variables: the x and y position, size, colour value, colour hue, shape, and orientation (Garlandini & Fabrikant 2009). An example of manipulating visual variables to represent uncertainty would be increasing the colour value to signify higher levels of uncertainty. Numerous studies have been conducted on the effectiveness of different intrinsic ways of representing uncertainty (Leitner &

Buttenfield 2000; Boukhelifa et al. 2012; Sanyal et al. 2009; Drecki 2002; Kunz et al. 2011; MacEachren et al. 2012) and all have different results and recommendations on how the visual variable should be manipulated.

An extrinsic approach is to define new objects, such as glyphs, to signify uncertainty. Borgo et al. (2013) defined a glyph as a small independent visual object that depicts data values (e.g., an arrow). Several studies have been conducted on the comparison between intrinsic and extrinsic techniques to create uncertainty visualisations: Newman and Lee (2004) found that three of their original extrinsic techniques outperformed intrinsic techniques, and Grigoryan and Rheingans (2004) found that users were more accurate when interpreting uncertainty represented by point displacement in a 3D display than when the uncertainty was represented with colour hues and values. Kinkeldey et al. (2014) studied a grid based extrinsic technique known as noise annotation lines and concluded that it was a viable alternative to intrinsic techniques. Past research has revealed that intrinsic uncertainty visualisations are often preferred by those whose main goal is to get an overview of what is being depicted. While extrinsic visualisations are preferred by those who want to gather detailed information (Kinkeldey et al. 2014).

3) Visually integral/separable

A visually integral uncertainty visualisation means that the uncertainty data and the original data appears as a single visualisation, in other words, one cannot read the two values separately. A visually separable uncertainty visualisation means that one can separate the two values and read them independently (MacEachren et al. 1998; Kinkeldey et al. 2014).

4) Coincident/adjacent

A coincident uncertainty visualisation is the same as the seamless integration defined by Pang et al. (1997) where the data and the uncertainty are integrated in a single representation. Similarly, an adjacent visualisation is the same as the side-by-side comparison where the data and the associated uncertainty are represented next to each other but in separate visualisations. Davis & Keller (1997) used the adjacent method as one of their methods to visualise and communicate uncertainty relating to slope stability. In their study, it was noted that this method could be advantageous as it is relatively simply to produce and is easily understood by non-professionals. However, it was also noted that this technique does not strongly convey the correlation between the data and the uncertainty.

Although participants in other studies have reported that adjacent maps are preferable because they are judged to be easier to use (MacEachren et al. 1998), it has since been established that there is no real difference in user performance between coincident and adjacent uncertainty visualisations (Kinkeldey et al. 2014). Past research has suggested that adjacent views are more suitable for tasks that require retrieval of single values, rather than for more complex tasks. Coincident visualisations are most preferable for simple representations as it is easier to interpret data and its associated uncertainty when it is seamlessly integrated. Coincident visualisations, can, however become more difficult to interpret as the data represented becomes multifaceted (Kinkeldey, et al. 2014). Davis & Keller (1997) made use of coincident displays in their slope stability study. Two different methods were used to produce two different coincident displays. The first method was to combine two maps (an uncertainty surface and a slope stability surface) into a single map using a Boolean AND operation. It was noted that this technique leads to improved focus on the data but at the expense of information content. The second method was the integration of fuzzy analysis directly into the visualisation which was achieved through the production of a worst case scenario map. An algorithm which made use of fuzzy analysis was used to produce a map of the most unstable zones. In this situation, the uncertainty is implicit in the visualisation and is not represented separately for the user to analyse. This method does not result in as much loss of information as with their previously mentioned Boolean AND method.

5) Static/dynamic

This category differentiates between traditional static visualisations and animated dynamic visualisations, which allow the user to interact with the map. There is little evidence to show that users interpret uncertainty better when it is displayed in a dynamic visualisation versus when it is displayed in a static visualisation (Kinkeldey et al. 2014). Howard & MacEachren (1996) suggested two techniques for creating interactive visualisations of uncertainty. One technique involves depicting data and uncertainty together in a bivariate symbol. In this instance, the uncertainty behaves like a second a variable. The second technique is to create visualisations depicting only the data of interest, but have interactive controls that will allow the user to decide on an uncertainty threshold. If the uncertainty is above the set threshold, then the associated data will not be displayed, or will be depicted unclearly (MacEachren et

al. 2005). There have also been several studies on animated dynamic uncertainty visualisations. Fisher (1993) created animated uncertainty visualisations of soil and land cover classification in rasters. The lower the uncertainty regarding the inclusion of a particular cell to a category, the more time that cell will be represented by a certain colour. The overall result is a map that indicates certain areas in a stable colour, and uncertain areas with a flickering colour (MacEachren et al. 2005).

2.3.4. Techniques for representing uncertainty

Many techniques used to represent uncertainty in studies have relied on the manipulation of Bertin's (1983) visual variables (Aerts et al. 2003). The visual variables are location, size, colour hue, colour value, grain, orientation, and shape. The visual variables relating to colour have often been used to represent uncertainty in visualisations (Boukhelifa et al. 2012; Bauer & Rose 2015).

Many examples of uncertainty visualisations can be found in the literature. The following section will discuss and show selected examples of the different 2D and 3D techniques used to represent uncertainty.

2.3.4.1. 2D techniques

Numerous studies have been conducted on the representation of uncertainty using 2D techniques. Table 2 summarises these studies. Each study was analysed and then categorised according to the characteristics defined in the table column headings. The table specifies which category of uncertainty map (from (Kinkeldey et al. 2014) the research covers as well as what the characteristics were for each map. The categories of uncertainty maps, as defined by Kinkeldey et al. (2014) are detailed in section 2.3.3. The characteristics of uncertainty maps were included based on their frequency of referral in the literature. The characteristics are as follows:

- Type of uncertainty (Kinkeldey, MacEachren, et al. 2014)
- Data geometry (Referred to as data type by Mason et al. (2016))
- Spatial dimension (referred to as location by Pang et al. (1997))
- Data type (referred to as data extent by Pang et al. (1997))

In some cases in Table 2, 2D techniques have been used to represent uncertainty in 3D displays.

The studies presented in Table 2 show that it is possible to use 2D techniques to represent uncertainty in a 3D display. The most common type of uncertainty handled in these studies is attribute uncertainty with intrinsic techniques being the most popular form of technique used. Most of the intrinsic techniques relied on the manipulation of some aspect of the colour visual variable to represent uncertainty. The majority of the studies looked at uncertainty in continuous data.

Study (Author, year)	Intrinsic techniques	Extrinsic techniques	Coincident	Adjacent	Static	Dynamic	Type of uncertainty	Data geometry	Display (spatial dimension)	Data type
Leitner & Buttenfield, 2000	Colour value, texture, saturation		X		X		Attribute	Point, field	2D	Discrete
Djurcilov, 2002	Transparency, speckles, noise, texture		X		X		Attribute	Field	3D	Continuous
Aerts et al., 2003	Colour hue Colour hue			side -by - side One after the other (loop)	X	Toggleing - model outputs and uncertainty were sequenced in a loop	Attribute Attribute	Field Field	2D 2D	Continuous Continuous
Slocum et al., 2003	Colour hue, colour value		X			Interactive	Attribute	Field	3D	Continuous
Newman & Lee, 2004	colour value, transparency, aliasing		X		X		Attribute	Field	2D	Continuous

Table 2: Summary of research studies focusing on the use of 2D techniques for representing uncertainty.

Study (Author, year)	Intrinsic techniques	Extrinsic techniques	Coincident	Adjacent	Static	Dynamic	Type of uncertainty	Data geometry	Display (spatial dimension)	Data type
Hope & Hunter, 2007	Dashed lines (indicating probability limit), Colour value		X		X		Positional	Line, field	2D	Continuous
		Textual statement, on screen probability statement	X			Animation	Positional	Field	2D	Continuous
Benke et al., 2011		Error bands	X		X		Attribute	Field	2D	Discrete
Kubíček & Šašinka, 2011	Saturation, whitening		X		X		Attribute	Field	2D	Continuous
	Saturation, whitening			Side – by – side	X		Attribute	Field	2D	Continuous
Boukhelifa et al., 2012	Blur, dashing, colour value, sketchiness		X		X		Attribute, Positional	Line, field	2D	Discrete

Table 2 continued: Summary of research studies focusing on the use of 2D techniques for representing uncertainty.

Study (Author, year)	Intrinsic techniques	Extrinsic techniques	Coincident	Adjacent	Static	Dynamic	Type of uncertainty	Data geometry	Display (spatial dimension)	Data type
Retchless & Brewer, 2012	Colour value			Side – by-side	X		Attribute	Field	2D	Continuous
	Texture, whitening, Colour saturation		X		X		Attribute	Field	2D	Continuous
Griffin et al., 2014		Colour coded points (red - high margin of error, green - low margin of error)	X		X		Attribute	Point	2D	Discrete
	Sketchiness		X		X		Attribute	Line	2D	Discrete
Kinkeldey, 2014		Noise annotation lines	X		X		Attribute	Line	2D	Discrete

Table 2 continued: Summary of research studies focusing on the use of 2D techniques for representing uncertainty.

Study (Author, year)	Intrinsic techniques	Extrinsic techniques	Coincident	Adjacent	Static	Dynamic	Type of uncertainty	Data geometry	Display (spatial dimension)	Data type
Bauer & Rose, 2015		Variable grid	X		X		Attribute	Field	2D	Continuous
Li et al 2015		Error bands	X		X		Positional	Polygons	3D	Discrete
Cheong et al, 2016	colour value, colour hue, transparency, texture, dashed line (burn likelihood)		X		X		Positional	Lines, field	2D	Discrete
		Text	X		X		Positional	Field	2D	Discrete
Lim et al, 2016	Colour value			side -by – side	X		Attribute	Field	2D	Continuous
		Performance bars (vertical bars)		2D side – by – side	X		Attribute	Field	2D	Continuous

Table 2 continued: Summary of research studies focusing on the use of 2D techniques for representing uncertainty.

Study (Author, year)	Intrinsic techniques	Extrinsic techniques	Coincident	Adjacent	Static	Dynamic	Type of uncertainty	Data geometry	Display (spatial dimension)	Data type
Lim et al, 2016	Colour value			side -by – side	X		Attribute	Field	2D	Continuous
McKenzie et al., 2016		Circle glyph (uniform blue circle with border vs Gaussian fade), centroid marker	X		X		Positional	Point	2D	Discrete

Table 2 continued: Summary of research studies focusing on the use of 2D techniques for representing uncertainty.

2.3.4.2. 3D techniques

In this section, techniques which make use of the third dimensions to represent uncertainty are discussed. The studies are summarised in Table 3 below. Each study was analysed and then categorised according to the characteristics defined in the table column headings. Table 3 has the same structure as Table 2 and was completed using the same criteria. A detailed description of the studies follow Table 3.

Slocum et al. (2003) developed a software program aimed at decision makers which allows for the visualisation of uncertainty associated with global water balance. The focus of the study was the visualisation of uncertainty using 3D displays. A water balance model which used results from different global climate models (GCMs) as input parameters was run repeatedly and the range of output values for each location was used as a measure of uncertainty. Both intrinsic and extrinsic techniques were used in the study to represent uncertainty in the visualisations. Intrinsic techniques involved using colour to indicate which input parameter was the source of the uncertainty and brightness to indicate the magnitude of the uncertainty.

Study (Author, year)	Intrinsic techniques	Extrinsic techniques	Coincident	Static	Dynamic	Type of uncertainty	Data geometry	Display (spatial dimension)	Data type
Slocum et al., 2003	Transparency	Vertical bars	X		Interactive	Attribute	Field	3D	Continuous
Grigoryan & Rheingans, 2004	Point and line displacement		X		Interactive	Positional	Point, line	3D	Discrete
Newman & Lee, 2004		Cone Glyphs	X	X		Attribute	Point	3D	Discrete

Table 3: Summary of research studies focusing on the use of 3D techniques for representing uncertainty.

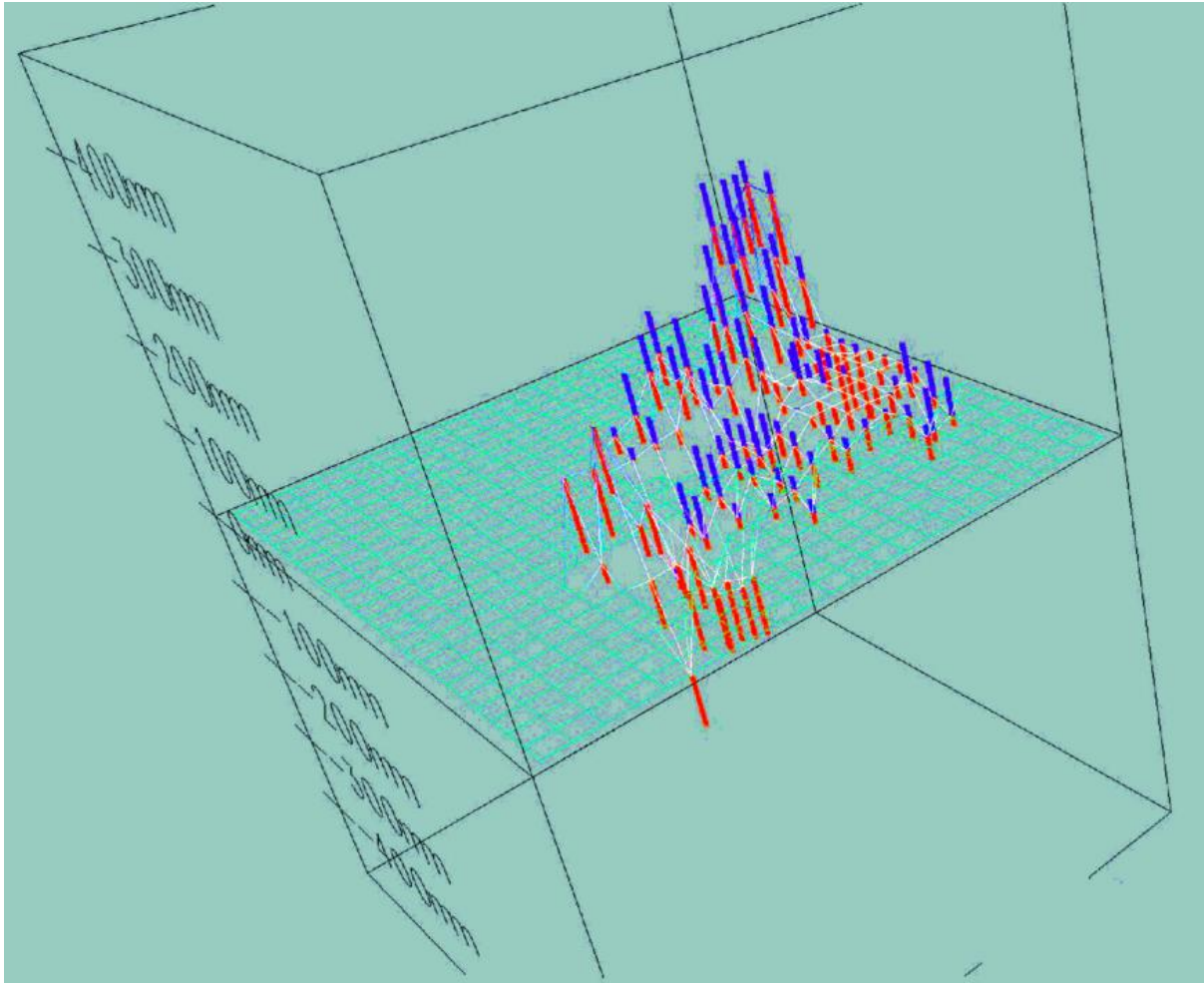


Figure 10: The vertical bars used by Slocum et al. (2003) to depict uncertainty in a water balance model.

The extrinsic technique used was a glyph based approach where vertical bars were used to indicate the source and magnitude of uncertainty. The colour of the bar corresponded to one of the four input parameters and the height of the bar indicated the magnitude of the uncertainty. Domain experts and decision makers were asked to test the visualisations in order to determine their usefulness. Results indicated that domain experts found the visualisations where the extrinsic techniques were used to be more useful as it provided more detailed information. Decision makers favoured the visualisations where intrinsic techniques were used as they felt it provided a better overview of the information. The study noted limitations for both intrinsic and extrinsic techniques. The intrinsic techniques made it difficult to decipher detailed information in the visualisation whereas the extrinsic methods were overly complex when a large geographic area was displayed.

In their study of visualising uncertainty in volumetric data, Newman & Lee (2004) proposed three original glyph based approaches to represent uncertainty. Uncertainty glyphs are a

method of combining the uncertainty and the data into a single visualisation without the use of additional visual variables (Zuk & Carpendale 2006). A computerised topography of a lobster was used as the volumetric surface for the experiments and the uncertainty data was synthetically generated. Wireframe cone glyphs (Figure 11) were used to indicate the amount of uncertainty present in the volumetric dataset. The diameter of the base of the cone indicates the level of uncertainty in the data in a particular region. The bigger the diameter of the base of the cone the higher the uncertainty is estimated to be in that region.

Grigoryan & Rheingans (2004) researched point displacement as a method of representing positional uncertainty in 3D tumour data. Tumours were used as a use case with which to visualise uncertainty. The tumours were modelled as a collection of points. A point was then displaced from its location by an amount proportional to its associated uncertainty. An area of displaced points leads to a fuzzy appearance of the feature being represented, which intuitively makes the data appear uncertain. Two of the noted advantages of this method are that the areas of high and low uncertainty are immediately apparent, and that the spatial extent of the area of uncertainty is clear as the area that the point is likely to be found is highlighted. Figure 12 from the study shows a tumour with uncertainty information integrated. The area pointed out by the red arrow shows high positional uncertainty (large point displacement), whereas the area pointed out by the blue arrow shows low positional uncertainty (small point displacement). Transparency was also included to further enhance the appearance of uncertainty (Figure 13). User studies showed that participants were 20% more accurate when interpreting the point displacement model as opposed to other uncertainty representation techniques.

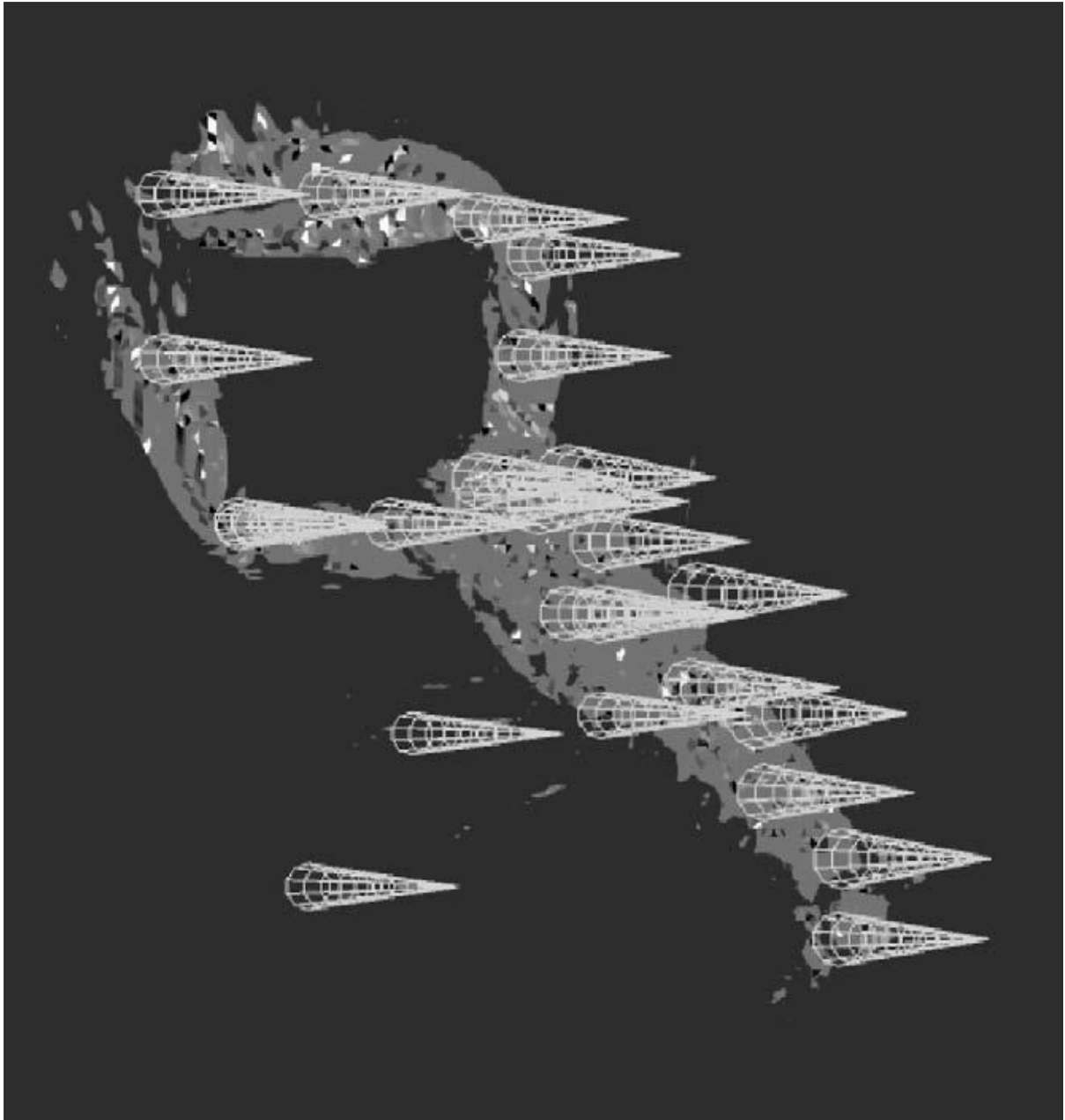


Figure 11: Local areas of uncertainty represented by cone glyphs. Source: Newman & Lee (2004).

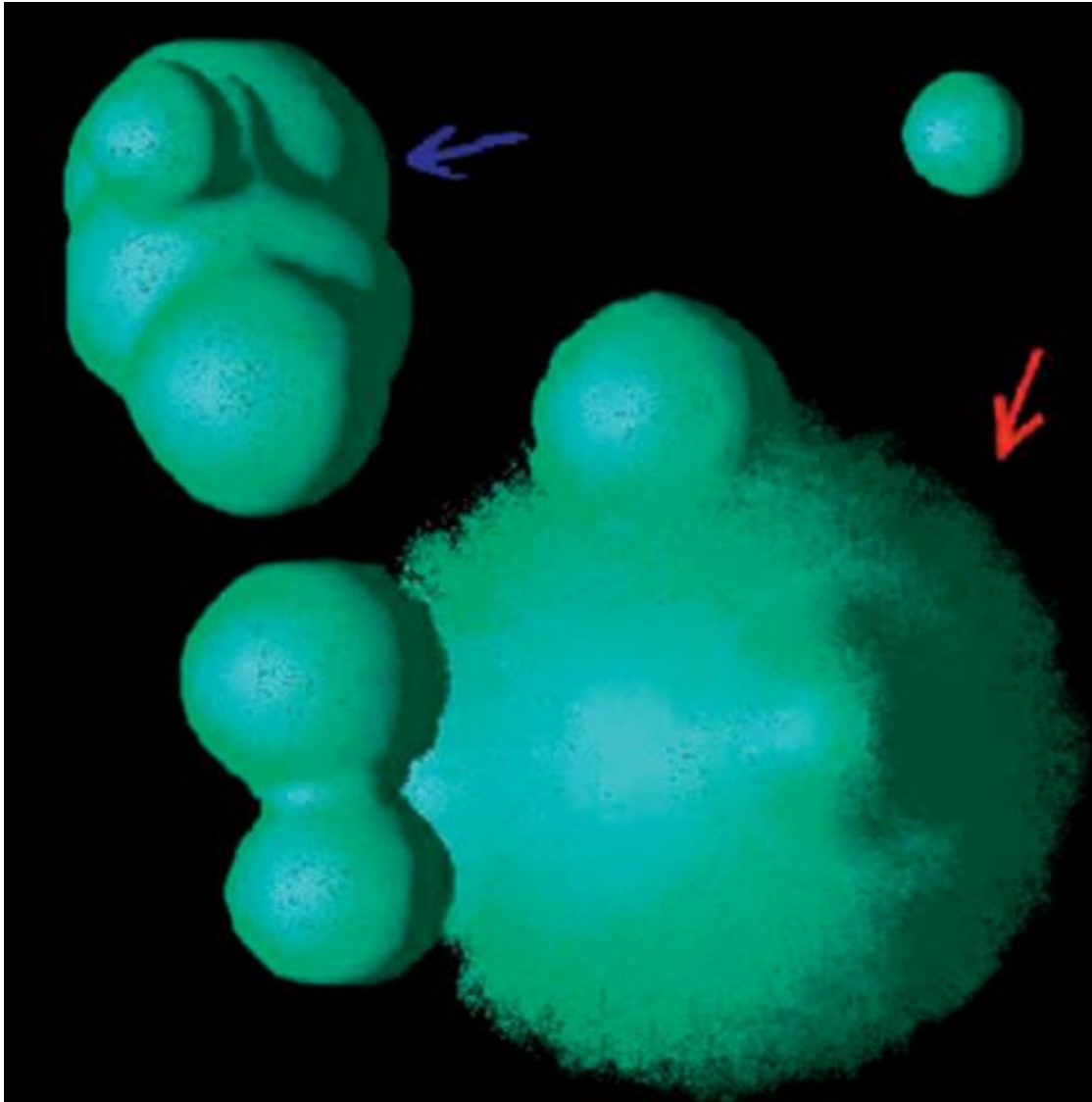


Figure 12: Point displacement representing uncertainty in 3D tumour data. Source: Grigoryan & Rheingans (2004).

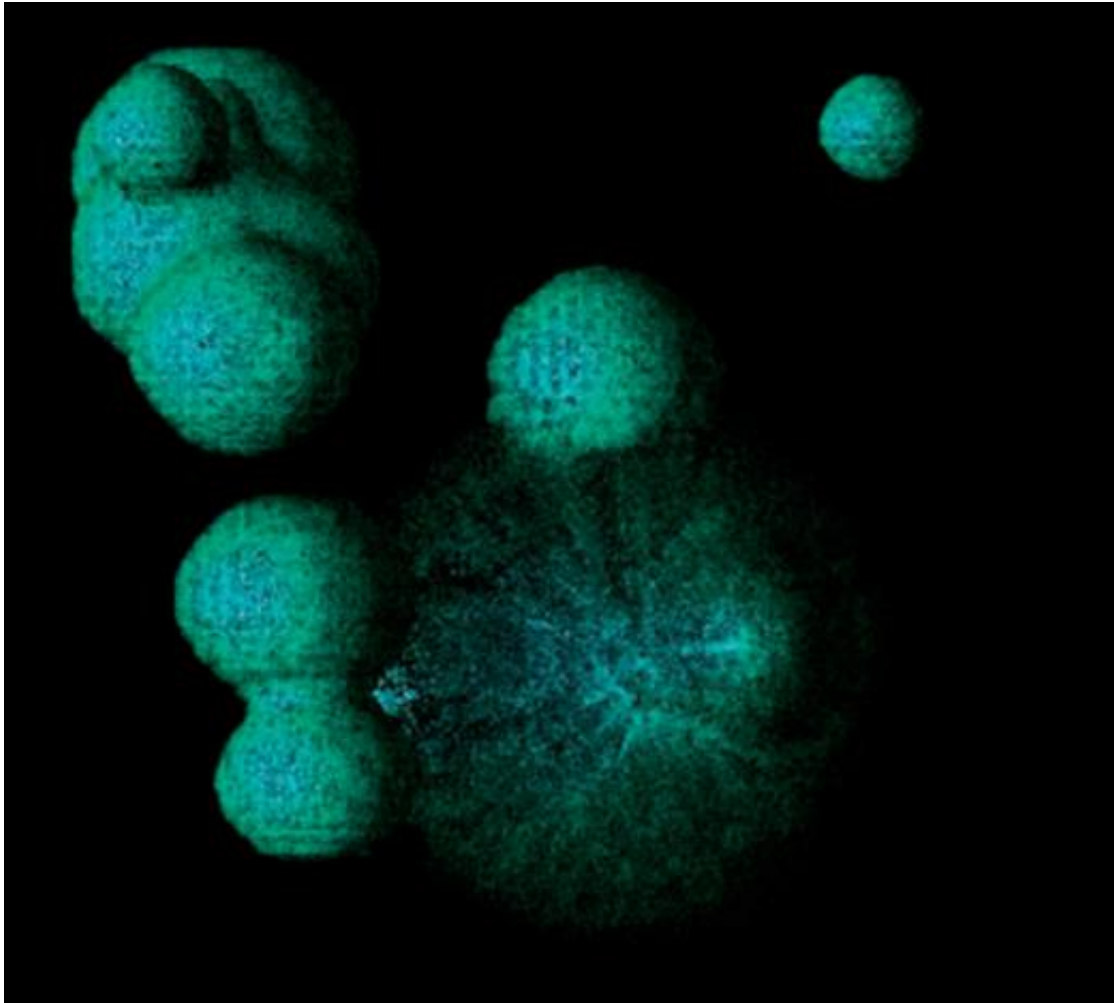


Figure 13: Point displacement used in combination with transparency to portray uncertainty. Source: Grigoryan & Rheingans (2004).

The studies summarised in Table 3 show that there are fewer studies focusing on 3D techniques than 2D techniques (see Table 2). A variety of intrinsic and extrinsic techniques were used with two of the three studies focusing on attribute uncertainty.

2.3.5. Visualising uncertainty in wind farm planning

One of the primary objective in wind farm planning is the optimal selection of a site based on the quality of local wind resources (Messac et al. 2012). Messac et al. (2012) looked at characterising and mitigating wind uncertainty in wind farms where uncertainty related to wind speed, wind direction, and air density was considered. The combination of the uncertainty relating to wind speed, wind direction, and air density can increase the uncertainty associated with the energy potential estimate of a wind farm. In their study, Messac et al. (2012) developed a new methodology to characterise uncertainty in wind farm

planning. The uncertainty was presented in the form of graphs (Figure 14). As can be seen in Figure 14, the third dimension is being used to represent uncertainty.

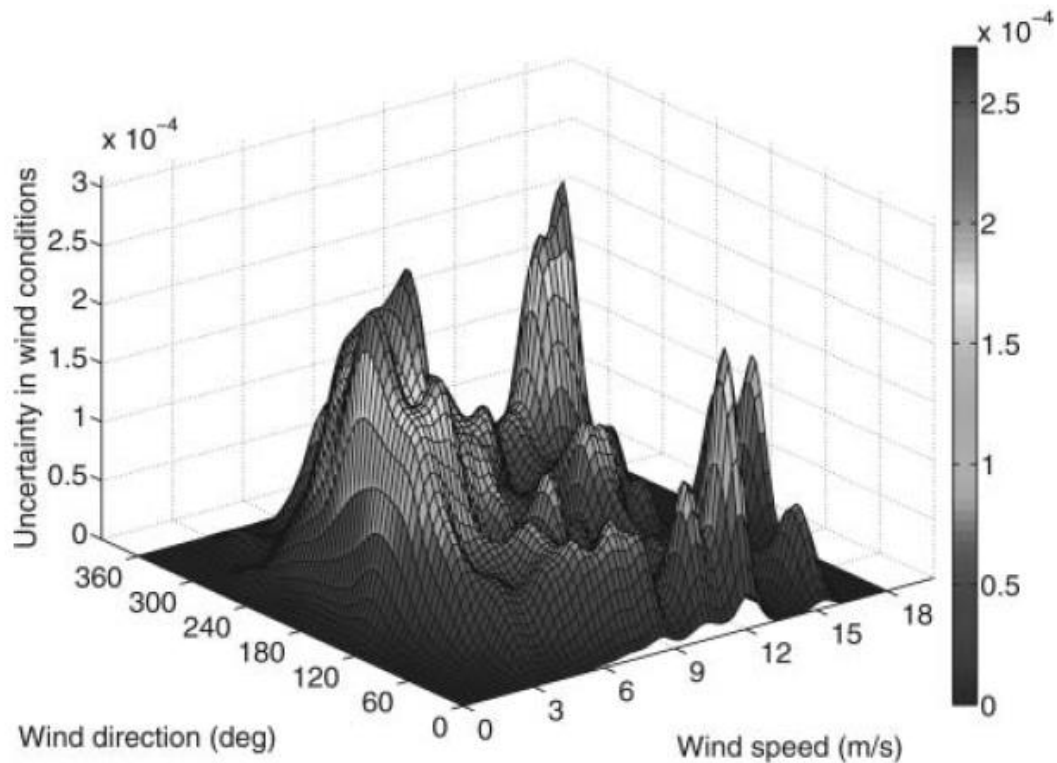


Figure 14: Uncertainty in the distribution of wind speed and wind direction presented in a graph format (Messac, et al. (2012))

Afanasyeva et al. (2016) researched the technical, economic and uncertainty modelling of a wind farm project. According to these authors, the natural variability of wind speed introduces a significant unavoidable uncertainty to wind farm evaluations. Graphs are used to represent uncertainty in this study as in Figure 15.

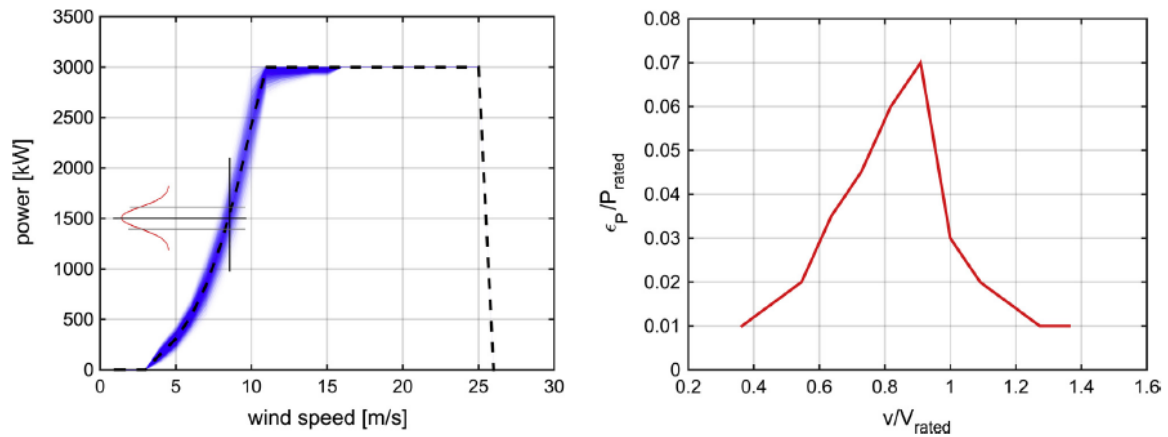


Figure 15: Normalised uncertainty in the power curve to normalised wind speed at hub height. Source: Afanasyeva et al. (2016)

2.4. 3D maps

2.4.1. Overview

Traditionally GIS has focused primarily on the visualisation of geographic information in two dimensions and it was only in the late 1990's that the third dimension had started to be incorporated (Kwan 2000). With the development of interactive virtual environments, maps are no longer constrained to being static 2D representations of the world and geospatial data is now being displayed and explored in these highly dynamic and interactive environments (MacEachren & Kraak 2001). 3D mapping is the utilisation of the z axis of an object in order to emphasize intensity and variation in the data (Hernandez 2007). Utilising the third dimension allows additional variables to be combined in a single view which provides the user with greater insight in to the relationships among the variables (Kraak 2003). As humans we live in a 3D world and therefore view entities in our surrounding environment stereoscopically (Deren et al. 2009). As a result there is a great deal of research being done on accurately and aesthetically recreating geographic landscapes (Deren et al. 2009).

3D maps are a component of modern geovisualisation and refer to 3D geovisualisations where the data is georeferenced and where the graphic appearance of objects is classified and symbolised by a legend (Häberling et al. 2008). 3D maps are becoming increasingly popular due to advances in computer graphics and technology (Bleisch 2012) and are receiving a lot of attention and interest in many application fields (Zamyadi et al. 2014). The recent interest and advancement in the fields of Augmented and Virtual Reality has led to improvements in the way in which users can interact with and experience 3D environments (Morton et al.

2012). Complete 3D maps of environments are becoming increasingly necessary in application fields such as architecture, engineering and construction, facility management, tourism, and urban planning and development, which has led to a rising need for 3D geospatial information (Altmaier & Kolbe 2003; Zhang et al. 2011; Bleisch 2012). The increased use of 3D data has resulted in increased interest in 3D spatial analysis (Brasebin et al. 2012).

3D maps have the potential to convey a large amount of information (Altmaier & Kolbe 2003) and their usefulness lies in their ability to portray, in addition to the representation of the real world, other attribute information that is usually invisible (Bleisch 2012). They are typically dynamic and generally provide users with navigational capabilities such as shifting the viewpoints which further allows information that is usually hidden to become visible (Bleisch 2012).

2.4.2. Advantages

3D maps enable the user to experience a more dynamic and flexible environment than traditional visualisation techniques (Kwan 2000). They also provide a more realistic and complex visualisation of urban environments than conventional GIS methods cannot (Kwan 2000). 3D maps facilitate exploratory spatial analysis and can make the identification of spatial relationships more prominent (Kwan 2000). In a study about the impact of 3D data geometric modelling on spatial analysis Brasebin et al. (2012) state that 3D data can result in better understanding of information and can lead to better informed decisions being made. 3D environments simulating the real world can provide an increased sense of realism as well as lead to an increased sense of presence in the simulated environment (Dalgarno & Lee 2010).

3D maps engage more complex dimensions of human perception and are perceived to be more aesthetically preferable than other visualisation techniques (Sheppard & Cizek 2009). Sheppard and Cizek (2009) explore the benefits of 3D visualisations (of which 3D maps are a subset) for both experts and lay people. For an expert (scientist) the advantage of using 3D visualisation in their work is that they can more effectively communicate their work and they can make it more relevant to their audience's experience. In addition, their findings can be more accessible and better understood by a wider audience. The implication of this is that the audience would be better able to understand information communicated using 3D maps. Members of the general public can benefit from 3D maps as it allows them to put complex

scientific information into perspective and helps them improve their spatial and global awareness (Sheppard & Cizek 2009).

In studies related to the effect of 3D environments on learning, results have shown that appropriately designed 3D environments offer improved learning over 2D technologies (Dalgarno & Lee, 2010). Huk (2006) has shown that students with a high spatial cognitive ability find that learning using 3D environments significantly reduces their cognitive load and can benefit greatly from them. It has been suggested that the most important characteristic of interactive 3D maps which makes them invaluable for learning is that the user can directly control the objects in the virtual world (Hedberg & Alexander 1994; Dalgarno & Lee 2010). This leads to more active learner participation and an overall superior learning experience (Hedberg & Alexander 1994).

2.4.3. Challenges

One major challenge of 3D maps is that there is little understanding and awareness on whether 3D visualisations perform as intended for specific tasks and target audiences (Çöltekin et al. 2016). In their study on the differences in visual attention in pedestrian navigation when using 2D maps and 3D geo-browsers, Liao et al. (2016) showed that 3D geo-browsers (a 3D map presented in a web browser) perform poorly with regards to spatial knowledge acquisition. The reason provided for this result is that information overload and object obstruction resulted in an extensive visual search for the users that increased their response time. In addition, it has been shown that navigation and interaction in 3D displays can increase the cognitive load (Shepherd 2008; Bleisch 2012).

Morton et al (2012) detail many of the challenges relating to 3D city models (a form of 3D geovisualisation) and reasons for them becoming obsolete. These challenges are not unique to 3D city models only, but are relevant to 3D mapping in general. One of the challenges is making sure that the minimum hardware and software requirements are met when building or using 3D models otherwise there is a great risk of 3D models becoming obsolete in that particular environment. In order to successfully create and use 3D models specific hardware and software are needed to successfully store and manage the mesh structure of the 3D models, process the typically large amount of data associated with 3D models, as well as render any texture mapping contained in the model (Bleisch 2012). 3D models therefore depend greatly on computer graphics and are costly to implement in terms of equipment and

computational power (Dalgarno & Lee 2010; Zhang et al. 2011; Bleisch 2012). Developing 3D models often requires highly skilled individuals and in, addition, can be a time consuming process which requires substantial effort (Rautenbach et al. 2015).

Accessing 3D maps can be a challenge (Zamyadi et al. 2014). In a study by Zamyadi et al. (2014) it was shown that some geoportals make no reference to 3D maps, while many others refer to, or describe, 3D maps by different keywords and definitions. This is a cause of confusion and misinterpretation (Zamyadi et al. 2014). The integration of 3D mapping tools also remains a challenge and it is often unclear which purpose specific 3D mapping tools are meant to serve (Jones et al. 2009). Generic 3D mapping tools that are meant to be used in several different application domains are common but can confuse the users (Jones et al. 2009).

2.4.4. Applications of 3D maps

Kwan (2000) used 3D maps (Figure 16 and Figure 17) to model human activity travel patterns. The data used in the 3D maps were the travel diaries of individuals which included the spatial locations in the form of x and y coordinates. The 3D maps aided in the exploratory analysis of travel activities of various groups of the population.

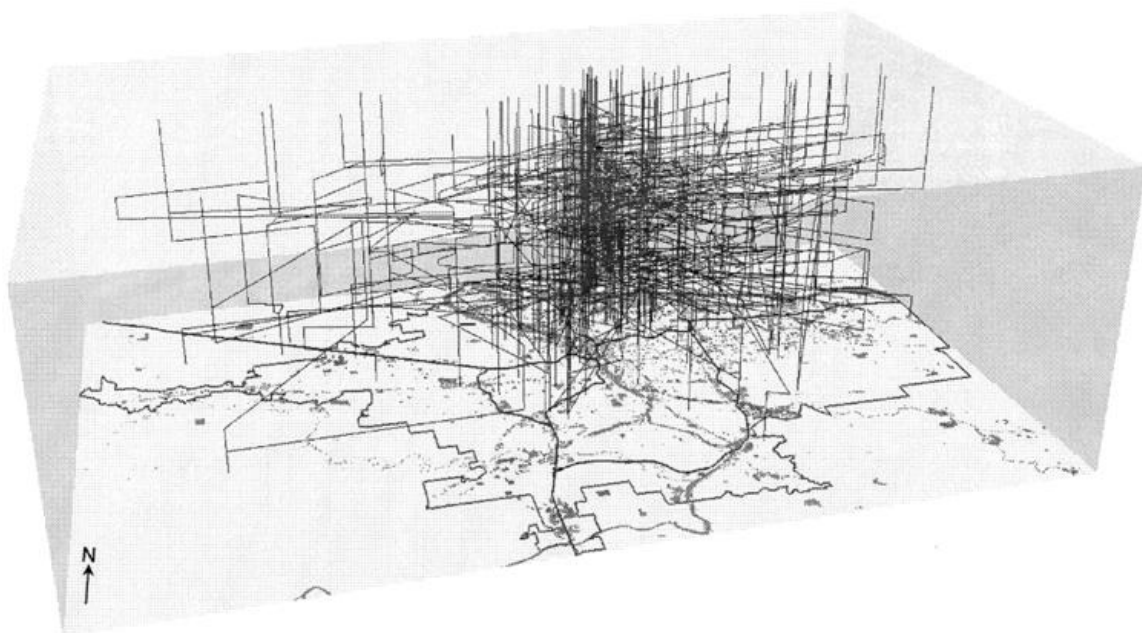


Figure 16: The 3D map Kwan (2000) developed to model human activity travel patterns.

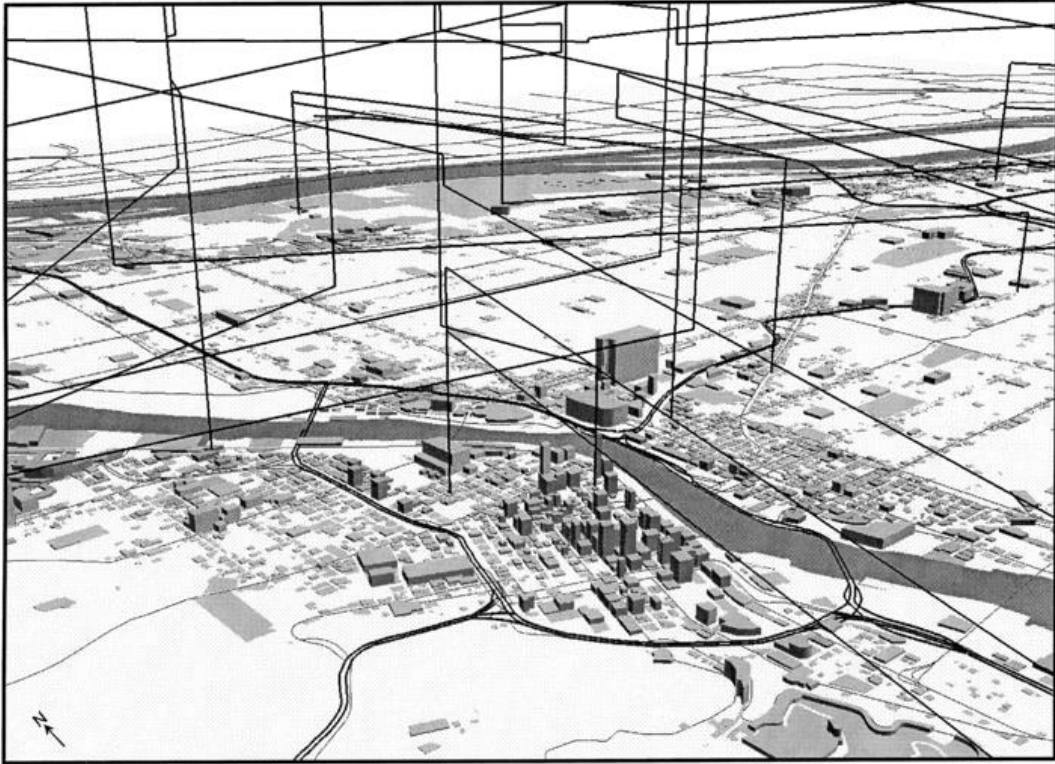


Figure 17: A closer view of Kwan's (2000) 3D map.

Kwan & Kotsev (2014) used 3D maps to study gender differences in commute time and accessibility. The 3D maps (Figure 18 and Figure 19) allowed important observations to be made regarding the differences between female and male travel patterns.

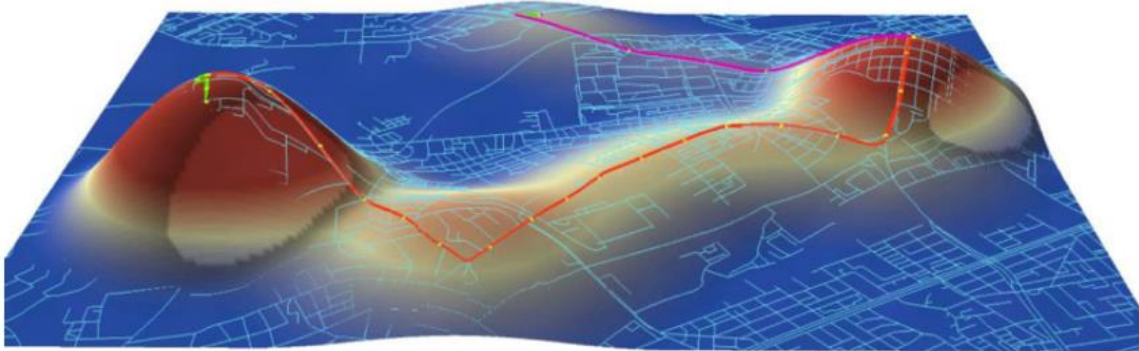


Figure 18: A 3D map from the study by Kwan & Kotsev (2014) showing an individual's commute times. The two peaks indicate the individuals waiting time for transport.

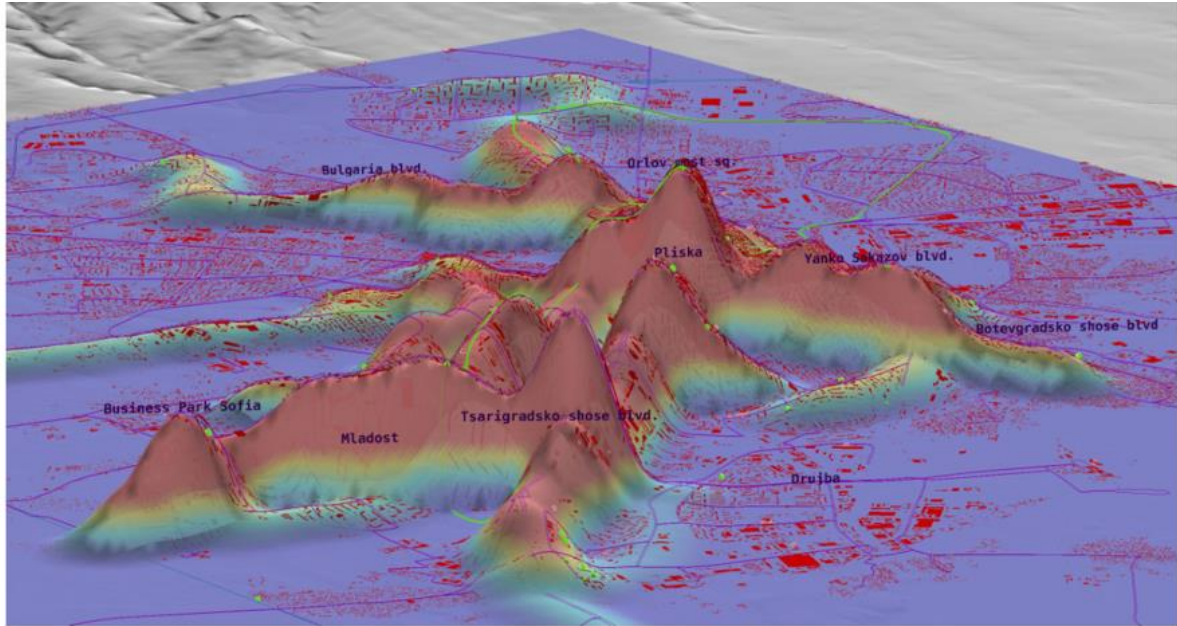


Figure 19: A 3D map from the study by Kwan & Kotsev (2014) showing the travel time for the women participants.

Lu & Fang (2014) used 3D maps to construct air pollution and risk maps. These maps aided in the visualisation of individual space-time paths, personal air quality indexes (Figure 20) and personal health danger zones (Figure 21).

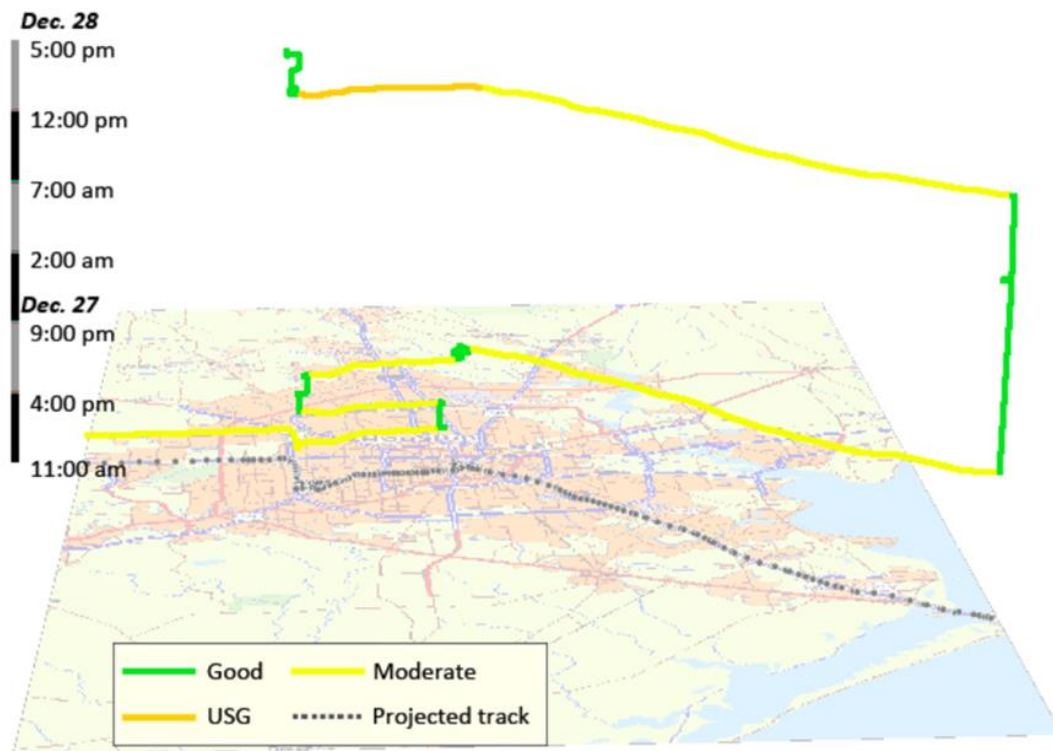


Figure 20: A 3D map from the study by Lu & Fang (2014) showing an individual's air quality index and space time path.

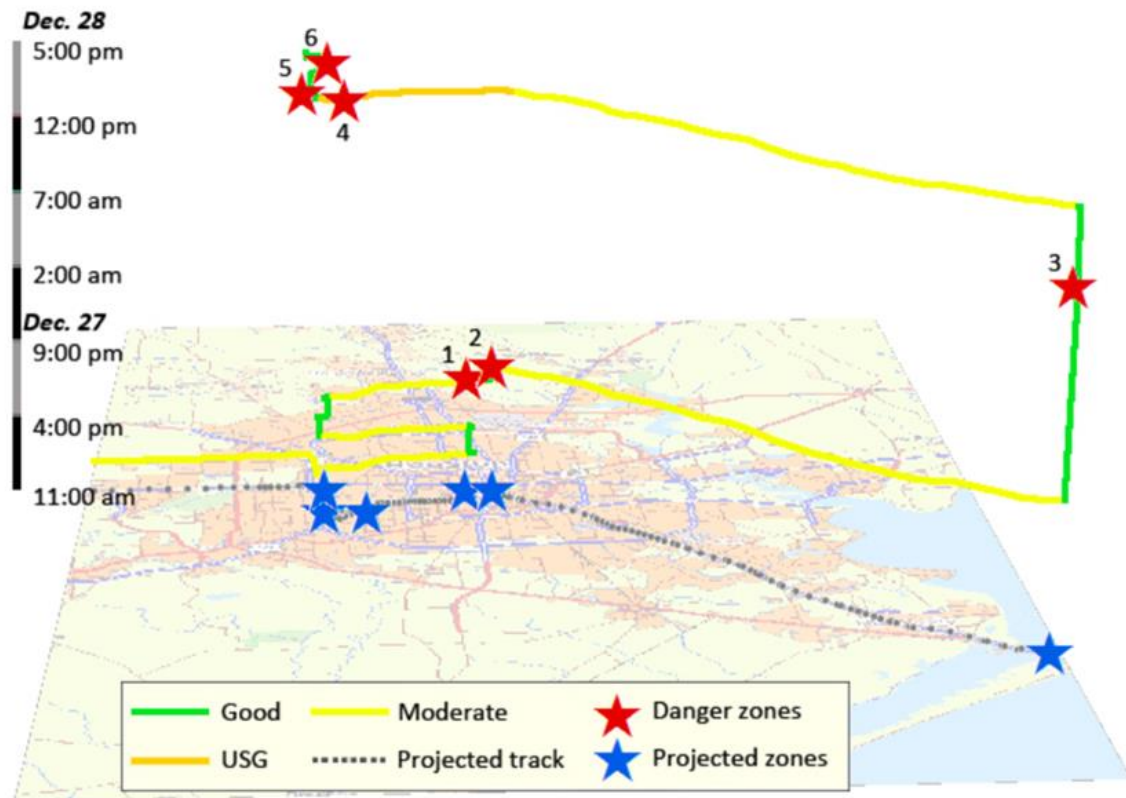


Figure 21: A 3D map from the study by Lu & Fang (2014) showing an individual's personal air pollution danger zone and space-time path.

Demšar et al. (2015) created a 3D map of stacked space-time densities in order to visualise the spatio-temporal aggregation of trajectories of tagged animals. This 3D mapping technique is based on a space-time cube and employs volumetric renderings of animal movements plotted in space and time (Figure 22). The conclusions from the study were that stacked space-time densities could be useful in animal ecology research.

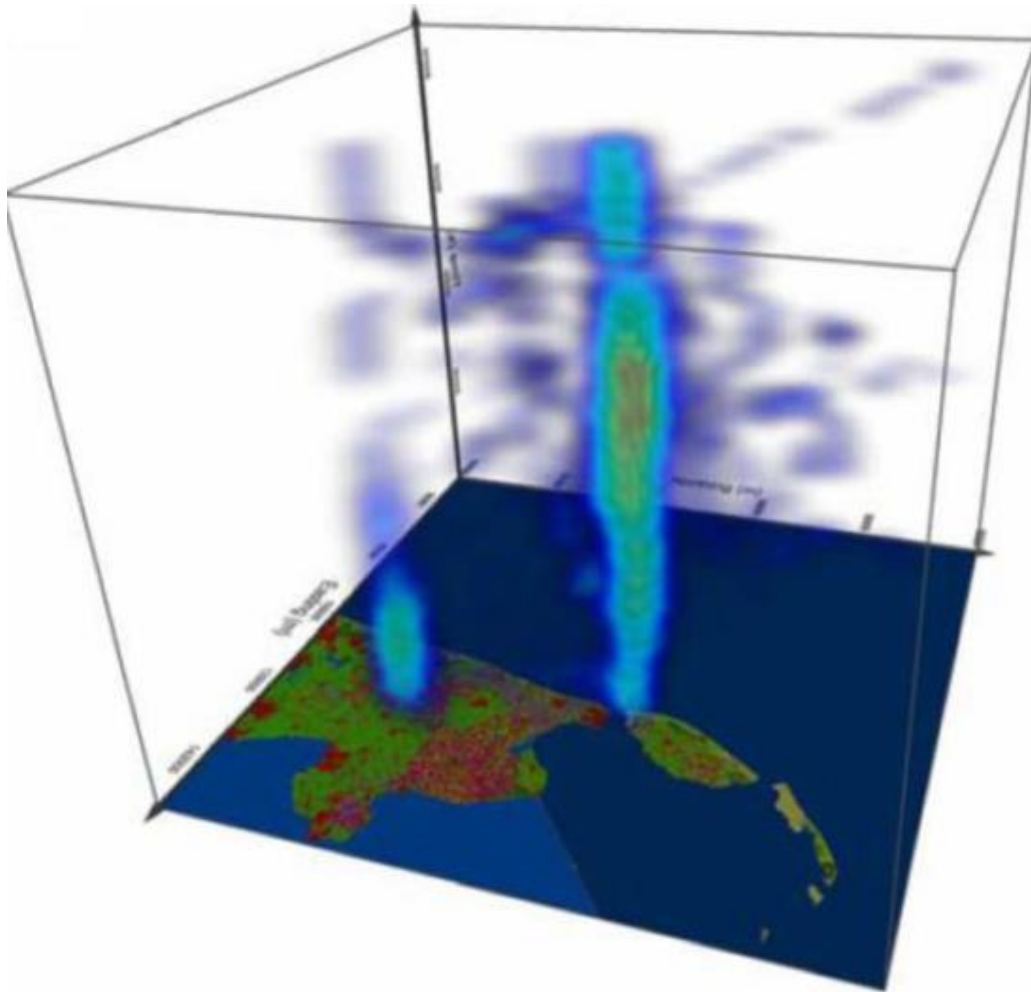


Figure 22: A space-time density map for a bird. Source: Demšar et al. (2015).

2.5. 3D maps in wind farm planning

Lange & Hehl-lange (2005) investigated the use of a virtual landscape model for participatory planning of wind turbines. Wind turbines had been proposed for a specific area and in order to facilitate a discussion regarding the acceptance of the proposed turbines, a participatory planning discussion was held with stakeholders. During this discussion, participants suggested alternatives which were incorporated into 3D models and visualised immediately. One of the aspects of the proposed turbines under discussion was the effect of shadow casting. The results of the study showed that 3D visualisation is an important method of communication and that an early adoption of 3D visualisations in the participatory planning approach is an effective way to identify potential conflicts in the early stages of the planning process.

Bishop & Stock (2010) developed a virtual reality environment which allowed users to explore both visual and noise pollution of a proposed wind farm (Figure 23). The environment was

built around 3D models of the wind farm. Users were able to move, and add, elements (e.g. add trees) to discover how the visual impact of the farm changed.

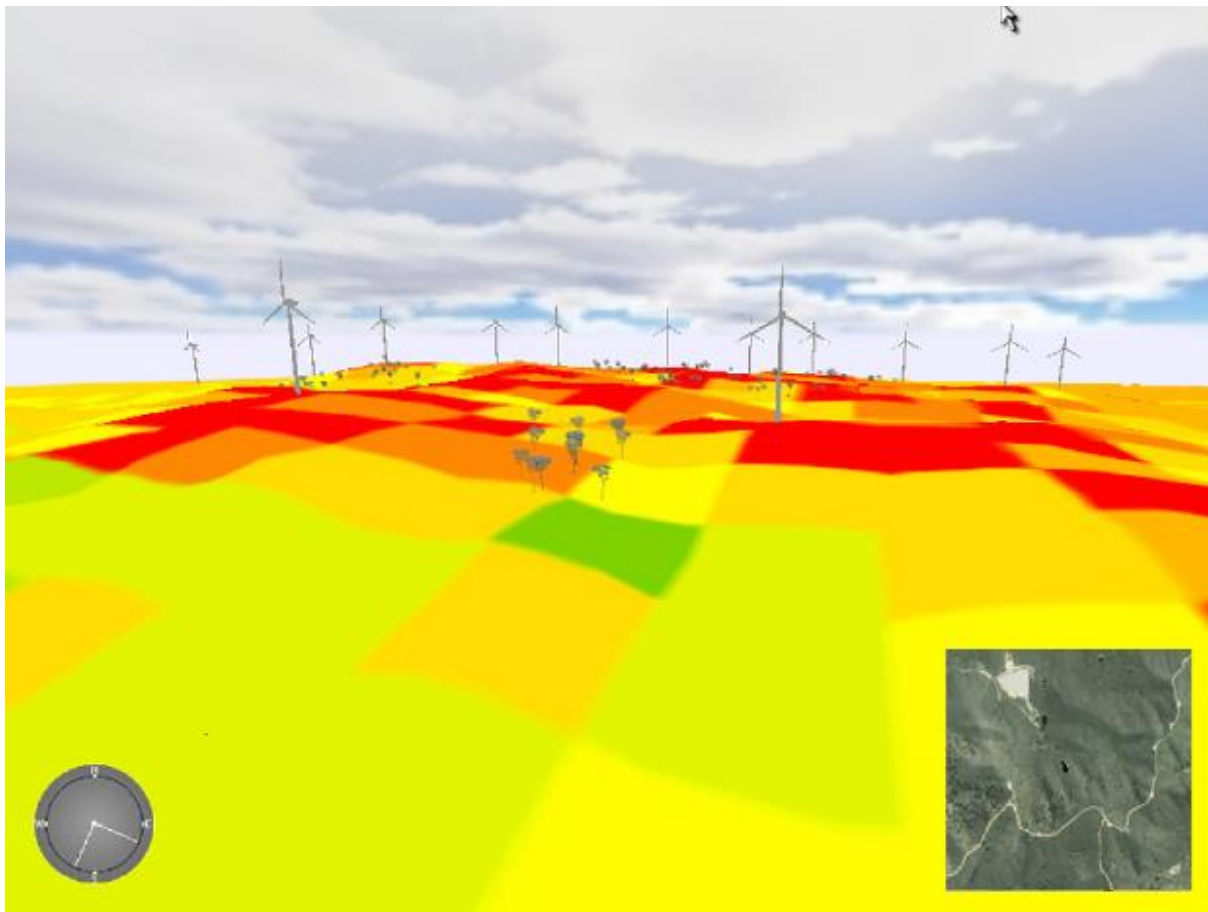


Figure 23: The visual impact assessment inside the virtual reality environment. Source: Bishop & Stock (2010).

Berry et al. (2011) showed that 3D maps can be used in the public participation phase of wind farm planning. The 3D map in Figure 24 was compared to a 2D map in a public participation survey. The results suggest that the 3D map was better interpreted and understood than 2D maps. The public participants were better able to assess the impact of planning proposals.



Figure 24: The 3D map used in the public participation survey in the study by Berry et al. (2011).

Wróżyński et al. (2016) used 3D models for the visual impact assessment of wind turbines. The 3D models incorporated the visibility range, angle of view, and wind direction (Figure 25). The 3D software, Blender, was used to create the 3D models.

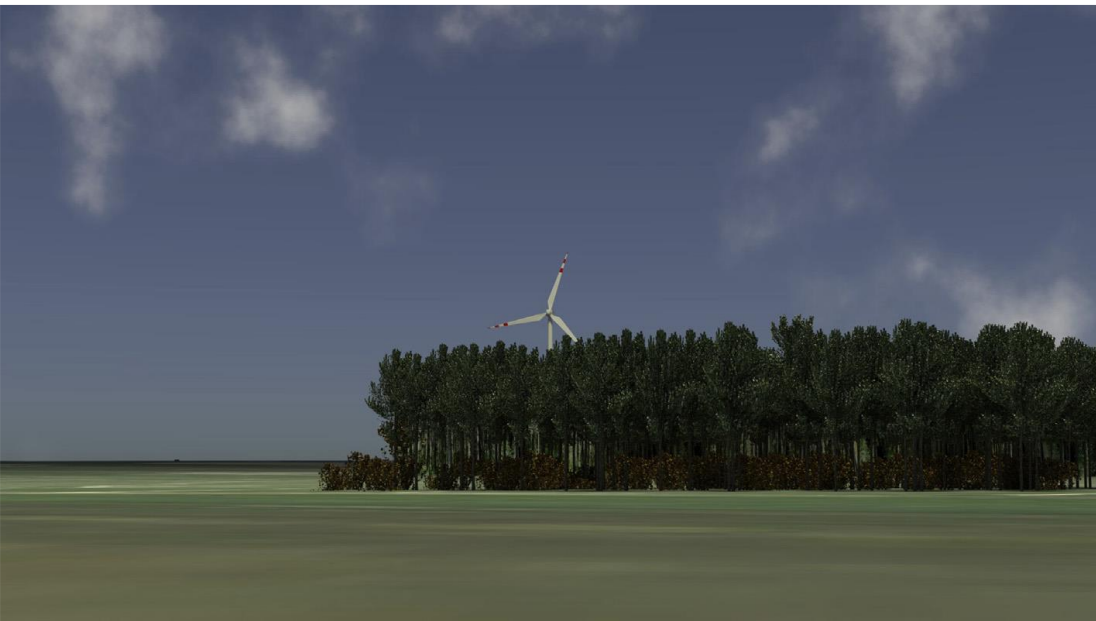


Figure 25: A 3D scene used for visual impact analysis of a proposed wind farm. Source: Wróżyński et al. (2016).

Chapter 3: Design and development of 3D maps

3.1. Introduction

The proceeding chapter provided a theoretical background on the current use of maps in wind farm planning, uncertainty and 3D maps (chapter 2). The chapter details the design and development of four 3D maps that visualise uncertainty created to support the research objectives.

This research will employ semi-structured expert interviews to gather opinions on the suitability and usability of different techniques for visualising uncertainty in 3D maps for use in regional level planning of wind farms. To achieve this goal, four interactive 3D uncertainty maps of wind speed and related uncertainty will be designed and built.

3.2. Wind farm planning and uncertainty

There are many factors that need to be considered before a renewable energy project can be installed at a particular location. Besides topography and land use/cover, wind speed plays a key role. However, in order to sustain electricity planning based on renewable energy types, macro planning approaches are followed which also take into account socio-economic, technical and legislative aspects (Mytilinou et al. 2015). Here, for determining suitable areas for installing wind farms, planners need to have an overview of wind speed, among the aspects, across a larger region allowing them to judge on the potential energy outcome for meeting the demands. This could even include the simulations of future wind speeds as predicted by regional climate models (RCM) (Jacob et al. 2014; Koletsis et al. 2016). Usually climate data and particularly future predictions have a certain degree of uncertainty associated with them (Slingo & Palmer 2011; Koletsis et al. 2016). Wind as a resource has many aspects (e.g., velocity direction, and annual variability) and is therefore highly uncertain (Messac et al. 2012). Uncertainty can relate to wind speed, wind direction, and air density (Messac et al. 2012). Therefore, interactive 3D maps linking wind speed, related uncertainty, and areas highly suitable for wind production from a socio-economic, technical and legislative standpoint, are considered here to help inform people involved in decision-making.

3.3. Study area

A region of Southern Europe was chosen as the study area (refer to Figure 26). This study area was chosen as it was covered by the received wind datasets (discussed in the following section) and the wind data for this area had a wide range of uncertainty values that would enable the uncertainty in the 3D maps to be adequately visible. The study areas was chosen to include land, ocean and mountainous areas so that there was a large variation in uncertainty.



Figure 26: Map of the study area.

3.4. Data

The data used to create the 3D maps was derived from several EURO-CORDEX¹ climate scenario datasets (see Table 4). The World Climate Research Program Coordinated Regional Downscaling Experiment Initiative for Europe (EURO-CORDEX) provides high-resolution regional climate change ensembles (Jacob et al. 2014). The CORDEX regional climate model (RCM) simulations are conducted at two different spatial resolutions of 0.44 degrees and 0.11

¹ <http://euro-cordex.net/060378/index.php.en>

degrees. The finer resolution models (0.11 degrees) were used in this research. RCM's are able to reproduce important climatic features at regional scales (Kotlarski et al. 2014). Five downscaled RCMs of Representative Concentration Pathway 8.5 (RCP 8.5) were used as a data source for the geovisualisations. There are four different pathways which are used in climate modelling for climate simulation experiments with the 8.5 pathway representing an increasing radiative forcing pathway leading to 8.5 W/m² by the year 2100 (van Vuuren et al. 2011). The five RCMs used in this research are detailed in Table 4.

Global Climate Model	Organization
CNRM CM5n	Meteo-France, CERFACS
ICHEC EC-EARTH	Irish Centre for High – End Computing
LPSL CM5a MR	Institute Pierre Simon Laplace
MOHC HdGEM2 ES	Met Office Hadley Centre
MPI ESM LR	Max Planck Institute for Meteorology

Table 4: The five downscaled RCMs used in this research and their developing organizations.

The five model simulate the wind speed at 10m above the surface of the earth for the years 2040 – 2069 (future simulation). The model data was received as a point feature class that had already been processed from the raw NetCDF files (running the models and processing the data was not part of this dissertation). The point feature class contained the attributes of the five model runs and recorded the mean wind speed values for each month for the years 2040 to 2069. The mean of the five model runs was also recorded in the feature class. Only the values for the European winter season (December, January, and February) were used in the analysis as there was greater variation in the uncertainty values. A fishnet grid was created from the points so that each point was located at the centroid of each cell. The fishnet grid did not alter the data but made it easier for visualisation purposes. A spatial join was then use to transfer the attributes from each point to the corresponding grid cell. These grid cells formed the basis for all the 3D maps.

3.4.1. Quantification of uncertainty

Model uncertainty as defined by Uusitalo et al. (2015) is portrayed in the 3D maps created for this research. If different models, which describe the same phenomenon, result in different estimates then it may be assumed that the uncertainty related to the estimate is large (Uusitalo et al. 2015). In order to quantify the uncertainty for the 3D maps, the range between the five climate model estimates were calculated. The minimum value for each point was subtracted from the maximum value to determine the range. This range was taken as the uncertainty. This is the same method of quantification used in the study by Slocum et al. (2003) where they used the model range in water balance models as a quantification for uncertainty (see section 2.3.4.2). Several other approaches exist to quantify uncertainty in geospatial data such as fuzzy set theory, Bayesian Belief Networks, and using the confidence interval of estimates.

3.5. 3D maps

Four 3D maps that visualised uncertainty were created for this research. For three of the maps the third dimension was used to represent the uncertainty and in the fourth map a traditional 2D cartographic technique to represent uncertainty was used. Both mean wind speed and uncertainty are represented in the maps. Table 5 highlights the characteristics of the four 3D maps as compared to general characteristics of uncertainty maps identified in the literature.

Type of uncertainty ²	Data geometry ³	Spatial dimension (display) ⁴	Data type ⁵
Positional	Point	2D	Discrete
Attribute	Line	3D	Categorical
Temporal	Polygon		Partitioning and Enumeration
Logical consistency	Network		Continuous Interpolation
Completeness	Field		
Lineage			

Table 5: Characteristics of uncertainty visualisations. The characteristics used in this research are indicated in red.

² Referred to as core information components by Kinkeldey et al. 2014

³ Referred to as data type by Mason et al. 2016

⁴ Referred to as location by Pang et al. 1997

⁵ Referred to as data extent by Pang et al. 1997

3.5.1. Prism map

3.5.1.1. Overview

The prism 3D map was inspired by the 3D map produced in the study by Slocum et al. (2003). In the prism map, the third dimension was used to represent uncertainty and was based on the fishnet grid. The fishnet grid cells were extruded and the height of each extrusion represented the degree of uncertainty i.e. the higher the column the higher the degree of uncertainty. The value of the model range attribute was used to determine the height that each cell should be extruded to. For visualisation purposes, the range value was multiplied by a value of 1000 to emphasise differences in the uncertainty values. The colour of the top of the columns represented the wind speed. After researching the symbology of wind speed in various weather maps it was discovered that there did not seem to be a standard colour ramp used to represent wind speed and a purple colour ramp was therefore chosen.

3.5.1.2. Characteristics

The three main categories of approaches to uncertainty visualisations (as described by Kinkeldey et al. 2014) and the different techniques used for each category are presented in Table 6. The techniques are based on the literature review presented in Table 2. The characteristics of the prism 3D map are highlighted in red. Slocum et al. (2003) referred to the prism technique as an extrinsic technique and therefore this classification is applied to the prism 3D map produced here.

Intrinsic	Extrinsic	Coincident	Adjacent	Static	Dynamic (animation, interactivity)
Colour hue	Glyph	Integrated view	Side – by - side	Classic map	Animation
Colour value	error bars, error bands		Linked views		Toggling
Texture (grain)	grid based (noise annotation lines, variable grid method (trustree))				Blinking, flickering
Size	Squares				User input (specifying uncertainty range, scaling by a factor)

Colour saturation	Text				Navigation (panning and zooming)
Colour whitening					
Clarity (crispness, resolution, transparency)					
Blur (fuzziness)					
Noise (speckles)					
Sketchiness					
Dash					
Aliasing					
Geometry displacement					

Table 6: The characteristics of the prism map in relation to other characteristics of uncertainty visualisations.

The prism 3D map was built using the ArcGIS API for JavaScript version 4.0. This API was chosen because the ArcGIS platform was readily available and it was deemed to have the necessary functionality to create the 3D maps. The API's maximum record count of 4000 polygons was one of the main contributing factors to the size of the study area. The 3D map was built by duplicating the fishnet grid which was stored in a SQL Server 2014 database. The one feature class was converted to a 3D feature class using the range value as the z (third dimension) attribute. The two layers were then published separately as feature services to ArcGIS for Server 10.4.1.

A web application was developed using the ArcGIS API for JavaScript and the published web feature services. An Esri terrain basemap was used to provide context information as well as to indicate the topography of the study area. The following diagram (Figure 27) indicates the workflow followed in the remainder of the script.

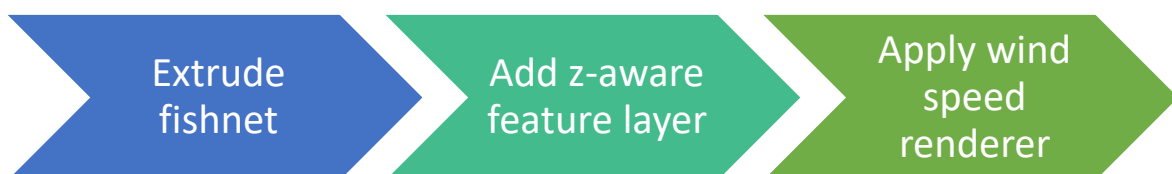


Figure 27: Workflow followed for the creation of the prism 3D map.

The fishnet was extruded to the range value specified in the attribute table (indicating uncertainty). The second z-aware feature service (the published 3D feature class) was added

which uses its z coordinate to position the layer on top of the extruded prisms. An offset was applied for visualisation purposes. A class break renderer was used to define the purple colour ramp which represented mean wind speed (refer to Table 7). The mean wind speed renderer was then applied to the top layer (the z-aware feature service). The Mean wind speed renderer is defined in Table 7 below:








Wind speed category (m/s)	Colour	Visual
2.02 – 3.00	#FCFBFD	
3.01 – 4.00	#E8E7F2	
4.01 – 5.00	#C6C7E1	
5.01 – 6.00	#9E9AC8	
6.01 – 7.00	#7970B2	
7.01 – 8.00	#705AA0	
8.01 – 9.00	#4C4496	

Table 7: The wind speed categories as defined in the mean wind speed renderer.

Because the prism 3D map is displayed in a web application the user can pan, rotate, and zoom in and out to fully investigate the different part of the geovisualisation. Figure 28 and Figure 29 are screenshots of the prism map. Figure 30 is the legend for the prism map.

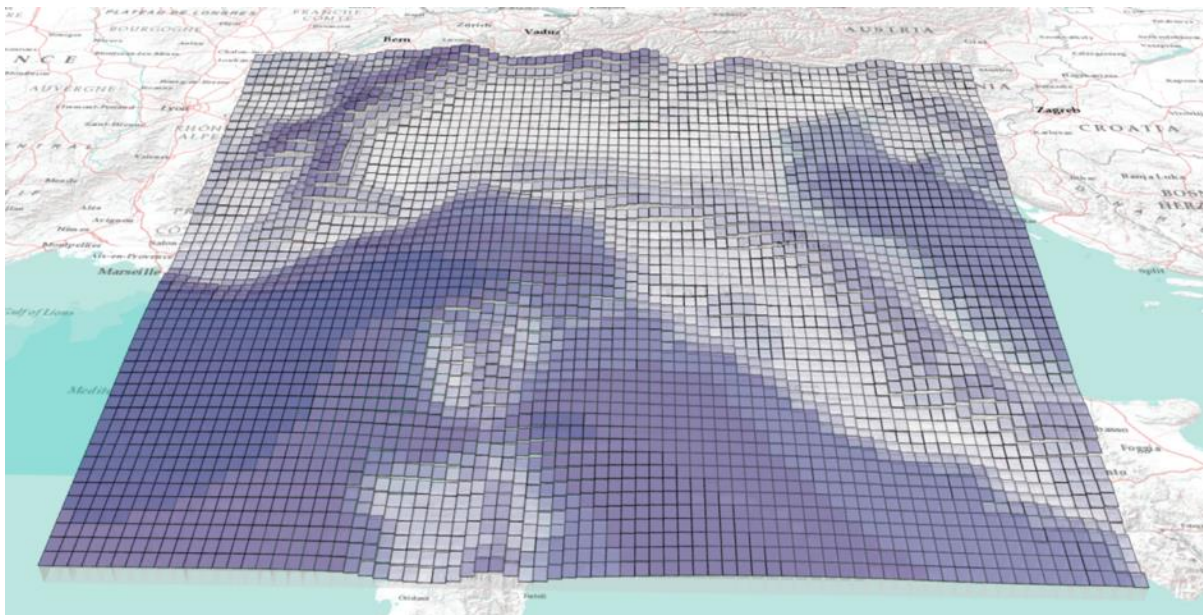


Figure 28: An aerial view of the prism geovisualisation.

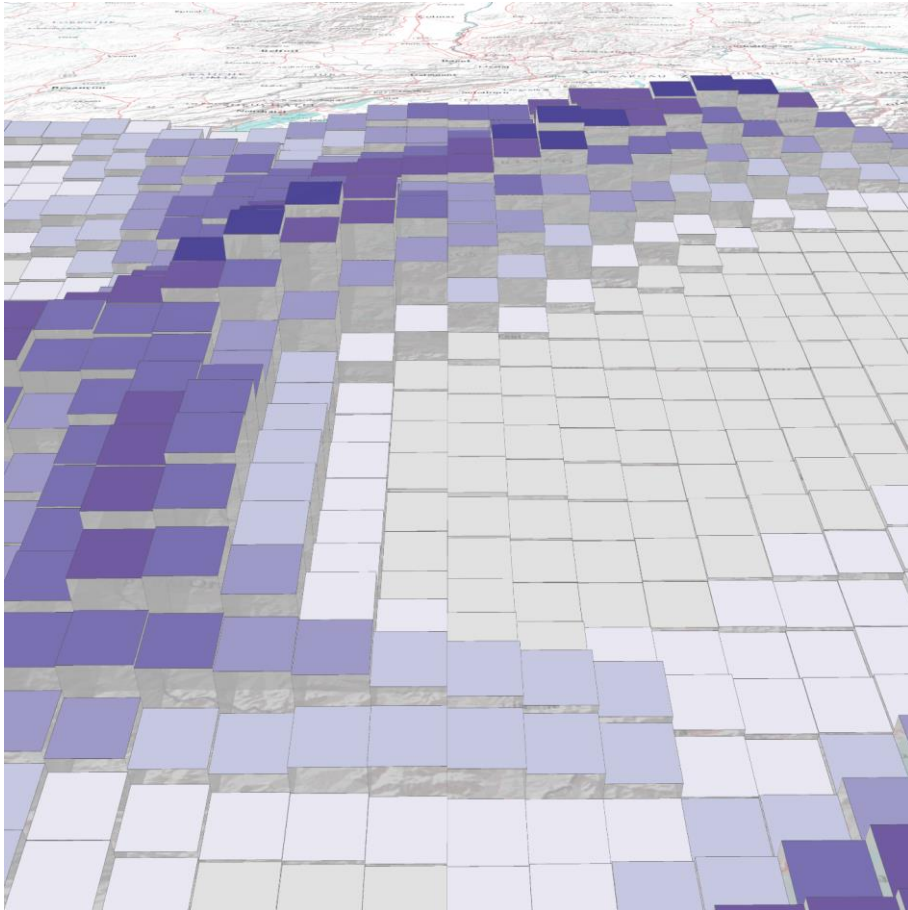
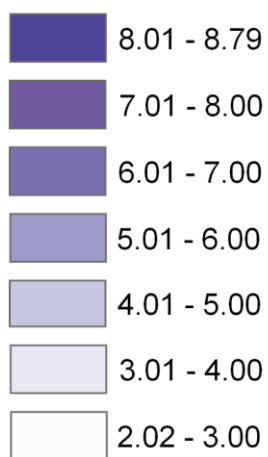


Figure 29: A zoomed in view of the prism map.

**Mean wind speed [m/s] 10 m
above ground
winter season (2040 - 2069)**



**Uncertainty
(modelling range)
expressed as height**

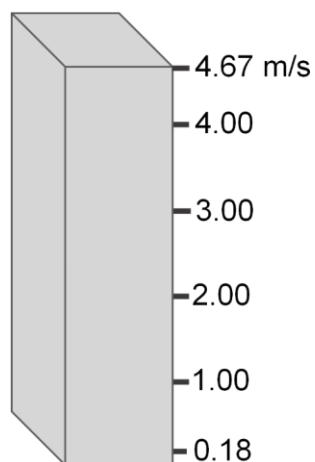


Figure 30: The legend for the prism map.

3.5.2. Pin map

3.5.2.1. Overview

The pin map also made use of the third dimension to represent uncertainty. Unlike the prism map, however, the uncertainty is indirectly conveyed in the third dimension. The pin map is composed of pins on which the mean wind speed for each model run and the overall average mean wind speed (of all five models) is indicated. The range of the mean wind speed can be seen visually on the pin which gives an indication of the uncertainty.

3.5.2.2. Characteristics

The three main categories of approaches to uncertainty visualisations (as described by Kinkeldey et al. 2014) and the different techniques used for each category are presented in Table 8. The techniques are based on the literature review presented in Table 2. The characteristics of the pin map are highlighted in red. Based on the study by Slocum et al. (2003) where representing model range in the 3rd dimension is classified as an extrinsic technique, and based on the fact that none of the visual variables were directly manipulated to represent uncertainty (see section 2.3.3, sub point 2), it was decided to classify the pin technique as an extrinsic technique.

Intrinsic	Extrinsic	Coincident	Adjacent	Static	Dynamic (animation, interactivity)
Colour hue	Glyph	Integrated view	Side – by - side	Classic map	Animation
Colour value	error bars, error bands		Linked views		Toggling
Texture (grain)	grid based (noise annotation lines, variable grid method (trustree))				Blinking, flickering
Size	Squares				User input (specifying uncertainty range, scaling by a factor)
Colour saturation	Text				Navigation (panning and zooming)
Colour whitening					

Clarity (crispness, resolution, transparency)					
Blur (fuzziness)					
Noise (speckles)					
Sketchiness					
Dash					
Aliasing					
Geometry displacement					

Table 8: The characteristics of the pin map.

Unlike the prism map, the uncertainty is represented implicitly in the pin map. This means that the uncertainty is expressed by showing alternatives as opposed to showing a measure of uncertainty. The centroid of each fishnet grid cell was calculated and converted to a point feature class. This point feature class was then duplicated seven times as it was used to create all the components on the pin map. The pin was created by extruding the point feature class to a height of 10500 meters. This height was selected to accommodate the maximum mean wind speed of all model runs. Figure 31 shows a small section of the pin map. Figure 32 shows the legend for the pin map.

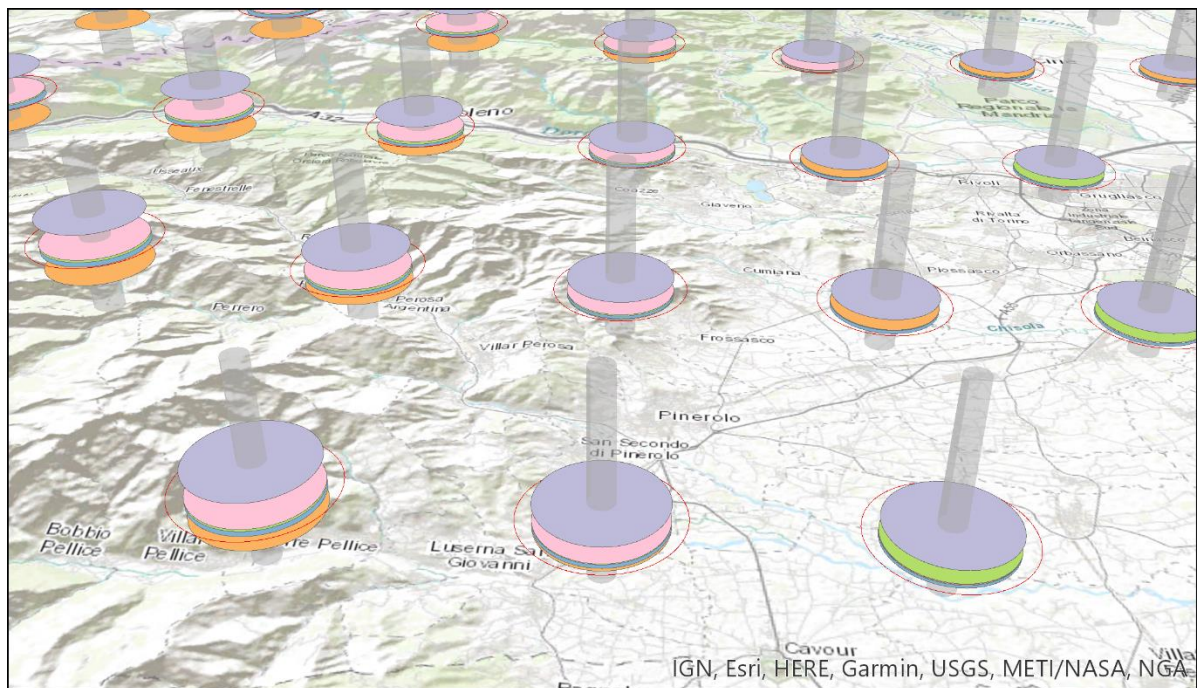


Figure 31: A small section of the pin map.

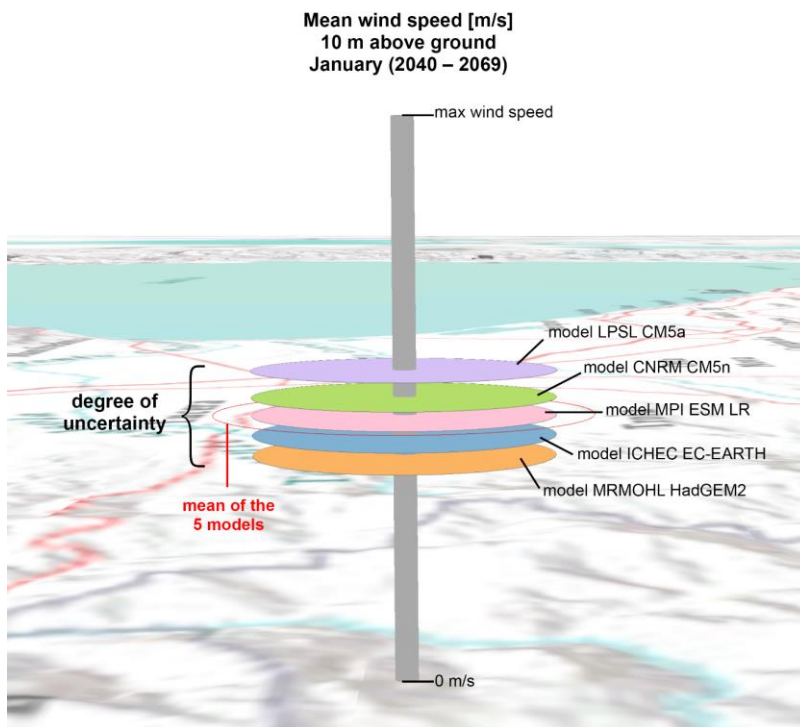


Figure 32: The legend for the pin map.

3.5.3. Texture map

3.5.3.1. Overview

The texture map makes use of the intrinsic 2D technique called texture a traditional cartographic technique to represent uncertainty. The map consists of a 3D basemap with wind data (wind speed and uncertainty) draped over it.

3.5.3.2. Characteristics

The same fishnet grid created for the prism map is used for the texture map. In addition, the same purple colour ramp used to represent wind speed in the prism map is also used in the texture map. The texture makes use of a line pattern where thicker lighter lines represent high uncertainty. The line pattern is superimposed over the wind speed layer so that each grid represents wind speed (colour) and uncertainty (line pattern). The wind speed and the uncertainty information are draped over a 3D terrain surface (Figure 33 and Figure 34). The legend for the texture map can be seen in Figure 35.

The three main categories of approaches to uncertainty visualisations (as described by Kinkeldey et al. 2014) and the different techniques used for each category are presented in

Table 9. The techniques are based on the literature review presented in Table 2. The characteristics of the texture map are highlighted in red.

Intrinsic	Extrinsic	Coincident	Adjacent	Static	Dynamic (animation, interactivity)
Colour hue	Glyph	Integrated view	Side – by - side	Classic map	Animation
Colour value	error bars, error bands		Linked views		Toggling
Texture (grain)	grid based (noise annotation lines, variable grid method (trustree))				Blinking, flickering
Size	Squares				User input (specifying uncertainty range, scaling by a factor)
Colour saturation	Text				Navigation (panning and zooming)
Colour whitening					
Clarity (crispness, resolution, transparency)					
Blur (fuzziness)					
Noise (speckles)					
Sketchiness					
Dash					
Aliasing					
Geometry displacement					

Table 9: The characteristics of the texture map.

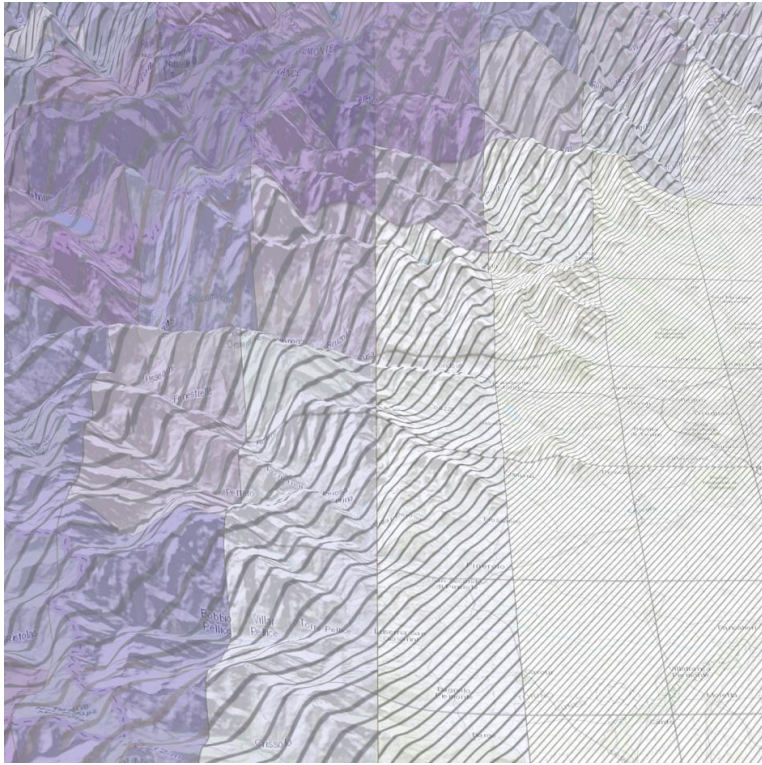


Figure 33: A zoomed in portion of the texture map.

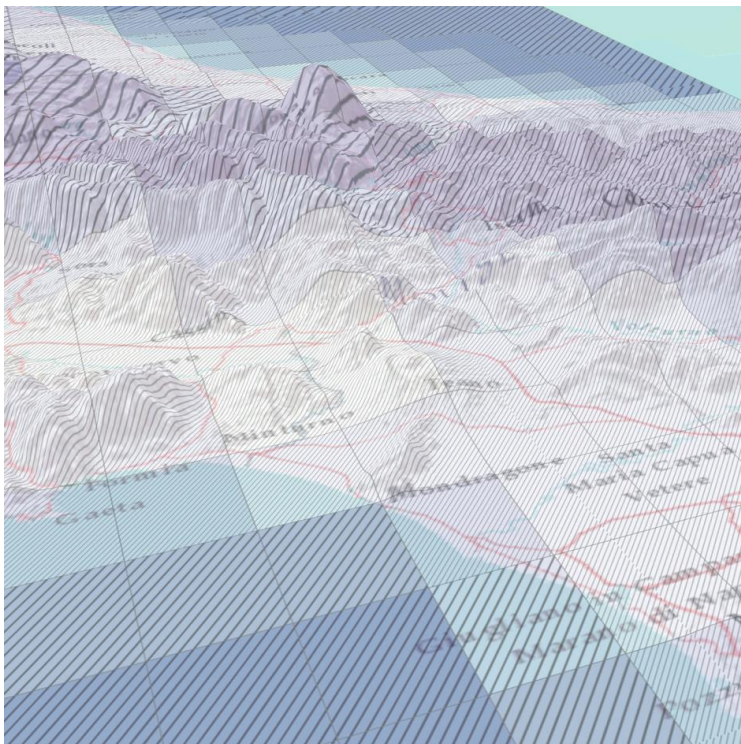


Figure 34: The texture map from a different angle. The 3D basemap is obvious in this screenshot.

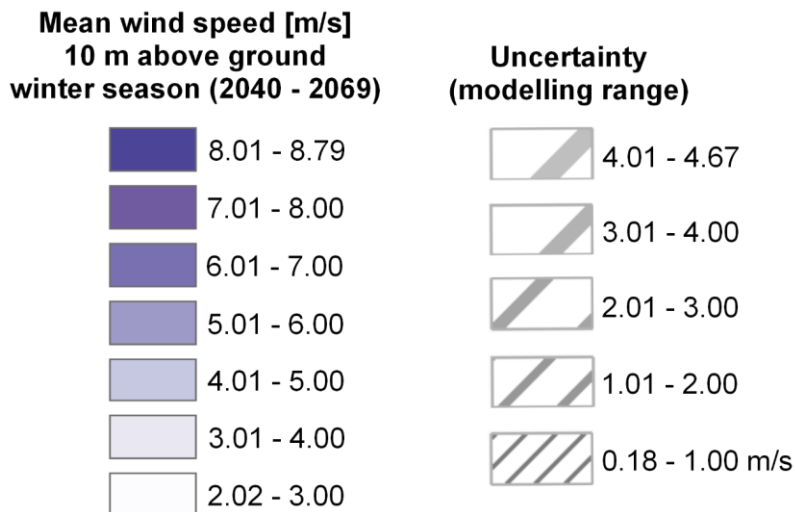


Figure 35: The legend for the texture map.

3.5.4. Trivariate map

3.5.4.1. Overview

The trivariate map is a variation of the prism map. The map uses the same technique to represent uncertainty as well as the same symbology for the wind speed as the prism map. The trivariate map, however, contains an additional suitability variable.

3.5.4.2. Characteristics

The trivariate map depicts three variables: the wind speed (colour), the uncertainty of the wind speed (height of the prism) and the percentage of the cell that is highly suitable for renewable energy projects (a proportional black square). The highly-suitable area data was produced from a model that takes numerous factors (i.e. environmental, social, technical and economical) into consideration to calculate the percentage of each cell that is highly suitable for wind farming. Figure 36 shows a zoomed in portion of the trivariate map. Prisms which do not contain a thick black square on top are not highly suitable for wind farming. Figure 37 is the legend for the trivariate map.

The characteristics of the trivariate map as compared to other uncertainty maps are the same as the prism map (see Table 6).

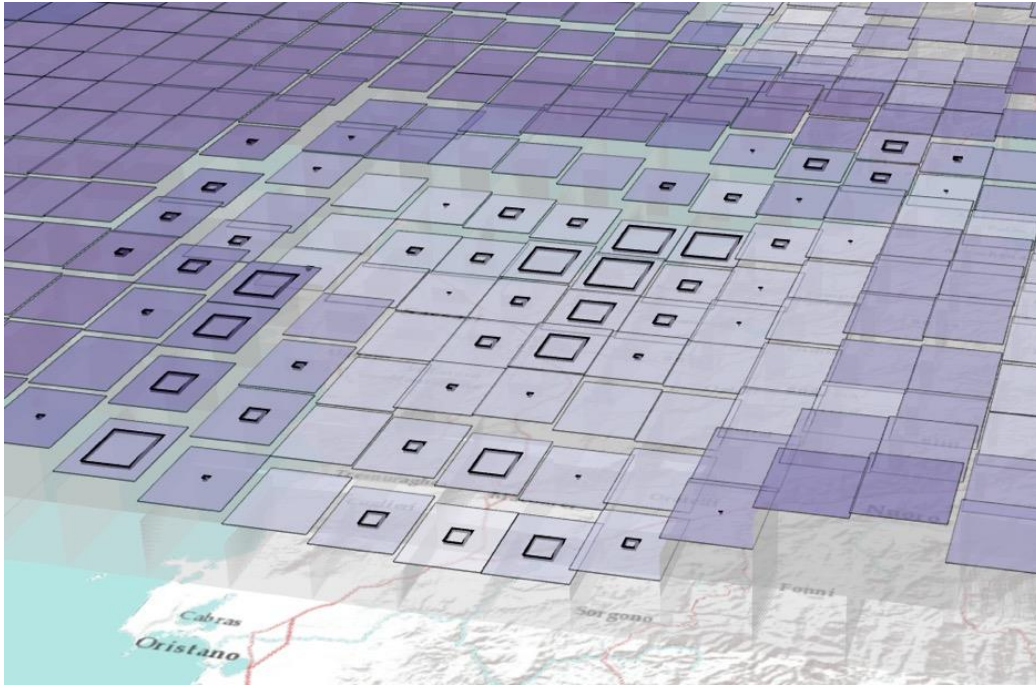


Figure 36: A zoomed in portion of the trivariate map. The thick black squares are a proportional indication of the suitability of that grid cell for wind farming.

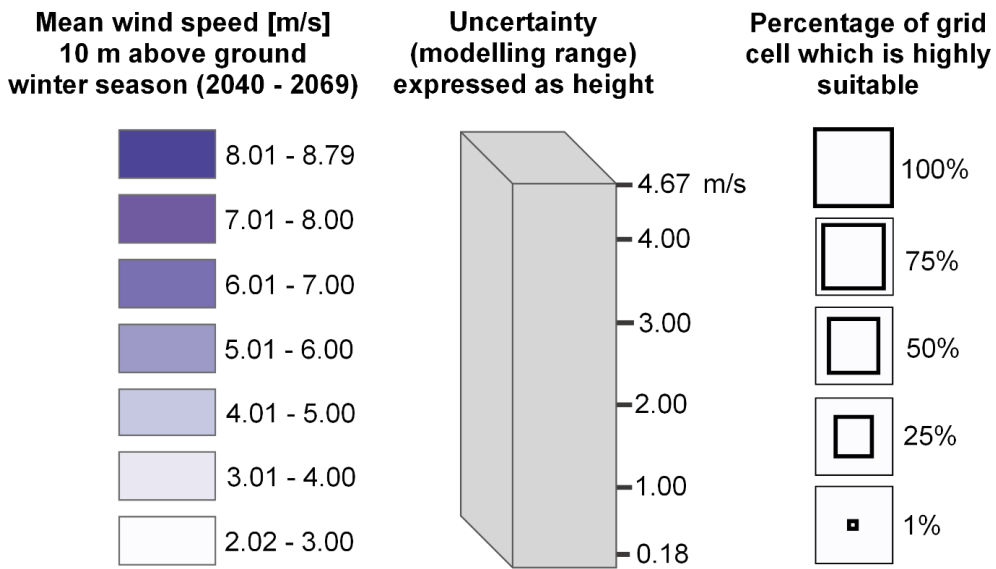


Figure 37: The legend for the trivariate map.

Chapter 4: Study design

4.1 Introduction

To achieve objective 3 as defined in chapter 1, face-to-face semi-structured expert interviews were conducted. Expert interviews were selected as the primary method for data collection as it is advantageous to have participants that represent the targeted levels of expertise for the 3D maps (Roth 2013). The experts interviewed represent the users that the 3D maps will eventually support. This chapter describes the design of the study with a focus on the design of the interview questions. The main aim of the expert interviews was to explore experts' perceptions regarding the usability and suitability of different techniques for visualising uncertainty in 3D maps for regional planning of wind farms. The 3D maps produced in chapter 3 were used as materials in the interview. The interview was semi-structured so as to allow the interviewer to follow topical digressions.

Two sets of interviews were conducted. The first set consisted of five interviews conducted with experts in the field of renewable energy in Germany. The second set of interviews was designed to address some of the issues detected in the first set of interviews and was conducted with four experts in the field of renewable energy in South Africa.

4.2 First set of interviews in Germany

4.2.1 Overview

The first set of interviews consisted of five semi-structured expert interviews that took place in Germany in June 2016. The participants of the interviews were German experts in the field of renewable energy. The aim of the interviews was to understand the usability and suitability of different visualisation techniques to express uncertainty in 3D maps. The interview questions centred around the 3D maps described in chapter 3.

4.2.2 Materials

The maps that were produced in chapter 3 were used as the materials for the expert interviews. The prism, pin, and trivariate maps were presented as interactive 3D maps on a computer while the texture map was presented as a static hardcopy perspective view presented on a colour A4 page. The digital 3D models were presented on a 15-inch screen with a resolution of 1920 x 1080 pixels. The combination of presentation formats was used to

save time. The full description of these maps can be found in chapter 3 but thumbnails of each map are presented below for convenience.

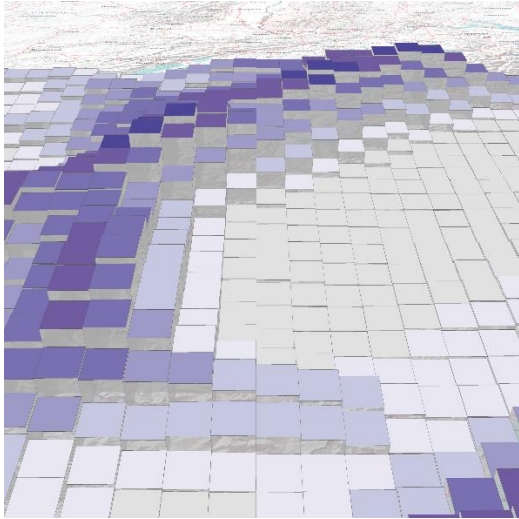


Figure 38: The prism map.



Figure 39: The texture map.

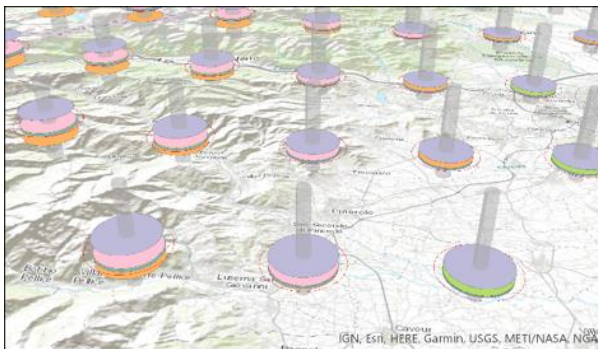


Figure 40: The pin map.

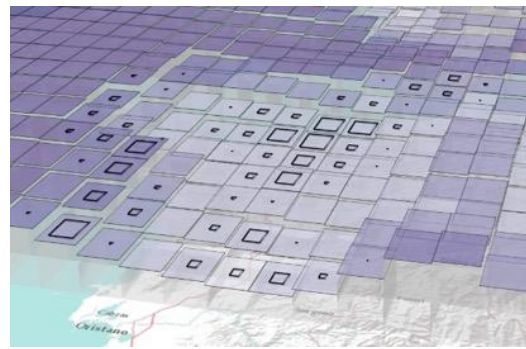


Figure 41: The trivariate map.

4.2.3 Procedure

The interviewer provided each interviewee with a brief overview of the navigational capabilities (e.g., panning and zooming) of the digital interactive 3D models. The interviewees were allowed to interact with the maps but were provided with the option of having the interviewer take over the navigation if they did not feel comfortable navigating themselves. All interviewees operated the 3D models themselves, and were successful with navigating around the map.

The interviews were conducted in English and consisted of 14 questions that took an average of 60 minutes to complete. In addition to the 14 questions, 8 background questions were asked. The interviews were designed to stimulate conversation about the perceived usability

and suitability of 3D uncertainty maps. The questions were a mix of tasks and opinion questions. In addition to the interviewer taking notes, each interview was also voice recorded.

4.2.4 Semi-structured interview questions

Semi-structured interviews were used as they allow the interviewer to follow topical digressions when appropriate. Relevant information can be extracted from digressions that might have been missed if structured questions or questionnaires had been used. Researchers such as Hill et al. (1997) believe that people respond more completely to interviews than to questionnaires.

The interview questions are presented in Table 10. These questions were designed to elicit the answers needed to meet objective 3 of this dissertation. Where applicable, the map(s) used for each question is listed in the Maps column in Table 10.

Questions	Maps
<p>1. Background questions</p> <p>1.1 Please specify your:</p> <p> 1.1.1 Age</p> <p> 1.1.2 Gender</p> <p> 1.1.3 Job title</p> <p> 1.1.4 Qualifications</p> <p>1.2 In which domain/application field do you work?</p> <p>1.3 How is your work related to the topic of renewable energies?</p> <p>1.4 Do you work with 3D maps? Please explain.</p> <p>1.5 Do you consider uncertainty in your work? Please explain</p>	None
<p>2. Testing intuitiveness of using the third dimension to represent uncertainty</p> <p>2.1 Describe what the visualisation is showing. Specifically, identify how wind speed and uncertainty are being represented respectively</p> <p>2.2 Can you describe what the uncertainty is related to?</p> <p>2.3 Imagine that you are responsible for identifying potential areas for locations of wind farms. In the initial stages of the project the goal is to identify large areas that could potentially be suitable for wind farms. Taking into account the wind speed and related uncertainty, which area do you think could be most suitable for wind farms to be located?</p>	Prism map without legend
<p>3. Investigating how well the visualisations convey uncertainty information</p> <p>3.1 Identify the areas that have the highest and lowest uncertainty respectively.</p> <p>3.2 Again, imagine that you are responsible for identifying potential areas for locations of wind farms. Which area do you now think could be most suitable for a wind farm to be located?</p>	Prism map with legend

<p>4. User preference with regard to using third dimension for uncertainty representation</p> <p>4.1 Using the prism and pin map, identify a mountainous area where both mean wind speed and related uncertainty are higher than in the immediate surrounding area. What does the uncertainty information reveal?</p> <p>4.2 Compare the maps in terms of advantages, ease of interpretation, and usefulness of tasks</p>	<p>Prism map and pin map with legends</p>
<p>5. Effectiveness and preference of using the third dimension to represent uncertainty in comparison to other method</p> <p>5.1 Using the prism map identify an onshore area which has relatively high uncertainty and discuss how you came to your conclusion.</p> <p>5.2 Use the texture map to identify an offshore area that has a relatively low uncertainty and discuss how you came to your conclusion.</p> <p>5.3 Choice of either map to identify an area where the wind speed is between 3 and 5 m/s and where the uncertainty is low</p> <p>5.4 Compare the maps in terms of advantages, ease of interpretation, and usefulness of tasks</p>	<p>Prism map and texture map with legends</p>
<p>6. Success of conveying uncertainty in complex (i.e. trivariate) visualisations</p> <p>6.1 Imagine that you are responsible for identifying potential areas for locations of wind farms. The goal is to identify large areas that could potentially be suitable for wind farms. Taking into account mean wind speed, uncertainty, and suitability area data, identify an area that would be most suitable for wind energy production.</p> <p>6.2 What would the advantages be of using such more complex (multivariate) maps over using a bivariate (variable plus associated uncertainty) map?</p>	<p>Trivariate map with legend</p>
<p>7. User opinions on usefulness of 3D maps in regional planning of wind farms</p> <p>7.1 Based on the maps you've seen today in this interview which kind of planning scenarios could you imagine where such visualisations could be helpful?</p> <p>7.2 In your opinion, what additional or other information (data variables) would add value to such maps?</p> <p>7.3 Do you think the maps you've seen today would be useful in your work?</p>	<p>None</p>

Table 10: The interview questions for the first set of interviews.

4.2.5 Participants

In order to achieve the objectives defined in chapter 1, experts in the field of renewable energy were interviewed. It is important to interview experts who have experience with wind farm planning in order to gain relevant insight and understanding.

Five experts in the field of renewable energy participated in the interview. The experts were invited to participate based on recommendations from colleagues. Participation in the interview was voluntary. Table 11 provides an overview of the background of the interviewees.

Interviewee	1	2	3	4	5
Work domain	Wind energy and planning	Renewable energy infrastructure	Renewable energy	Wind energy	Air quality
Background	Mechanical engineering	Civil engineering	Economics	Environmental planning	Meteorology
Focus area of work	Project management	Lecturing on wind energy	Renewable energy management	Noise analysis surrounding wind farms	Climate models and air quality
Experience with 3D maps	No	No	Yes	No	No
Experience with working with uncertainty	Yes	Yes	Yes	Yes	No
Level of English competency	Good	Good	Good	Fair	Fair

Table 11: Overview of the background of the interviewees who participated in the first set of interviewees.

4.2.6 Domains of uncertainty research covered

Based on Mason et al's. (2016) visual summary of domains of uncertainty visualisation research (section 2.3.2), the following visual summary (Figure 42) is applicable for the first set of interviews. Table 10 outlines the reasons for this.

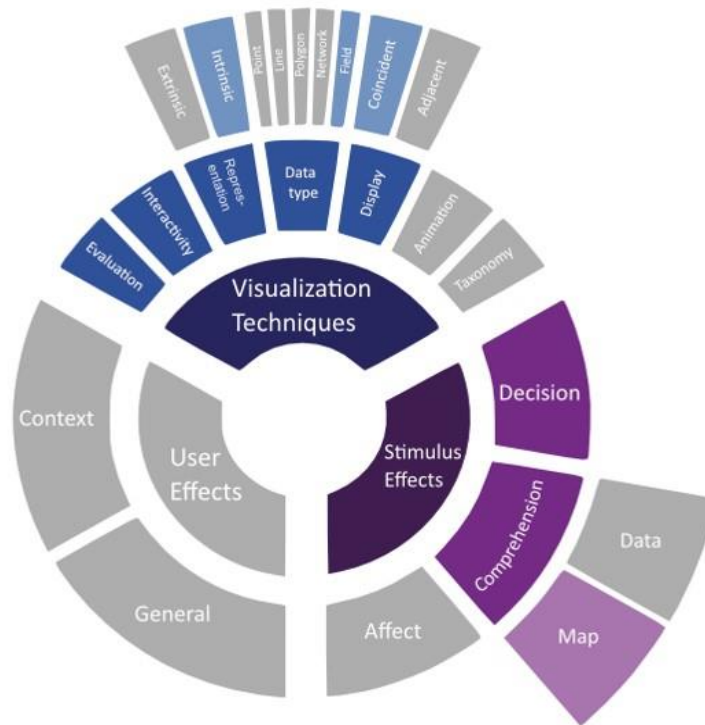


Figure 42: A visual summary of the domains of uncertainty visualisation research covered by the expert interviews in the first set of interviews. Adopted from Mason et al. (2016).

Main Category	First sub-category	Second sub-category	Reason
Visualisation Techniques	Evaluation		The interviewees evaluate the technique used to visualise uncertainty
	Interactivity		Users can pan, zoom, and rotate the maps
	Representation	Intrinsic	The visual variables (size and texture) are directly manipulated to signify uncertainty
	Data type	Field	The uncertainty is associated with an attribute value (wind speed)
	Display	Coincident	Data and uncertainty are shown in the same map
Stimulus Effects	Comprehension	Map	The interview questions are based on whether experts can interpret the uncertainty values

			based on map symbology
	Decision		Interviewees are asked to make decisions based on the maps (e.g. identifying suitable areas)

Table 12: The visual summary (Figure 42) explained.

4.3 Second set of interviews in South Africa

4.3.1 Overview

Based on the experience gained from the first round of interviews, as well as, the comments received from peer-reviewers for the journal submission, it was decided to revise the interview questions. The issues that were addressed were removing quantitative questions from the interview, only presenting the 3D maps digitally and not allowing the interviewees to navigate around the 3D maps themselves. The semi-structured expert interview questions from the first interview were modified to remove any quantitative aspect and in some cases were rephrased for better comprehension. Additional questions were added to better understand the workflows followed by experts to improve conclusions and understanding about expert preference regarding the suitability of visualising uncertainty in 3D maps for regional level wind farm planning.

The aim of the second round of interviews remained the same, which was to explore expert perceptions regarding the usability and suitability of different techniques to visualise uncertainty in 3D maps for regional planning of wind farms. Four South African experts in the field of renewable energy participated in the second set of interviews.

4.3.2 Materials

The same 3D maps that were used in the first set of interviews were used in the second set. All maps were presented in a digital format in ArcGIS Pro 2.0, as opposed to a combination of digital and hardcopy as in the first interview. The prism map, which was presented in a web browser for the first interview, was recreated and presented in ArcGIS Pro. All maps were therefore presented in the 3D scene view in ArcGIS Pro that allowed for the panning, zooming and rotating of the maps. The maps were presented on a 17 - inch screen with a resolution of 1920 x 1080 pixels. Hardcopy legends were made available to the interviewees and they could refer to the legends at any time. During the interview, the interviewer navigated around the

3D maps in order to ensure the discussion did not focus on the usability of the software but rather on the maps themselves as suggested by Kinkeldey & Schiewe (2014).

4.3.3 Semi-structured expert interview questions

As in the first set of interviews, semi-structured interviews were used in the second set. The interviews were conducted in English in South Africa and consisted of 14 questions that took an average of 60 minutes to complete. In addition to the 14 questions, 6 background questions were asked. The interviews were designed to stimulate conversation about the perceived usability and suitability of techniques for visualising uncertainty in 3D uncertainty maps for regional level planning of wind farms. The questions were all opinion questions and there were no task questions. The interviewees were shown all four maps and legends where appropriate and they could refer to them at any time. None of the questions required the interviewees to directly compare two maps as in the first interview. Some of the questions required the interviewees to consider the following scenario:

Imagine that you are responsible for identifying potential areas for locations of wind farms. In the initial stages of the project the goal is to identify large geographic areas where the uncertainty regarding wind speed is relatively low. In the later stages of the above scenario, one must compare wind speed uncertainty for a specified number of locations.

The interview questions are presented in Table 13. Each section of questions corresponds to a specific aim (in bold in Table 13).

Questions
<p>1. Background questions</p> <p>1.1. Please specify your:</p> <p>1.1.1. Age</p> <p>1.1.2. Gender</p> <p>1.1.3. Job title</p> <p>1.1.4. Qualifications</p> <p>1.2. In which domain or application do you work?</p> <p>1.3. Please specify how your work is related to the topic of renewable energy</p>
<p>2. Understanding workflows followed</p> <p>2.1. Describe a typical project that you would do that involves taking into consideration the wind speed for wind farm planning.</p> <p>2.2. Describe the process or workflow followed in the initial stages of a wind farm planning project.</p>
<p>3. Understanding current use of 3D models and uncertainty in the South African wind energy sector</p> <p>3.1. Do you currently use 3D models/3D maps in the workflow?</p>

3.2. Do you currently consider uncertainty in the workflow? If yes, how do you represent the uncertainty?
4. Exploring preference of technique 4.1. Which visualisation would provide the best overview of the study area (in terms of information) in the initial stages of a project? Why? (<i>refer to scenario in section 4.3.3</i>) 4.2. Given the above scenario, which 3D map do you think would be most advantageous for this task ⁶ ? 4.3. Out of the 4 techniques, which do you prefer for uncertainty visualisation? Why?
5. Benefits of representing uncertainty in 3D maps 5.1. Based on your experience, which of these maps would be beneficial in your workflow? Explain how you would use it. 5.2. Would you say that, for this specific task, it is beneficial to represent uncertainty in the 3D map or would you prefer it to be presented with an overall statistical value of the uncertainty?
6. Drawbacks of 3D uncertainty maps 6.1. What drawbacks did you experience with the 3D maps? Why?
7. Expert opinion on representing uncertainty in 3D maps 7.1. Based on your experience with wind planning projects and the four visualizations that I showed to you, what is your opinion about representing uncertainty in 3D maps? 7.2. Would you recommend 3D geovisualisations of uncertainty? Why or why not?
8. Usefulness of 3D uncertainty maps 8.1. Can you suggest other planning scenarios where such 3D maps would be useful? 8.2. Can you suggest other variables that would be useful for inclusion in 3D maps that visualise uncertainty?

Table 13: The interview questions for the second set of interviews.

4.3.4 Participants

Four experts participated in the interview of which three were male and one was female. One expert was recruited at a conference on wind energy held in South Africa. This expert then recommended three other experts for invitation to participate. Participation in the interviews was voluntary. Table 14 provides an overview of the background of the interviewees.

Interviewee	Interviewee 1	Interviewee 2	Interviewee 3	Interviewee 4
Work domain	Renewable energy (power generation)	Renewable energy	Renewable energy	Wind energy production
Background	Chemical Engineering and Engineering Management	Mechanical Engineering	Metallurgical Engineering	Process automation
Focus area of work	Project management	Project management (engineering)	Project management	Engineering management

⁶ The interviewee only considered to consider a task in the scenario and were not asked to actually complete it

Use of 3D models in current workflows	Yes	No	Yes	Yes
Consideration of uncertainty in current workflow	Yes	Yes	Yes	Yes

Table 14: Overview of the background of the interviewees.

4.3.5 Domains of uncertainty research covered

Based on Mason et al's. (2016) visual summary of domains of uncertainty visualisation research (section 2.3.2), the following visual summary (Figure 43) is applicable for the second set of interviews. The visual summary is slightly different to the one for the first set of interviews as the questions had different aims. Table 15 outlines the reasons for the visual summary.

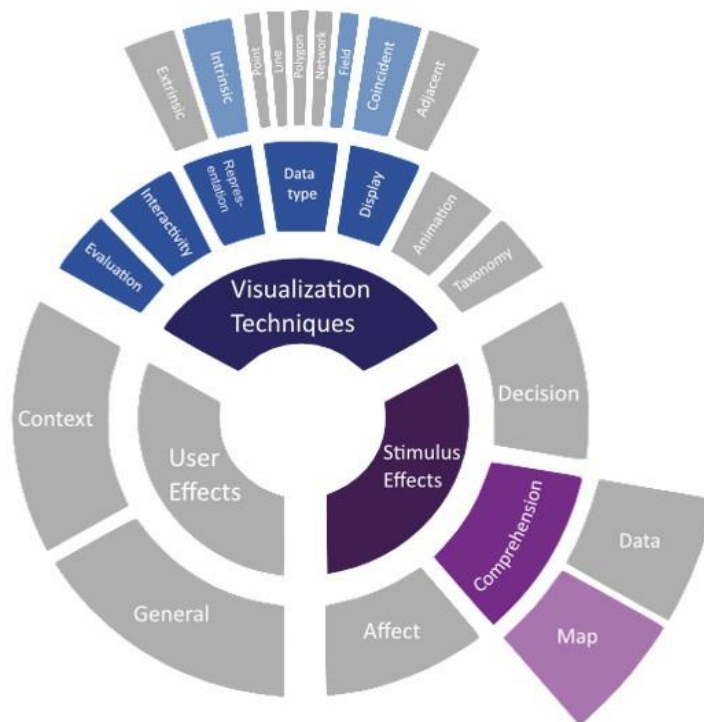


Figure 43: A visual summary of the domains of uncertainty visualisation research covered by the expert interviews in the second set of interviews. Adopted from Mason et al. (2016).

Main Category	First sub-category	Second sub-category	Reason
Visualisation Techniques	Evaluation		The interviewees evaluate the technique used to visualise uncertainty
	Interactivity		Users can pan, zoom, and rotate the maps
	Representation	Intrinsic	The visual variables (size and texture) are directly manipulated to signify uncertainty
	Data type	Field	The uncertainty is associated with an attribute value (wind speed)
	Display	Coincident	Data and uncertainty are shown in the same map
Stimulus Effects	Comprehension	Map	The interview questions are based on whether experts can interpret the uncertainty values based on map symbology

Table 15: The visual summary (Figure 43) explained.

Chapter 5: German expert opinions on using the third dimension to visualise wind speed uncertainty in wind farm planning

This chapter was published under the same title in the *International Journal of Cartography* in 2017 as a peer reviewed published paper. The paper has been reformatted to match the format of the rest of the dissertation. The figures in this chapter are same as the figures presented in chapter 3 but are presented here again for convenience.

Published article reference:

Bevis, Y., Schaab, G., Rautenbach, V., and Coetzee, S., 2017: Expert opinions on using the third dimension to visualise wind speed uncertainty in wind farm planning, *International Journal of Cartography*, 3(1), 61-75, DOI: 10.1080/23729333.2017.1301349

5.1 Abstract

To date, most studies on uncertainty visualisations have focused on 2D representations. The closing of the software gap between 3D graphics and geovisualisation presents new opportunities for the visualisation of uncertainty. The goal of our research is to understand the usability and suitability of different visualization techniques for representing uncertainty in the third dimension. In this paper, we present the perceptions of experts in the fields of renewable energy and climate modelling regarding 3D uncertainty maps. Four different maps, each representing uncertainty of mean wind speed in a different way, were prepared for expert interviews. Interviewees were asked questions about different usability and suitability aspects of the maps for regional planning of wind farms. Their responses provide valuable insights for the usability of the third dimension to represent uncertainty in maps, and the suitability in regional level planning of wind farms. These exploratory research results can be used to guide the design of controlled user studies to further investigate the usability of the third dimension for uncertainty representations, and the suitability for wind farm planning.

5.2 Introduction

All geospatial data incorporates uncertainty and ignoring it can lead to negative or unforeseen consequences for spatial analysis and decision making (Kinkeldey, Mason, et al. 2014; Newman & Lee 2004; Zhang & Goodchild 2002). Researchers have suggested that communicating uncertainty using visualisations can increase trust in the results, and can

support analysis(Deitrick & Edsall 2006; Fisher et al. 2012; Hope & Hunter 2007). Numerous studies have been conducted on visualising uncertainty in GIScience and other related fields (MacEachren et al. 2005). The majority of these studies focused on two-dimensional (2D) representations (Benke et al. 2011; Hope & Hunter 2007; Retchless & Brewer 2015) rather than three-dimensional (3D) visualisations.

There has been much debate on the usefulness and effectiveness of 3D representations (Hegarty et al. 2009; Herbert & Chen 2015; Rautenbach et al. 2016) with researchers stating that 3D representations assist with orientation and understanding of landforms (Chen et al. 2011; Smallman et al. 2007; van Lammeren et al. 2010). However, other researchers have postulated that 3D representations contribute to an increase of cognitive load and may detract from the visualization (Bleisch & Nebiker 2008; Métral et al. 2012; Richards & Taylor 2015).

Currently, fossil fuel is used to produce the majority of the world's electricity, and this dependence on fossil fuel is becoming increasingly problematic (Mohr et al. 2015; Shafiee & Topal 2009). A more environmentally friendly alternative is renewable energy (Panwar et al. 2011). Wind is a prominent form of renewable energy (Mytilinou et al. 2015). Much research has been done on the different aspects of using geographic data to support the utilization of wind for power production (e.g. Borah et al. (2013)). Commonly, wind power prediction should convey a forecast, as well as, the associated uncertainty. Uncertainty is usually communicated by means of a statistical measure, such as root mean square error related to average wind speed. Uncertainty is necessary as it allows the risk of trusting the prediction to be evaluated (Lange et al. 2001).

The ultimate goal of the research is to understand the usability and suitability of different visualization techniques to express uncertainty in 3D maps. In this paper, we present perceptions held by experts regarding usability and suitability of 3D uncertainty maps for regional planning of wind farms. Exploring perceptions is important because they influence how 3D uncertainty maps should be designed and they also contribute to the general understanding of 3D uncertainty maps. The paper is structured as follows: Section 2 details the study design, the results are presented and discussed in Section 3, and in Section 4 concluding remarks are presented.

5.3 Study design

5.3.1 Overview

The aim of the semi-structured expert interviews was to explore expert perceptions regarding the usability and suitability of 3D maps with representations of mean wind speed uncertainties for macro regional planning of wind farms. The focus was on ascertaining expert preference regarding the usability and suitability of different techniques to express uncertainty in 3D maps. The interview centred around four different 3D maps of predicted wind speed for the time period 2040 – 2070.

The interviews were conducted in Germany in June 2016 with five different experts in the field of renewable energy and climate modelling. The interviews were carried out in English and consisted of 14 questions that took an average of 60 minutes to complete. The interviews were designed to stimulate conversation about the perceived usability and suitability of 3D uncertainty maps.

The interview questions are presented in Table 16. In addition to the interviewer taking notes, each interview was also recorded.

Map(s)	Media	Aim of questions	Tasks / topics addressed by questions
Prism map without a legend (Fig. 2 & 3)	D*	Testing intuitiveness of using the third dimension to represent uncertainty	<ul style="list-style-type: none"> • Describe visualization and identify which variables represent wind speed and uncertainty respectively (task 1) • Describe what the uncertainty is related to (task 2) • Identify large area suitable for locating wind farm (task 3)
Prism map with a legend	D	Investigating how well the visualisations convey uncertainty information	<ul style="list-style-type: none"> • Identify highest and lowest uncertainty (task 4) • Identify area suitable for locating wind farm (task 5)
Prism map and pin map (Fig. 4 & 5)	D	User preference with regard to using third dimension for uncertainty representation	<ul style="list-style-type: none"> • Identify mountainous area where wind speed and uncertainty are relatively high (task 6) • Compare the visualisations in terms of advantages, ease of interpretation, and usefulness of tasks (task 7)

Prism map and texture map (Fig. 6 & 7) with a legend	H ⁺	Effectiveness and preference of using the third dimension to represent uncertainty in comparison to other method	<ul style="list-style-type: none"> • Using the prism map to identify an onshore area that has relatively high uncertainty (task 8) • Use the texture map to identify an offshore area that has a relatively low uncertainty (task 9) • Choice of either map to identify an area where the wind speed is between 3 and 5 m/s and where the uncertainty is low (task 10) • Compare the maps in terms of advantages, ease of interpretation, and usefulness of tasks (task 11)
Trivariate map (Fig. 8 & 9)	D	Success of conveying uncertainty in complex (i.e., trivariate) visualisations	<ul style="list-style-type: none"> • Identify large areas suitable for locating a wind farm taking into account wind speed, uncertainty, and suitable area data (task 12) • Specify the advantages of such complex map
None		User opinions on usefulness of 3D maps in regional planning of wind farms	<ul style="list-style-type: none"> • Suggestion of other planning scenarios where 3D uncertainty maps would be useful • Identification of other useful variables for inclusion in maps • Opinion on whether maps presented in interview would be useful in line of work

Table 16: Overview of the interview questions

* Digital

+ Hardcopy

5.3.2 Materials

Four 3D maps of predicted future mean wind speeds and associated uncertainty for a part of Southern Europe (Figure 43) were used for the interviews to investigate different techniques of representing uncertainty in 3D maps. Uncertainty associated with the mean wind speed was depicted in all 3D maps. The data used to create the maps was derived from five EURO-CORDEX climate scenario datasets that provided the simulated wind speed at 10m above the surface of the earth.

The maps were presented either as interactive 3D models on a computer or as a static hardcopy perspective views (A4 colour maps). The digital 3D models were presented on a 15-inch screen with a resolution of 1920 x 1080 pixels. The combination of presentation formats was used to save time.

The interviewer provided each interviewee with a brief overview of the navigational capabilities (e.g., panning and zooming) of the digital interactive 3D models. The interviewees were allowed to interact with the maps but were provided with the option of having the interviewer take over the navigation if they did not feel comfortable navigating themselves.

All interviewees operated the 3D models themselves, and were successful with navigating around the map.



Figure 44: The study area (delimited by the red rectangle) in Southern Europe.

The following maps were used in the interviews:

a) Prism map

The prism map (Figure 45 & Figure 46) makes use of the third dimension to represent the uncertainty of the wind speed. The colour represents the wind speed whereas the height of the prism indicates uncertainty. The taller prisms indicate areas of higher uncertainty. The initial zoom level of the prism map was 9500m above the surface of the earth. The prism map was required more often for tasks and therefore was presented in a browser as well as in hardcopy format (Table 16).

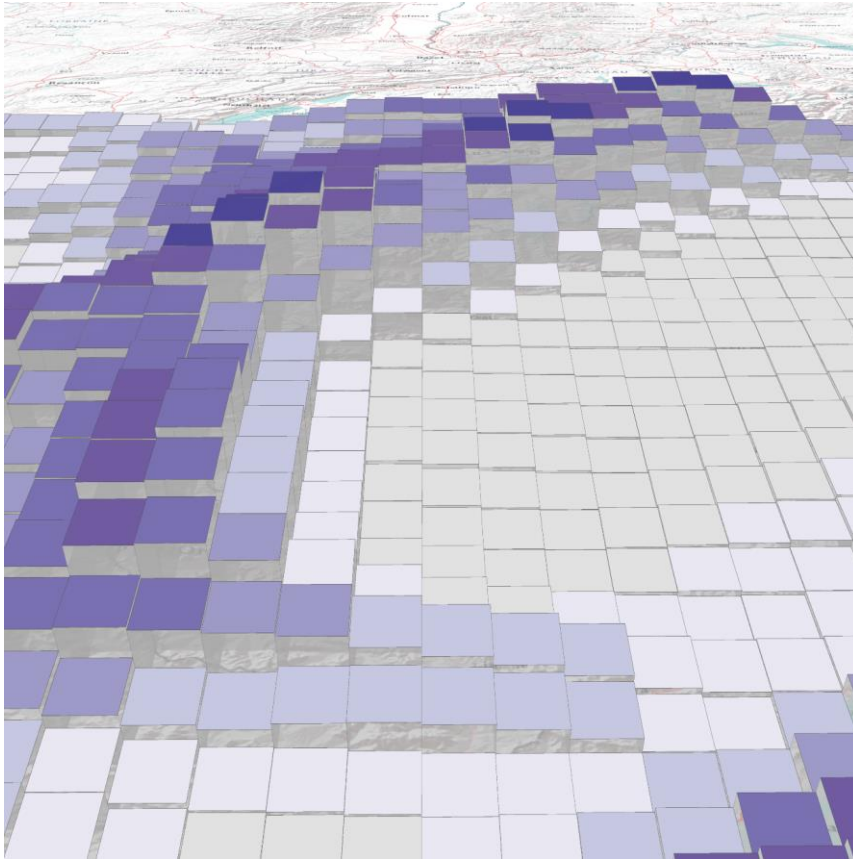


Figure 45: A part of the prism showing the uncertainty of the wind speed.

**Mean wind speed [m/s] 10 m
above ground
winter season (2040 - 2069)**

**Uncertainty
(modelling range)
expressed as height**

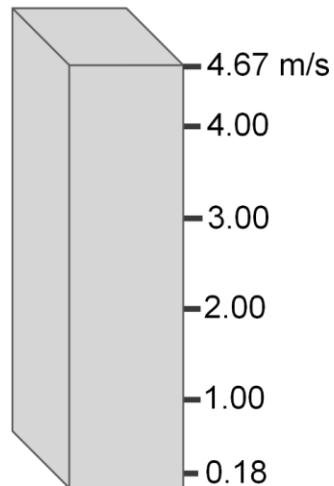
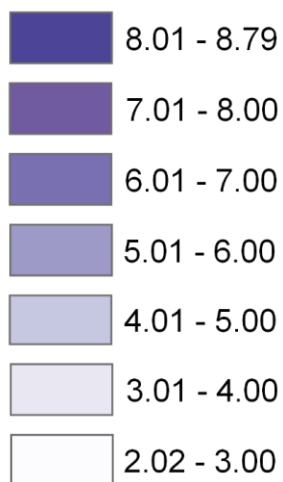


Figure 46: The prism map legend.

b) Pin map

The pin map (Figure 47 & Figure 48) makes use of the third dimension to indirectly represent uncertainty. The position of a disc on the pin represents the mean wind speed of a specific climate model. The hollow red ring indicates the average wind speed of all the model outputs. Therefore, the larger the range in disc positions on the pin, the larger the uncertainty. The initial zoom level of the pin map was 5000m above the surface of the earth. This is lower than the prism map due to rendering performance and because the details on the map were more readable. The pin map was presented in ArcGIS Pro as it provided the capabilities needed to produce such a visualisation.

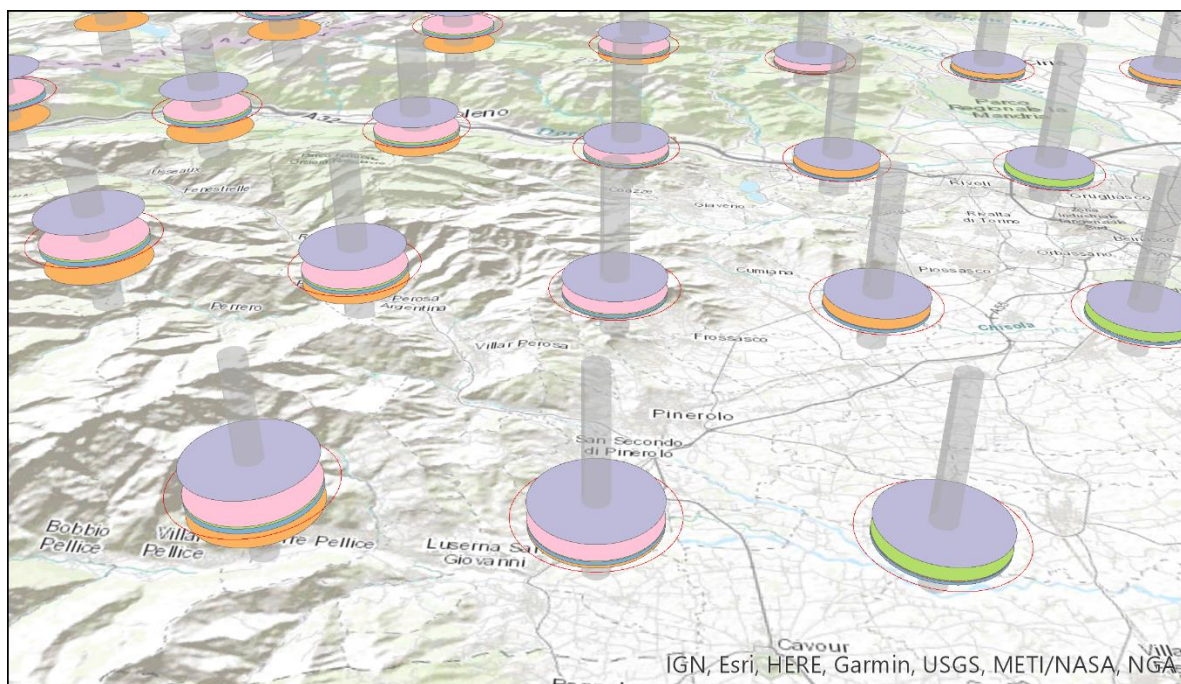


Figure 47: The pin map. The position of a disc on the pin represents the mean wind speed of a specific climate model. The hollow ring indicates the average wind speed of all the model outputs.

Mean wind speed [m/s] 10 m above ground: winter season (2024 - 2069)

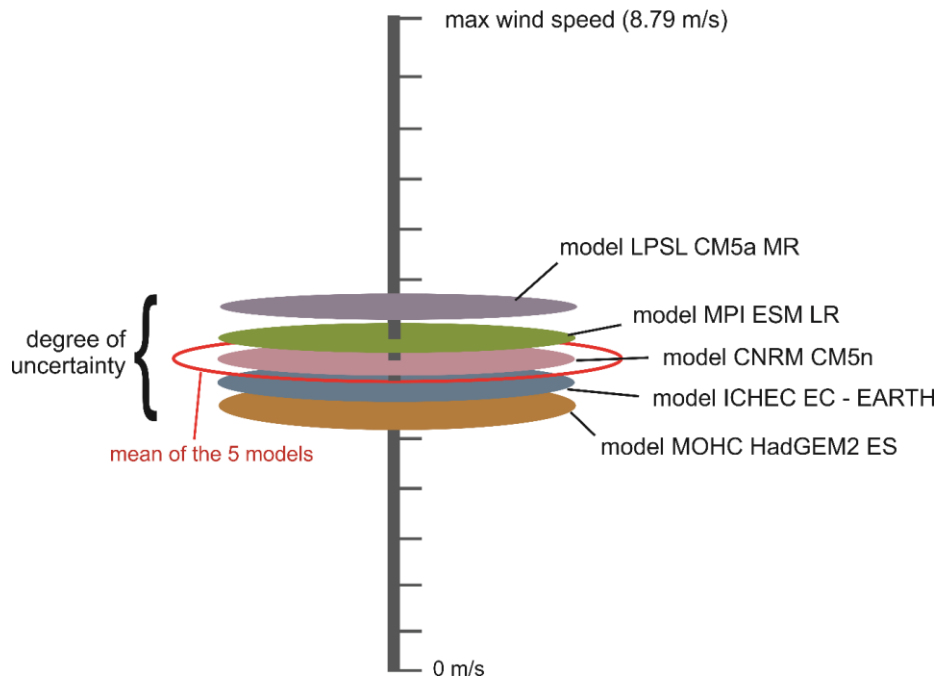


Figure 48: The pin map legend.

c) Texture map

The texture map (Figure 49 & Figure 50) makes use of patterns to represent uncertainty. In this case, the pattern of the diagonal lines indicates the degree of uncertainty. Thin lines that are close together indicate areas of low uncertainty.

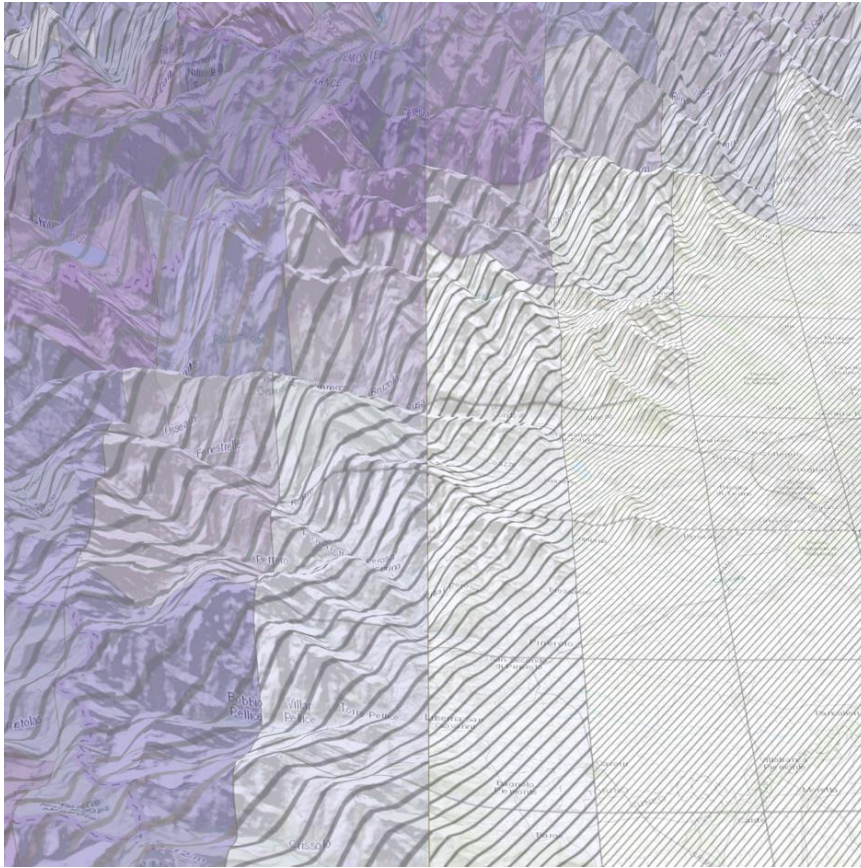
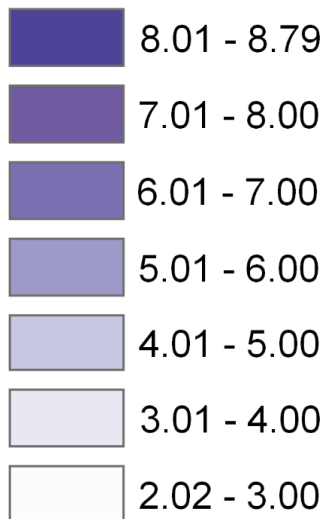


Figure 49: A zoomed in section of the texture map. The pattern of the diagonal lines indicates the degree of uncertainty. Thin lines that are close together indicate areas of low uncertainty.

**Mean wind speed [m/s]
10 m above ground
winter season (2040 - 2069)**



**Uncertainty
(modelling range)**

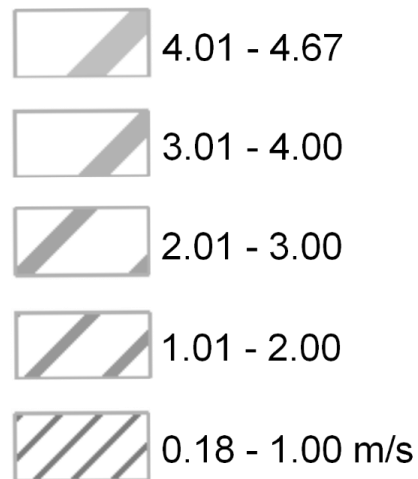


Figure 50: The texture map legend.

d) Trivariate map

The trivariate map is a modification of the prism map (Figure 51 & Figure 52). In this map, there are three variables being represented: the wind speed (colour), the uncertainty of the wind speed (height of the prism) and the percentage of the cell that is highly suitable for renewable energy projects (a proportional black square). The highly-suitable area data was produced from a model that takes different factors (environmental, social, technical and economical) into consideration to calculate the percentage of each cell that is highly suitable for wind farming. This map has a higher semantic complexity than the previous ones as it depicts more data variables.

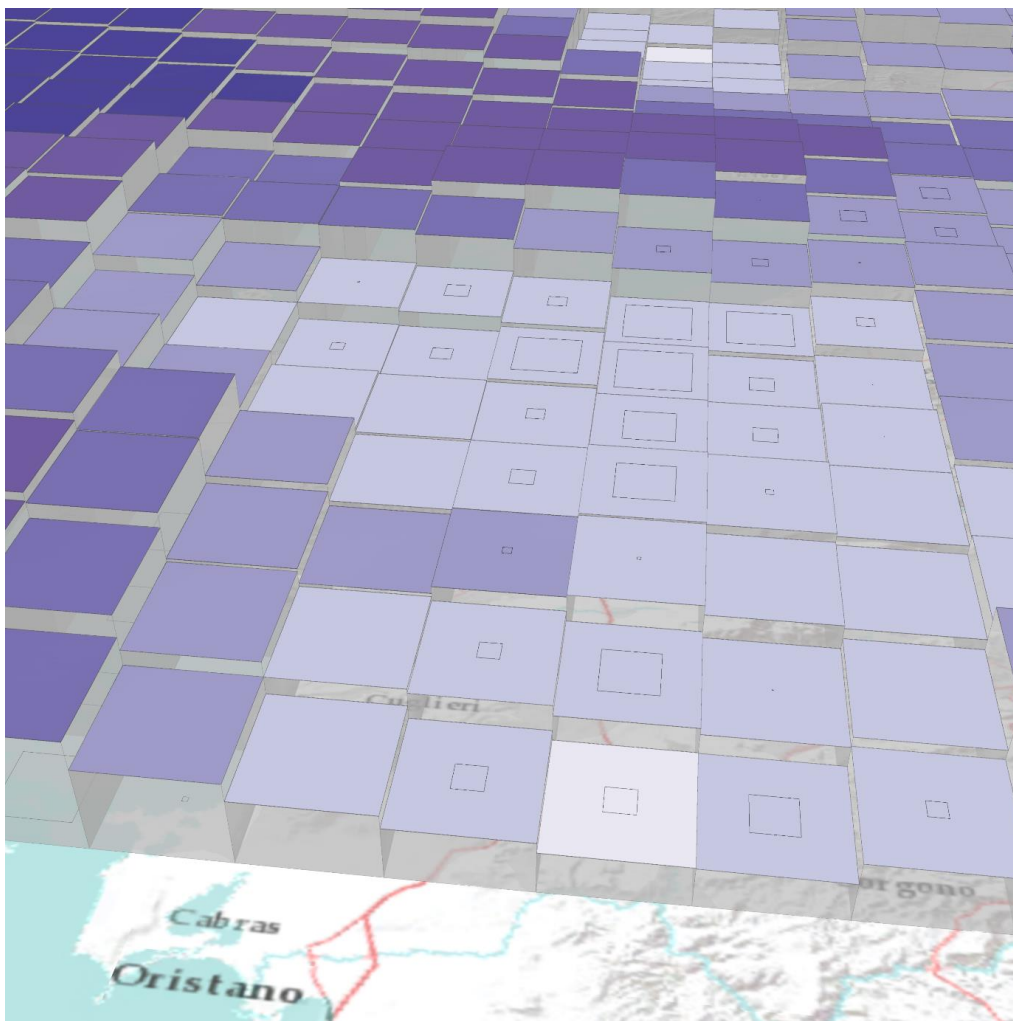


Figure 51: A zoomed in part of the trivariate map. Three variables are being represented: the wind speed (colour), the uncertainty of the wind speed (height of the prism) and the percentage of the cell that is highly suitable for renewable energy.

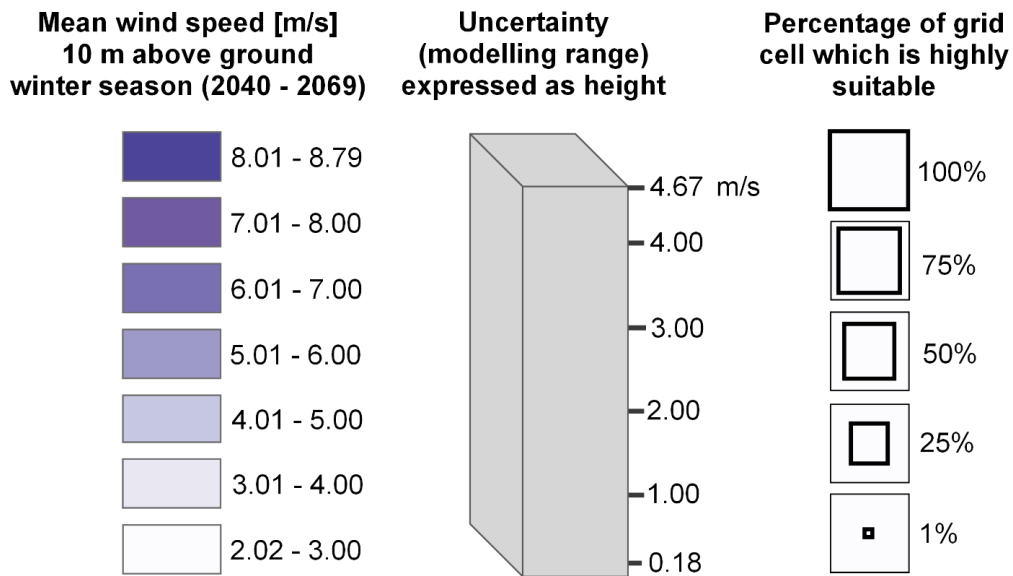


Figure 52: The trivariate map legend.

5.3.3 Interviewees

Five experts participated in the interview of which three were female and two were male. The pronoun “he” is used when describing an individual interviewee’s comments but this should be interpreted as being gender neutral. Table 17 provides an overview of the background of the interviewees. Four interviewees indicated that they did not have any experience with 3D maps and one did not have any experience in working with uncertainty on maps.

Interviewee	1	2	3	4	5
Work domain	Wind energy and planning	Renewable energy infrastructure	Renewable energy	Wind energy	Air quality
Background	Mechanical engineering	Civil engineering	Economics	Environmental planning	Meteorology
Focus area of work	Project management	Lecturing on wind energy	Renewable energy management	Noise analysis surrounding wind farms	Climate models and air quality
Experience with 3D maps	No	No	Yes	No	No
Experience with working with uncertainty	Yes	Yes	Yes	Yes	No

Level of English competency	Good	Good	Good	Fair	Fair
------------------------------------	------	------	------	------	------

Table 17: Summary of the background of each interviewee.

5.4 Results and discussion

The results from the expert interviews are discussed in relation to: the intuitiveness of using the third dimension to represent uncertainty; effectiveness and user preference of technique with regard to using the third dimension for representing uncertainty; success of conveying uncertainty in complex maps; and user opinions on the usefulness of 3D uncertainty maps in regional planning of wind farms (see aim of questions in Table 16).

Intuitiveness of using the third dimension to represent uncertainty. Two interviewees interpreted the height of the prism as the variable to represent uncertainty (task 1 in Table 14). Of these two, only one was confident in his answer while the other was quite hesitant. The interviewee who hesitantly answered, noted that the prism map was a new perspective that made him unsure of the proper interpretation. The same two interviewees also correctly associated the uncertainty with the mean wind speed. The results suggest that using the third dimension to represent uncertainty might not be intuitive if there is no legend available. Interviewees interpreted the uncertainty better when they had access to legends for tasks 4 and 5.

User preference with regard to using the third dimension for uncertainty representation. Four interviewees indicated that they preferred the prism map over the pin map with regards to uncertainty representation – it is simply easier to interpret. Interviewee 3 initially found the prisms to be misleading as the uncertainty represented as higher prisms could be confused with mountainous areas. However, after examining the legend, the purpose of the prisms became clear. Another interviewee preferred the pin map as he felt that the uncertainty was easier to interpret. The other four interviewees did comment that the pin map offered a more detailed view of the uncertainty but they still preferred the prism map. One interviewee commented that the pin map would only be useful to users who were very familiar with, and understood, the data. Therefore, visualising uncertainty directly in the third dimension seems to be preferred to an indirect visualisation (i.e., as used in the pin map) for ease of interpretation.

Effectiveness and preference of using the 3rd third dimension to represent uncertainty in comparison to other method. All interviewees successfully identified an onshore area of relatively high uncertainty using the prism map and indicated that the height of the prism is what guided their decision. This could indicate that using the third dimension is effective for representing uncertainty. Two interviewees were not able to correctly identify areas of low uncertainty using the texture map (task 9). A contributing factor could be that the texture map was presented in a hardcopy format that prevented the interviewees from zooming in to get a better view. Another two interviewees chose to pick several areas instead of being limited to one area. In both cases there was no consistency with regards to uncertainty as they both picked areas of both high and low uncertainty. One interviewee was successful in identifying areas of low uncertainty using the texture map. Uncertainty seems to be less effectively represented in the texture map.

When prompted to choose between the prism and texture map for task 10, all interviewees chose to use the texture map. This indicates that although the interviewees were more successful with interpreting uncertainty using the prism map, they seemed to have a preference in terms of usability for the texture map. All interviewees were successful when asked to take into account both a specific wind speed category and a low uncertainty for a specific situation (task 10) using the texture map. When asked to compare the prism and texture maps all of the interviewees verbalised their preference for the texture map. Different reasons for their preference were given, summarised in Table 18. The main advantage seems to be the use of value categories.

Two interviewees noted that the prism map provided a good initial overview of the wind speeds. Another indicated that they simply did not like the technique to represent uncertainty. One interviewee suggested that the pattern on the texture map could be overwhelming for some users.

Interviewee	1	2	3	4	5
Reason for preferring texture map	Uncertainty is more distinguishable	Information is more clear and the uncertainty categories are more distinct	Specific uncertainty values could be determined	The uncertainty is easier to interpret and there is no occlusion of other data	It was easier to use

Table 18: Reason for user preference for texture map over prism map.

Success of conveying uncertainty in complex (i.e., trivariate) visualisations. The interviewees were asked to use a complex (multivariate) uncertainty map to identify areas that met specific criteria (see task 12 in Table 16) and what advantages such maps might hold. When conducting task 12, most the interviewees appeared to focus on the wind speed and suitable area information. It would appear that when confronted with additional information, uncertainty becomes a less important consideration. One interviewee mentioned that the additional variables detracted from uncertainty. This appears to be true based on the order of importance of the variables that the interviewees seemed to consider.

Interviewees mentioned that the advantage of multivariate 3D maps was that the additional information helped focus attention on specific geographic areas of interest. Quicker decisions could therefore be made, compared to the other maps shown in the interview, as all the information is immediately available.

User opinions on usefulness of 3D maps in regional planning of wind energy production. Interviewees were asked about their opinions on the usefulness of 3D uncertainty maps for planning applications, as well as for their specific field of work. They were also asked which additional variables they would find useful in such maps. Table 19 provides a summary of the user opinions.

Interviewee	1	2	3	4	5
Other planning scenarios where such maps could be useful	Other high level and regional planning scenarios	General planning scenarios, representing uncertainty of electrical outputs of wind farms, and stakeholder buy in	Planning of renewable energy sites for other types of renewable energy and in energy grid planning	Site selection for wind energy projects, and in flood modelling	None suggested (possibly due to lack of experience in planning)
Additional variables for inclusion	Additional suitability (relating to suitability of potential areas) data	None suggested	Energy demand	Legal regulation data and land ownership data	Actual wind speeds as opposed to mean wind speed
Usefulness for line of work	No as 2D maps are sufficient	For stakeholder buy in	Very useful	No as he focuses on projects where uncertainty should have already been considered	Useful in wind energy applications and possibly in air quality applications

Table 19: Summary of user opinions on the usefulness of 3D maps.

Interviewee 1 did note that if such a map could be adapted for micro-siting (site assessment for small geographic areas), they could be useful for stakeholder buy-in for specific wind farms. This would require an adjustment of the resolution of the grid cells used in the map to a smaller grid cell size (2km was suggested by the interviewee). Overall, the interviewees agreed that 3D uncertainty maps could be useful in different applications. But, some indicated that they may not be useful in their current work. A common comment was that 3D uncertainty maps could be more useful if they included additional information relevant for a specific application, as depicted in the trivariate map that added suitable area information to the prism map.

5.5 Conclusions

In this paper, we presented expert perceptions gathered from semi-structured expert interviews regarding usability and suitability of 3D uncertainty maps for regional planning of wind farms.

Expert perceptions suggest that prisms are an easy to understand representation of wind speed uncertainty, but a legend is necessary. The analysis also suggests that visualisation of uncertainty directly in the third dimension (prism map) is preferred to an indirect visualisation (pin map). The direct visualisations seem to be preferred in situations where the user needs to get an overview of the general trend of the uncertainty over large geographic areas. Representing the uncertainty of the wind speed in the third dimension seems to be suitable for getting a high-level overview of the trend of the uncertainty but a more detailed 3D uncertainty map is needed when working at larger scales (smaller geographic areas). When asked to choose one of the maps to perform a task, most of the interviewees chose the texture map over the prism map. This could indicate a preference in terms of usability for 2D maps where uncertainty is represented using traditional 2D cartographic techniques, rather than using the third dimension, even though uncertainty seems to be represented less effectively. There was consensus that 3D maps that include uncertainty could be useful but more work and research is needed to provide such maps that are useful for specific applications. In terms of 3D multivariate maps, there was consensus that the additional information helped to focus the user on specific geographic areas of interest that allowed decisions to be made more quickly. Faster decisions would be made because many datasets could be considered in a single map, instead of considering one map per dataset.

Based on the interview results, the suitability of 3D uncertainty maps for micro-siting should be investigated. This would require data and visualizations at a much larger scale than those used in the research presented in this paper. Some of the recommendations for the improvement of the tested maps include filtering data to meet specific thresholds relevant for a specific project and including markings on the pin map to provide a reference for measurement. The experts agreed that wind speed uncertainty map, in combination with additional information, as exemplified in the trivariate map, would be more useful for their work than an uncertainty map for wind speeds on its own. Such 3D uncertainty maps are more useful for regional level planning of wind farms.

The perceptions presented in this paper contribute to the general understanding of the usability and suitability of 3D uncertainty maps, and specifically for regional level planning of wind farms. They are also important because they contribute to the understanding of how 3D uncertainty maps should be designed. Even though the results from the interviews were clear, the small number of interviewees and the qualitative nature of the interviews does not allow for general conclusions. The preference of an interviewee could have been influenced by the combination of presentation formats (digital and hardcopy); the background of an interviewee; the cognitive load and possible misinterpretation of the symbology used in the maps; and lastly, the nature of the semi-structured interviews.

As a next step, the results obtained from the expert interviews will be used to design and develop a follow up quantitative user study that will be performed in a controlled environment that will evaluate the usability, efficiency, and accuracy of using the third dimension for uncertainty representation.

Chapter 6: South African expert opinions on techniques to visualise wind speed uncertainty in 3D maps for wind farm planning

6.1 Introduction

In this chapter, the results of the second set of interviews are presented. The results of the second set of interviews achieve objective 3 as defined in chapter 1. The results of the interviews were qualitatively analysed. The qualitative data analysis software Atlas.ti 8.0 was used to structure and manage the responses and build a conceptual framework on which the analysis was performed.

6.2 Qualitative analysis of the results

Due to the nature of the interview questions and the small number experts interviewed, the results of the interview were analysed qualitatively. Unlike quantitative analysis, qualitative analysis does not rely on statistical principles (e.g. frequency analysis) to draw conclusions about a phenomenon (Smit 2002). According to Patton (2002), qualitative research employs a naturalistic approach to understand phenomena in context-specific settings (Golafshani 2003). Qualitative data analysis was facilitated using Atlas.ti 8.0, a powerful software package for the analysis of text, visual, and audio data (Smit 2002). Atlas.ti allows the researcher to codify (label) sections of text to develop domains, topic areas (Hill et al. 1997). These domains are used to build a conceptual framework to manage the data and to use as a starting point for analysis (Hill et al. 1997; Smit 2002; Patrizi 2005). One type of report which can be created using Atlas.ti is a network. A network is a visualisation of the data, codes, and quotes in the project (Petrova 2014). Networks are useful as they expose the conceptual foundations upon which interpretations are formulated (Smit 2002).

6.2.1 Results and discussion

The results from the expert interviews are presented in the same order as which they appear in Table 13 in chapter 5. Table 13 is presented here again as Table 20 for convenience.

Questions
1. Background questions
1.1. Please specify your:
1.1.1. Age
1.1.2. Gender

<p>1.1.3. Job title</p> <p>1.1.4. Qualifications</p> <p>1.2. In which domain or application do you work?</p> <p>1.3. Please specify how your work is related to the topic of renewable energy</p>
<p>2. Understanding workflows followed</p> <p>2.1. Describe a typical project that you would do that involves taking into consideration the wind speed for wind farm planning.</p> <p>2.2. Describe the process or workflow followed in the initial stages of a wind farm planning project.</p>
<p>3. Understanding current use of 3D models and uncertainty in the South African wind energy sector</p> <p>3.1. Do you currently use 3D models/3D maps in the workflow?</p> <p>3.2. Do you currently consider uncertainty in the workflow? If yes, how do you represent the uncertainty?</p>
<p>4. Exploring preference of technique</p> <p>4.1. Which map would provide the best overview of the study area (in terms of information) in the initial stages of a project? Why? (<i>refer to scenario in section 4.3.3</i>)</p> <p>4.2. Given the above scenario, which 3D map do you think would be most advantageous for this task?</p> <p>4.3. Out of all of the techniques shown, which do you prefer for uncertainty visualisation? Why?</p>
<p>5. Benefits of representing uncertainty in 3D maps</p> <p>5.1. Based on your experience, which of these maps would be beneficial in your workflow? Explain how you would use it.</p> <p>5.2. Would you say that, for this specific task, it is beneficial to represent uncertainty in the 3D map or would you prefer it to be presented with an overall statistical value of the uncertainty?</p>
<p>6. Drawbacks of 3D uncertainty maps</p> <p>6.1. What drawbacks did you experience with the 3D maps? Why?</p>
<p>7. Expert opinion on representing uncertainty in 3D maps</p> <p>7.1. Based on your experience with wind planning projects and the four visualizations that I showed to you, what is your opinion about representing uncertainty in 3D maps?</p> <p>7.2. Would you recommend 3D geovisualisations of uncertainty? Why or why not?</p>
<p>8. Usefulness of 3D uncertainty maps</p> <p>8.1. Can you suggest other planning scenarios where such 3D maps would be useful?</p> <p>8.2. Can you suggest other variables that would be useful for inclusion in 3D maps that visualise uncertainty?</p>

Table 20: The interview questions developed for the second set of interviews.

The 3D maps used in the interview are described in chapter 3 but thumbnails are presented here for convenience.

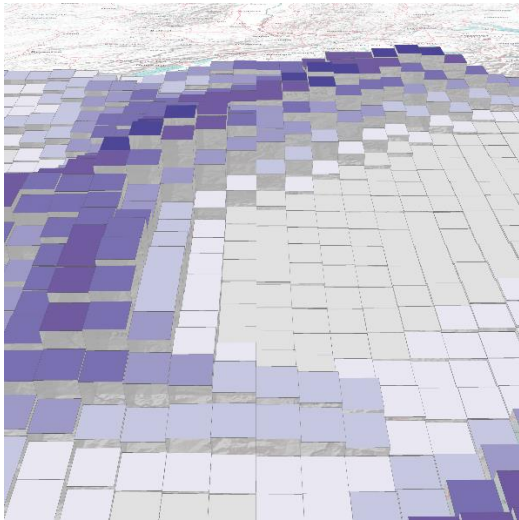


Figure 53: The prism map.



Figure 54: The texture map.

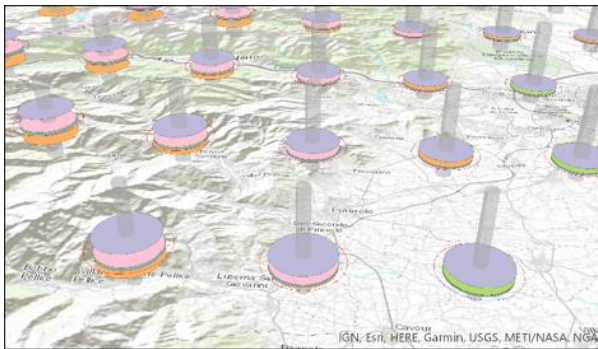


Figure 55: The pin map.

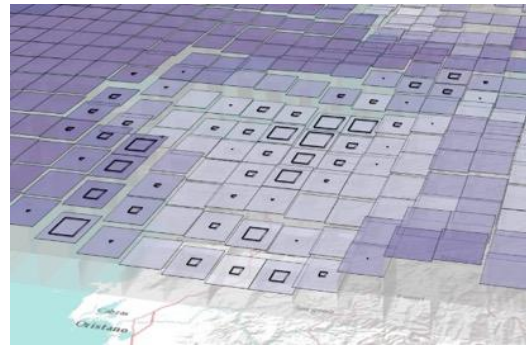


Figure 56: The trivariate map.

6.2.1.1 Workflows followed

Each interviewee was asked to describe the workflow they follow in the initial stages of a wind farm planning project. All the responses indicated that the following general workflow (Figure 57) is followed by the interviewed experts when working on wind farm planning projects.

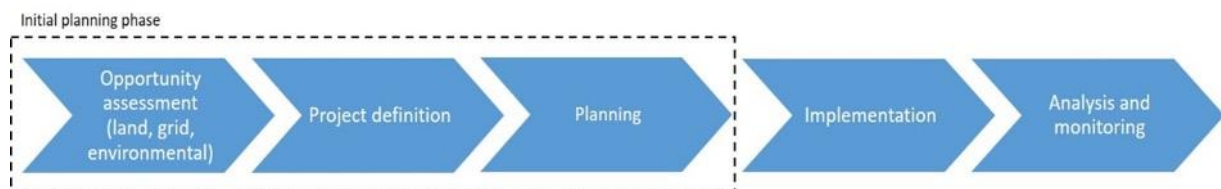


Figure 57: The general workflow applicable to wind farm projects as described by the interviewees in the interview.

There are numerous documented planning workflows for wind farm planning and renewable energy planning in general. For example Mourmouris & Potolias (2013) proposed the

following four step workflow for decision analysis regarding Renewable Energy Sources (RESs) for regional energy planning:

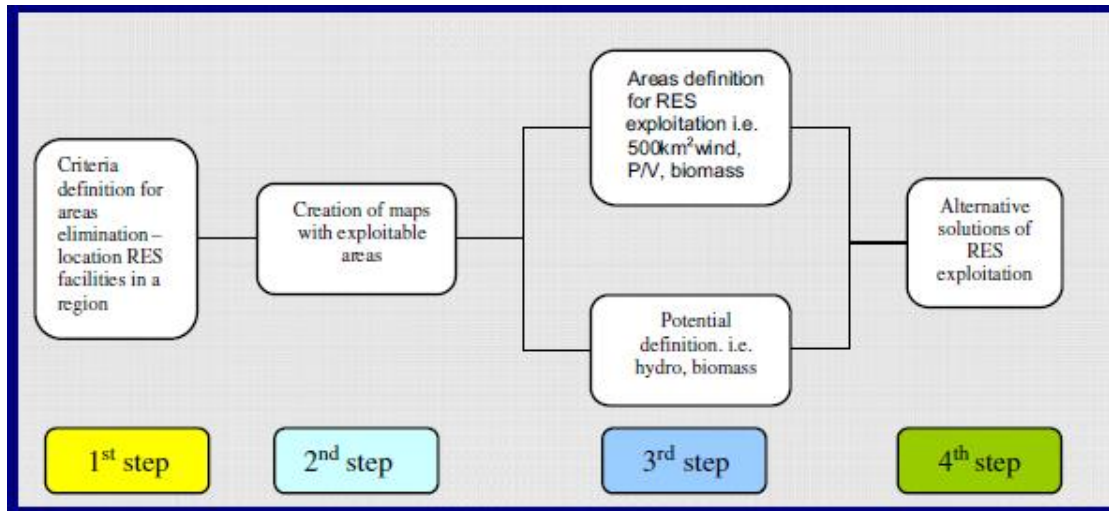


Figure 58: The four steps of decisions analysis for regional energy planning. Source: Mourmouris & Potolias (2013).

Tsoutsos et al. (2015) implemented the following workflow for regional siting decisions of large wind farms:



Figure 59: The workflow implemented by Tsoutsos et al. (2015) for regional wind farm planning.

Although the workflow specified by the interviewed experts differs from the ones presented in Figures Figure 58 and Figure 59, there are similarities, especially with the workflow used by Tsoutsos et al. (2015). For example the first two steps in Tsoutsos et al.’s (2015) workflow is to analyse the current situation (such as environmental aspects and physical resources) and then to identify which of the areas would be legally suitable to develop. This is similar to the *Opportunity Assessment* step in the workflow presented in Figure 57 as it also involves assessing the current state of areas in terms of environmental factors, physical resources and legal aspects.

6.2.1.2 Current use of 3D models and uncertainty in the South African wind energy sector

Three of the four interviewees indicated that they do use 3D models in their current workflows. Interviewee 2 said that he does not use 3D models directly as his involvement is more on the operational side of wind farms. Table 21 outlines the purposes for which 3D

models are used by the interviewees and in which phase of the workflow (Figure 57) they use it.

Interviewee	Purpose	Phase
1	Visualise terrain and wind energy resources	Opportunity assessment phase
2	Does not use 3D models	
3	Visualise wind energy sites for decision making	Planning
4	Visualise wind turbines	Planning, analysis and monitoring

Table 21: Purposes for which 3D models are used by interviewees.

Interviewee 1 and 3 use 3D models in the opportunity assessment phase (refer to Figure 57). Interviewee 4 indicated that he uses 3D models in the planning, and analysis and monitoring phase. The 3D models used are of the physical landscape, proposed farm layouts, and of actual farm layouts. These 3D models do not incorporate uncertainty. Because 3D models are already being utilised in the opportunity assessment, planning, and analysis and monitoring phase it is possible that 3D uncertainty maps could also be useful in these phases.

All the interviewees said that they do consider uncertainty. The uncertainty considered is related to the wind energy production potential and does not have a spatial component. Figure 60 represents the network created in Atlas.ti for this question. The starting point indicates the start of the network. In this case, the starting point is current uncertainty representation. The four answers from the experts on how they represent uncertainty are nodes off the starting point in the network. Linked to the topic on representing uncertainty is the opinion on uncertainty. Three interviewees continued their statements on how they represent uncertainty with an opinion on uncertainty (as can be seen in Figure 60). This network helped identify the link between the method of representing uncertainty and the interviewees opinion on uncertainty.

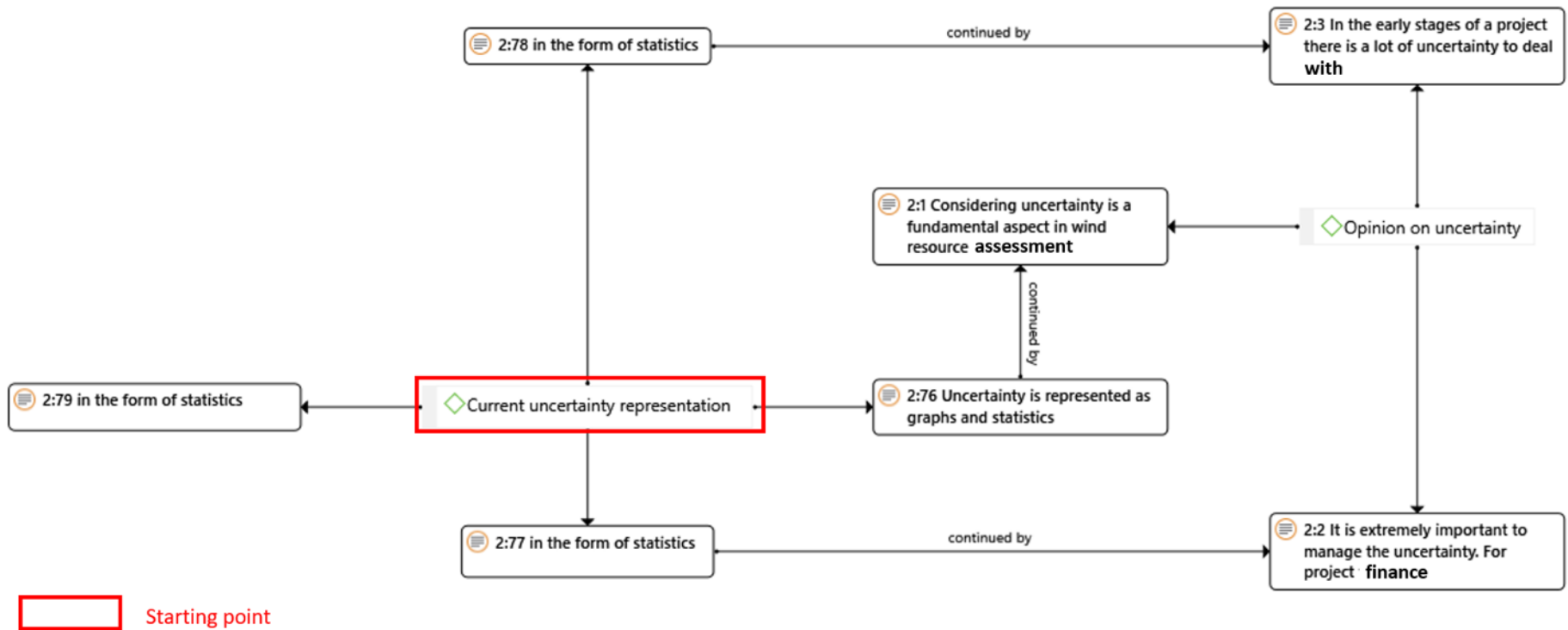


Figure 60: Atlas.ti network of responses on uncertainty representation.

When asked how the uncertainty is represented, all the interviewees responded that they work with uncertainty in the form of statistical values and tables. Figure 61 shows a typical table of uncertainty values used in wind farm performance evaluation. As can be seen from the table, there is no indication of a spatial component. Therefore, it is not possible to identify how uncertainty varies with location. Figure 62 shows a graph used to represent the uncertainty in wind speed. As in the table in Figure 61, there is an absence of a spatial component.

AEP (kWh)	Uncertainty in AEP (kWh)	COE (\$/kWh)	Uncertainty in COE (\$/kWh)
1.93e08	7.59e06	0.024	0.001

Figure 61: An example of uncertainty representation related to wind farm performance. Source: Messaac (2011).

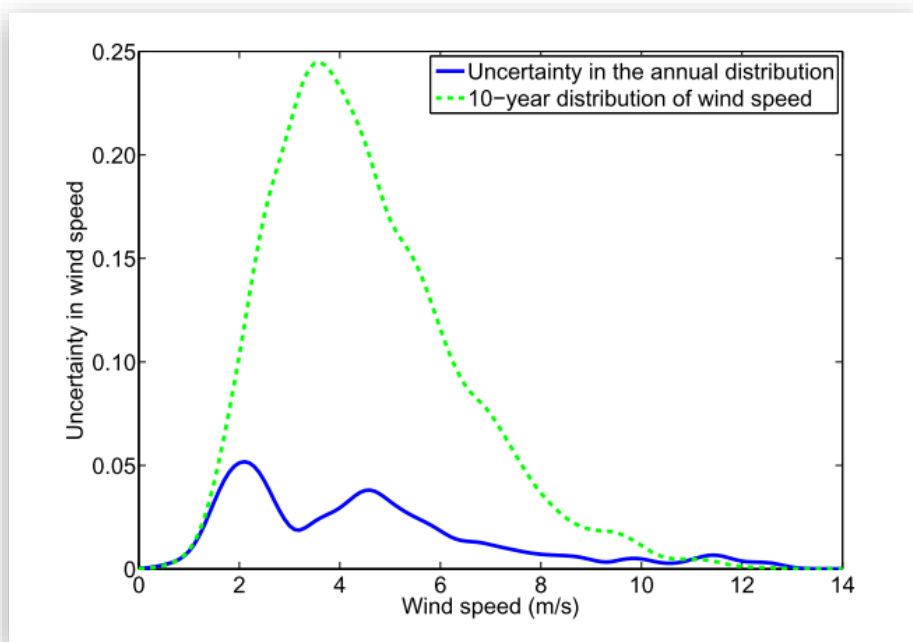


Figure 62: A graph showing uncertainty in wind speed for a specific wind farm. Source: Messaac (2011).

Two of the of interviewees highlighted the importance of uncertainty in the wind energy planning sector with one interviewee commenting that considering uncertainty is a fundamental aspect of wind resource assessment (first step of the workflow in Figure 57).

Interviewee 3 noted that managing uncertainty is important in any wind energy project as it is a critical consideration for project finance. He also noted that there is a considerable amount of uncertainty regarding wind energy potential to deal with in the beginning planning phases of a wind energy project. This uncertainty regarding the wind energy potential is linked to an individual farm as seen in Figure 61.

From the responses of the interviewees, it is evident that understanding the uncertainty associated with planning a new wind farm is a critical part of the planning workflow. As most of the interviewees indicated that they do use 3D models as part of their current workflow, the barrier to entry for the 3D uncertainty maps could be lower. According to Khatib et al. (2007) introducing and implementing 3D models in an organization is not an easy task and training is required, which causes a barrier for entry. If potential users of the 3D maps have already received training on, and are using 3D models, then it is one barrier less.

6.2.1.3 Preference of technique

In order to determine preference of technique, interviewees were asked to consider a scenario and a task. Preference of technique (i.e. prism, pin, or texture) was analysed in terms of the following aspects: 1) getting an initial overview of the uncertainty of the study area, 2) completing a specific task, and 3) overall preference of technique for uncertainty visualisation. Although there are four maps, there are only three techniques used: prism, pin, and texture. The trivariate map uses the prism technique for uncertainty visualisation.

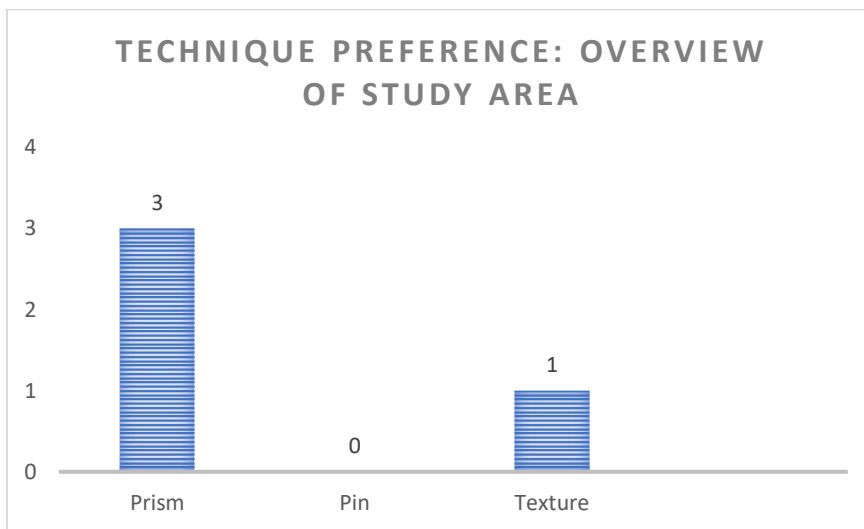
Each aspect of the topic of preference of technique is visualised with a network created using Atlas.ti. The networks provide an overview of the interview responses and lay the foundation for the qualitative analytical discussion.

6.2.1.3.1 Preference of technique for acquiring an initial overview of the information in a study area

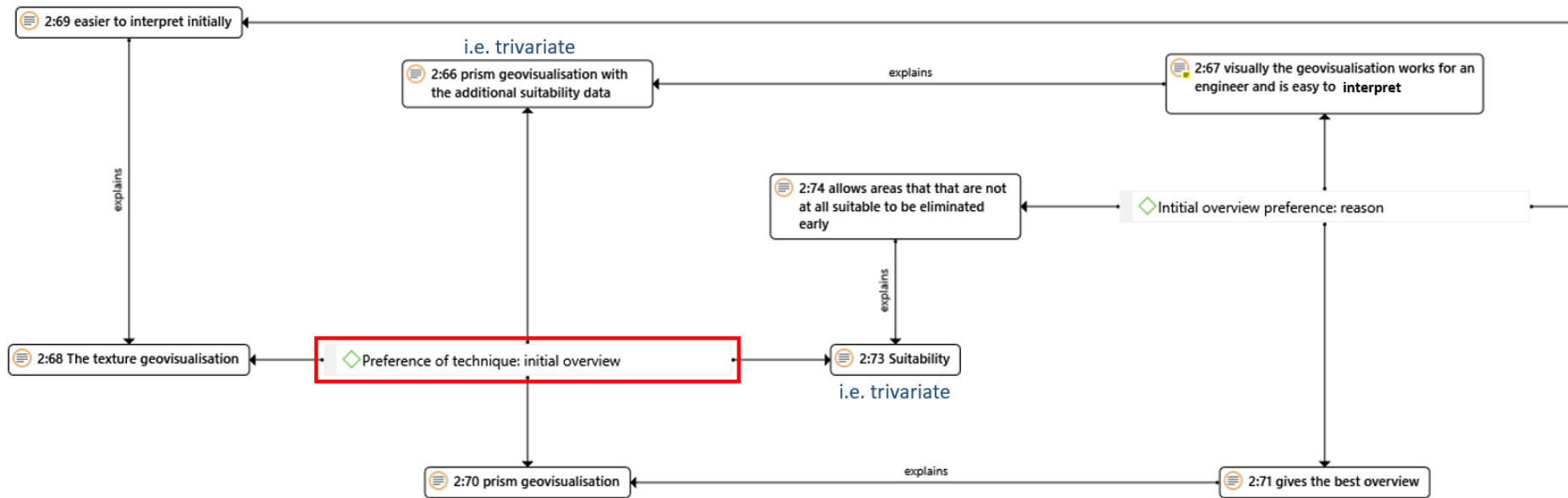
In order to determine preference, interviewees were asked to consider the following scenario:

Imagine that you are responsible for identifying potential areas for locations of wind farms. In the initial stages of the project the goal is to identify large geographic areas where the uncertainty regarding wind speed is relatively low.

Interviewees were then asked which technique provided the best overview of the study area (question 4.1 in Table 20). Figure 63 shows the network created based on the responses to question 4.1. The network indicates the preferred maps, as well as, the reasons for the preference. For this question, one of the interviewees referred to the trivariate map (prism technique) as the suitability map which is reflected in the network in Figure 63. Graph 1 depicts the responses in a graphical format. Although it is not customary to use graphs to depict responses from such a small number of respondents, graphs are used in this chapter to more easily convey the results.



Graph 1: Graph showing technique preference for acquiring an overview of information in a study area.



Starting point

Figure 63: The Atlas.ti network of the responses to the question on preference of technique for acquiring an initial overview of the study area.

Interviewee 1 and 4 responded that they thought the prism technique provided the best overview of the information in the study area. Interviewee 1 responded positively to the height of the prisms as a technique to represent uncertainty and commented that the map would be easy for engineers to interpret. Interviewee 4 noted that the trivariate map allowed for unsuitable areas to be eliminated early on in the workflow which would make for a more efficient planning process. The trivariate map gives the most information and therefore it is reasonable that interviewees preferred it for getting an overview of an area. The trivariate map provides the most information which allows for a more detailed overview. Interviewee 2 said that the texture map provided the best overview as it was the easiest to interpret. Interviewee 2 indicated that he did not regularly use 3D models therefore it is possible that he preferred the texture map as it most closely resembles a traditional map of which he is more familiar with. Interviewee 3 chose the prism map as it gives the best overview of the study area. Interviewee 3 was focused on uncertainty, rather than the other variables, and therefore felt that the prism gave the best overview as the uncertainty is clearer when looking at the study area as a whole.

The responses to this question are varied, however three of the four interviewees selected maps which use the prism technique to represent uncertainty. The trivariate map seems to be preferred for getting an initial overview of the study area but this seems to be solely due to the inclusion of the additional suitability information. Using the height of the prisms to represent uncertainty offers the flexibility to include other variables for visualisation. This suggests that the prism map would be most suitable for acquiring an overview of the information in a study area. Although there is a preference for using the prism technique, it does not necessarily mean that the experts would be better at applying this technique to interpret uncertainty. It is possible for a person to prefer a map or technique, but not be successful at using it.

6.2.1.3.2 Preference of technique for comparing uncertainty in different areas

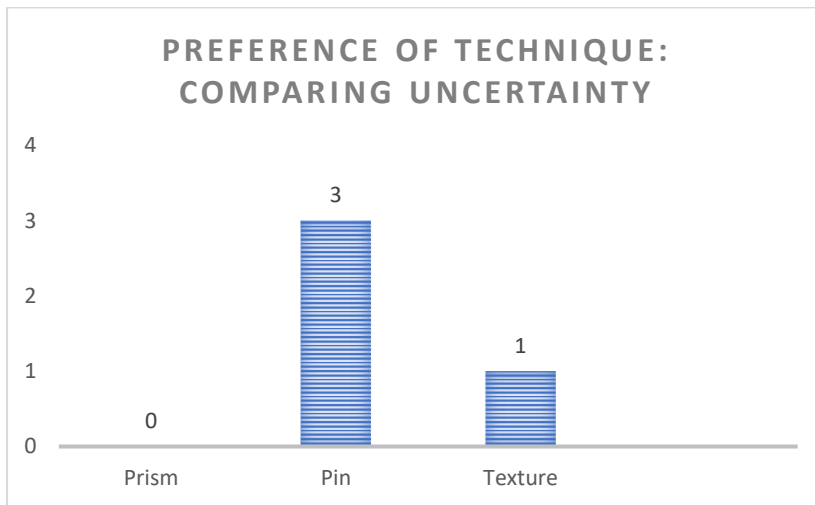
All the interviewees were asked which map they thought would be most advantageous in the given scenario. The scenario is defined as follows:

Imagine that you are responsible for identifying potential areas for locations of wind farms. In the initial stages of the project the goal is to identify large geographic areas where the

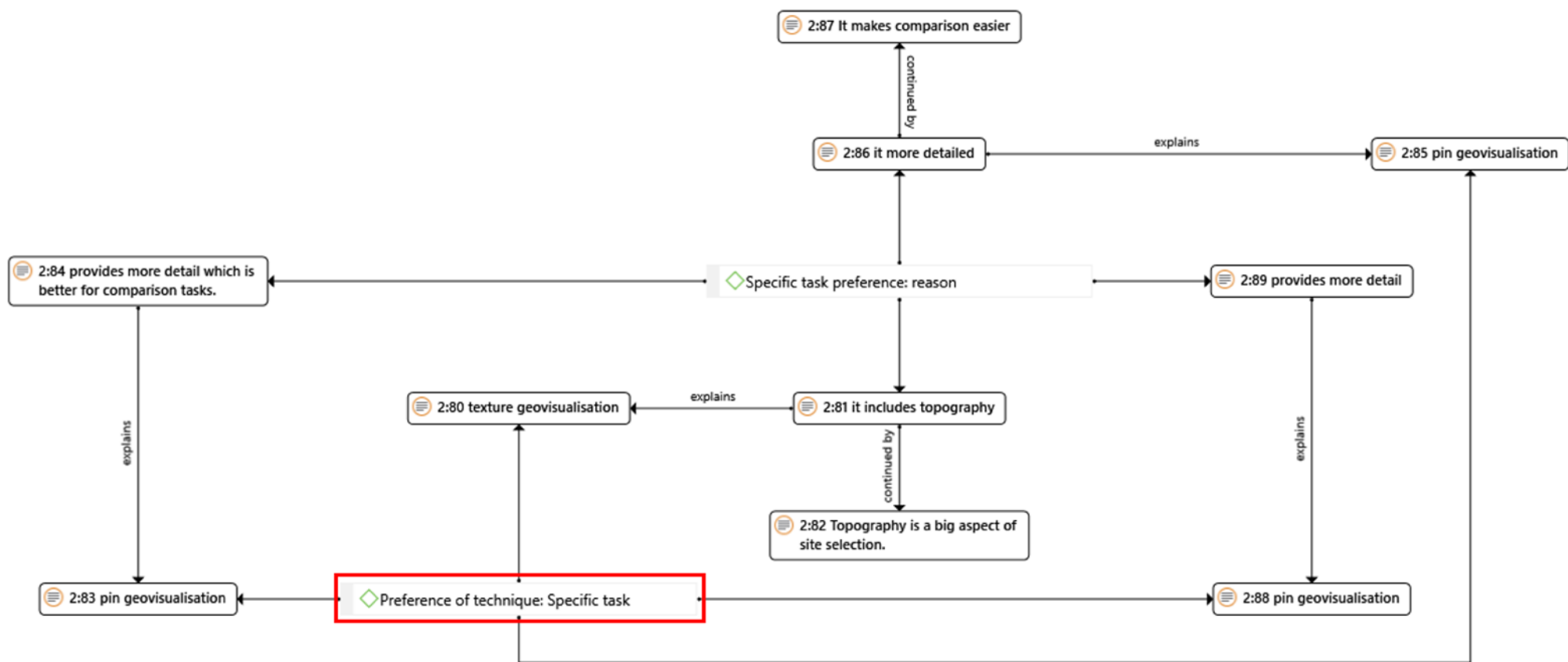
uncertainty regarding wind speed is relatively low. In the later stages of the above scenario, one must compare wind speed uncertainty for a specified number of locations.

The latter part of this scenario was referred to as a task in the interview, however, the interviewees did not have to complete the task, they were only asked to consider it.

Figure 64 shows the network created based on the responses to question 4.2. The network indicates the preferred maps, as well as, the reasons for the preference. Graph 2 depicts the preference for technique for comparing uncertainty.



Graph 2: Preference of technique for comparing uncertainty for different areas.



Starting point

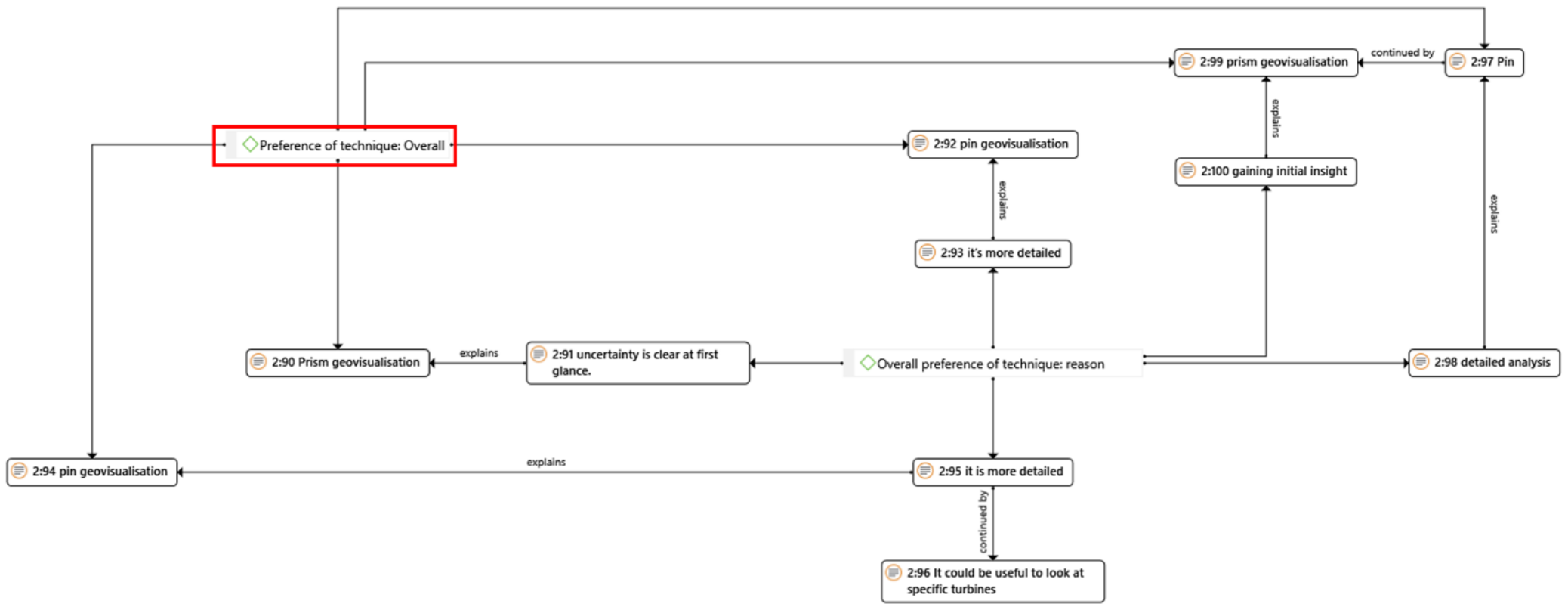
Figure 64: The Atlas.ti network of the responses to the question on preference of technique for comparing uncertainty.

Three of the four interviewees specified that the pin map would be most advantageous. All three of these interviewees felt it was more advantageous as it was more detailed which would be helpful for such a detailed task. All of the interviewees requested to zoom in to smaller areas in order to study the individual pins. This points to the pin map being more useful when analysing smaller areas. Although the uncertainty information and the average wind speed is the same as displayed in the other maps, the interviewees perceived it to be more detailed. One possible reason for this perception is that on a single pin, six variables (the five wind speeds and the average wind speed) and the uncertainty can be deduced. The pin map gives the most information in terms of wind speed when zoomed in to smaller areas as the five wind speed models are shown in relation to one another. This allows the spread of the predicted wind speeds to be investigated which gives an indication of the reason for the uncertainty value (e.g. one wind speed model prediction could be significantly different to the others causing the uncertainty to increase). On the texture and prism map only the uncertainty and the average wind speed can be deduced for each grid but there these two maps do not contain the data which gives an indication on why the uncertainty is either high or low. For example, on the pin map, if one wind speed prediction is significantly higher or lower than the other models, this will cause the uncertainty to be higher as the range is larger. A user will be able to see this from the pin map. If it is only one wind speed model that is significantly different to the other models then the expert user can decide if the resulting uncertainty value is influential enough to affect analysis. If for example, all of the wind speed model predictions are dispersed (which can be deduced by their position on the pin) then the user can safely assume that the uncertainty is high in that area. Interviewee 1 selected the texture map as the topography was more visible which he felt would be important for completing the task. Interviewee 1 often considers topography in the *opportunity assessment* phase of a project, which is reflected in his map preference. Based on the way the interviewees interacted with the pin map (requesting to zoom in to smaller areas), it seems this technique would be more useful when studying the uncertainty for smaller geographic areas.

6.2.1.3.3 Overall preference of technique for uncertainty visualisation

Interviewees were asked which technique for representing uncertainty they preferred. Figure 65 shows the network created based on the responses. The network indicates the preferred maps, as well as, the reasons for the preference.

Interviewee 1 selected the prism map as the uncertainty is immediately obvious. Having an immediate indication of the uncertainty, as opposed to conducting a more thorough analysis, is important in Interviewee 1's workflow. Interviewees 2 and 3 both selected the pin map as it is more detailed (see discussion in section 6.2.1.3.2). Interviewee 3 commented that that the pin map would be useful to look at the uncertainty associated with specific wind turbines. This is a reasonable statement for the interviewee to make, as it seems that the pin map is more useful for smaller geographic areas (see section 6.2.1.3.2). His preference is therefore based on the conclusion that the pin map would be useful in his own workflows. Interviewee 4 commented that his preference of technique depended on the use case for the map. For more detailed analysis the pin map would be preferable but the prism map is preferable for gaining initial insight.



Starting point

Figure 65: The Atlas.ti network of the responses to the question on overall preference of technique.

6.2.1.3.4 Conclusion: Preference of technique

Table 22 is a summary of which techniques were preferred for each category.

Category	1	2	3	4
Overview of study area	Prism	Texture	Prism	Prism
Specific task	Texture	Pin	Pin	Pin
Overall preference	Prism	Pin	Pin	Prism & Pin

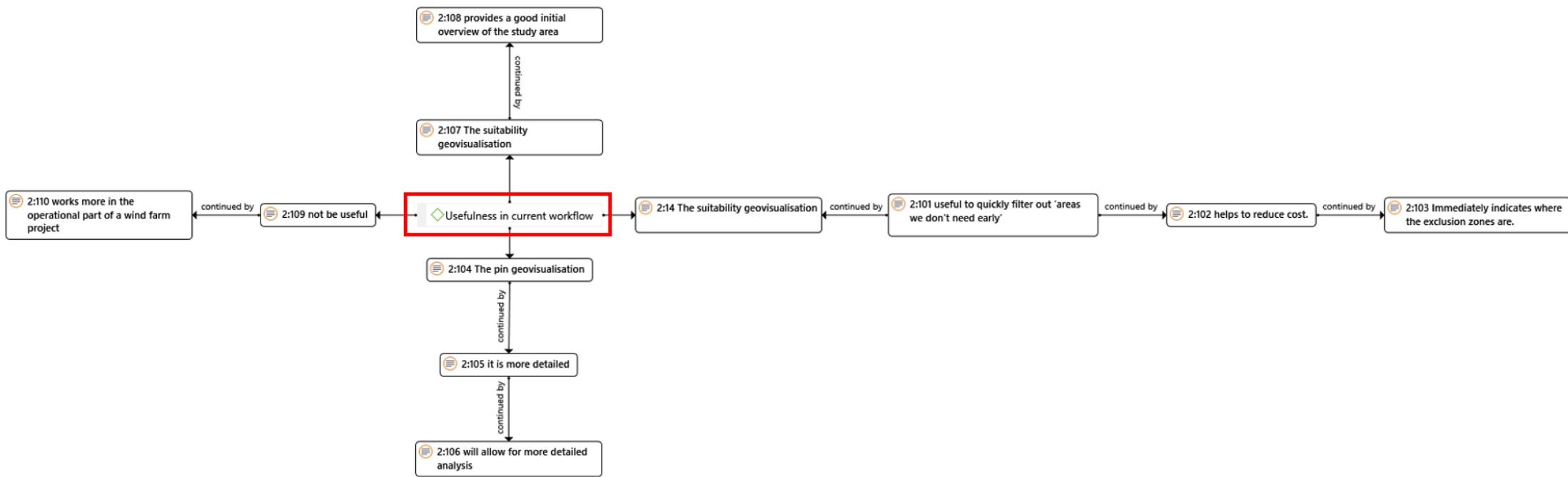
Table 22: Summary of technique preference. Where interviewees specified the trivariate map it was interpreted that they preferred the prism technique.

Interviewees 1 and 4 both selected the trivariate map as their preference for acquiring an overview of the study area but chose the prism map as their overall preference. This could be as a result of the wording of question 4.3, which specifically asks which technique was preferred, as opposed to which map was preferred.

Based on the responses from the interviewees there is evidence that the preference of technique for representing uncertainty is largely dependent on the use case. It is clear that the pin map is preferred for more detailed analysis and precise tasks as it indicates the reason for the uncertainty. The prism technique is preferred for more general analysis, such as when acquiring an overview of the information in a study area.

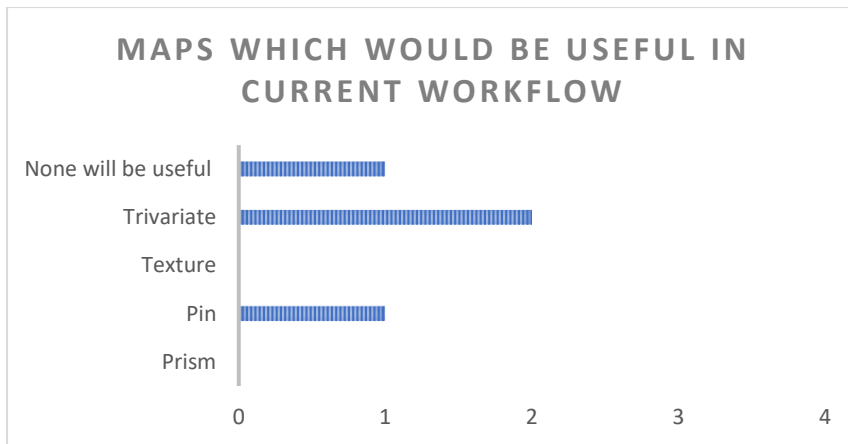
6.2.1.4 Benefits of representing uncertainty in 3D maps

The aim of question 5 was to ascertain the benefits of representing uncertainty in 3D maps. In question 5.1, interviewees were asked which of the four maps would be beneficial in their current workflow. Figure 66 shows the network created based on the responses. Graph 3 shows the responses to the question as a graph.



Starting point

Figure 66: The Atlas.ti network of the responses to the question on which maps would be useful in their current workflow.



Graph 3: Graph showing which maps interviewees thought would be useful in their current workflow.

Two interviewees (interviewee 1 and 3) selected the trivariate map. Interviewee 1 commented that the trivariate map is useful to quickly filter out ‘areas we don’t need early’ which helps to reduce cost. The trivariate map is useful in Interviewee 1’s workflow as it immediately indicates where the exclusion zones are. Interviewee 3 noted that the trivariate map is useful as it provides a good initial overview of the study area that includes all relevant variables/factors. This corresponds to the answers given to question 4.1 as two interviewees selected the trivariate map as their preferred map for acquiring an overview of the study area. The appeal of the trivariate map to the two interviewees is that it incorporates more information which allows for quicker decision making. The prism technique offers the flexibility to include additional variables for visualisation. Interviewee 2 said that the pin map would be most beneficial as it allows for more detailed analysis which is an important aspect of his workflow. The pin map was also his preferred technique for uncertainty visualisation (question 4.3). Although he does not use 3D models directly (see Table 21), Interviewee 2 is involved in monitoring existing wind farms. Perhaps the additional wind speed information portrayed in the pin map makes him think that it could be useful in the monitoring stage. Interviewee 4 said that none of the maps would be useful in his current workflow as he works in the operational side of wind farm projects.

Interviewees were asked in question 8.1 whether it was beneficial to represent uncertainty visually or whether they preferred the uncertainty to be represented in the form of statistics. Figure 67 shows the network created based on the responses.

Interviewees 2,3, and 4 said that that after seeing the 3D maps presented in the interview, they preferred a visual representation of uncertainty rather than being presented with an overall statistical value. Interviewee 2 mentioned that that he preferred the visual representation as the uncertainty is quicker to interpret. This correlates with Wise et al. (1995) who stated that mentally processing text is much slower than using the human brain's primary parallel processing powers of visual perception. Interviewee 1 said that in the initial stages of a planning project a visual representation of uncertainty is suitable to identify the overall trends and patterns but thereafter he would prefer statistical graphs and tables for more detailed analysis. It is possible that the interviewee trusts the statistical values he is used to more than the uncertainty represented in the 3D map. It is also possible that the type of uncertainty information typically provided in the statistical graphs and tables contain more information than what is included in the 3D maps. It would be beneficial in future research to ensure that the uncertainty that the experts are used to working with is represented in the maps. This could improve expert trust in the 3D maps. Interviewee 1's responses could indicate a vagueness in the question posed. Overall the interviewed experts in the wind energy sector would welcome 3D maps which visually portray uncertainty.



Figure 67: The Atlas.ti network of the responses to the question on interviewee's opinion on representing uncertainty statistically vs visually.

6.2.1.5 Drawbacks of 3D maps that visualise uncertainty

Interviewees were asked what drawbacks they found when using the 3D maps. Figure 68 shows the network created based on the responses.

Many of the responses point to drawbacks of the technique used to represent uncertainty.

Table 23 presents a summary of the responses.

Interviewee	1	2	3	4
Prism map		Not useful if stationary. The user needs to interact with the map by panning and rotating to understand the full picture.		
Pin map	Difficult to identify wind speed.	Difficult to interpret at small scales.	Hard to interpret.	Difficult to interpret initially.
Texture map	The density of the lines makes the uncertainty unclear.	“Difficult on the eye” initially.	Unsuitable for high level detail.	

Table 23: Summary of the drawbacks of the 3D maps as identified by the interviewees.

Overall, the pin map had the most comments regarding drawbacks. All the interviewees mentioned that the pin map is difficult to interpret. Interviewees 3 and 4 both mentioned that it was difficult to interpret overall but interviewees 1 and 2 were more specific. Interviewee 1 identified wind speed as the variable which is difficult to interpret whereas interviewee 2 mentioned that the map was difficult to interpret “when zoomed out”. Although all interviewees mentioned drawbacks of the pin map, based on the responses from question 5.1, it seemed to be a preferred technique as it allowed for more detailed analysis (see section 6.2.1.3.2). Interpreting the pin map appears to be overwhelming for users at first but after studying the legend and spending a couple minutes interacting with the map, all of the experts seemed confident in their interpretation of the map. It would appear that the advantages of the pin map outweigh the drawbacks. A possible reason for this is that the pin map is the only map to give an indication of the reason for the uncertainty. Although the pin map seems to be difficult to interpret the information it conveys is valuable.

The prism map had the least number of drawbacks. Interviewee 2 felt that the prism map is only useful if the user actively explores the map by panning and rotating. Although all of the maps support panning and rotating, interviewee 2 only commented on the prism map at this stage. Interviewee's 2 answer could be due to the fact that he does not have any experience with 3D models and therefore sees the need to pan and rotate as an additional task (compared to when using a traditional 2D map). Panning and zooming around the map did not appear to be a concern for the other interviewees who all use 3D models already in their workflows. There were a variety of drawbacks mentioned for the texture map. Two of the interviewees implied that the uncertainty is not clearly conveyed enough for detailed analysis. Interviewee 2 commented that the texture map is "difficult on the eye" initially which could potentially be as a result of information overload as described by (Liao et al. 2016).

Interviewee 4 was the only interviewee who mentioned collective drawbacks of the 3D uncertainty maps. He commented that all the maps need to include version numbers and date information. He also commented that a significant drawback of the 3D maps is that they cannot be adequately portrayed in the 2D reports presented to stakeholders. This aligns to one of the challenges of 3D visualisations as noted by Turner (2006) which is that the fixed views of standard publications impose restrictions on how 3D models and similar complex visualisations can be interpreted.

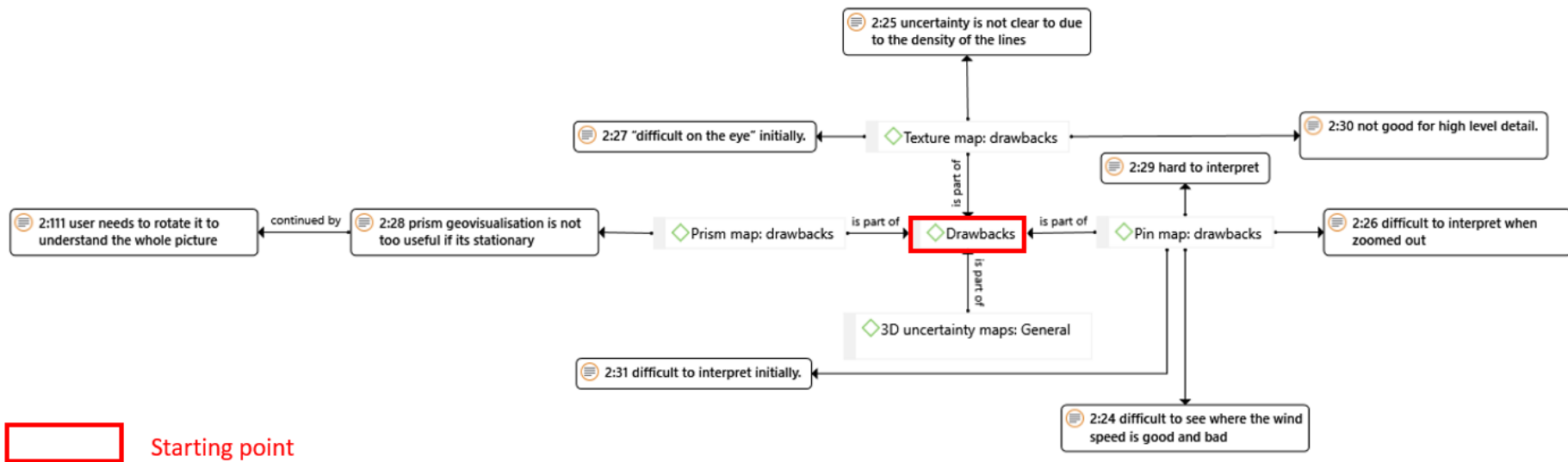


Figure 68: The Atlas.ti network of the responses to the question on the drawbacks of the 3D maps.

6.2.1.6 Expert opinions on representing uncertainty in 3D maps

Question 7 addresses user opinions on visualising uncertainty in 3D maps. In question 7.1, interviewees were asked what their opinion is regarding visualising uncertainty in 3D maps. Figure 69 shows the network created based on the responses.

All interviewees had positive, but different, opinions. Interviewee 1 said that the 3D uncertainty maps are helpful, but that they would be more helpful on a micro (large) scale. He would also prefer to have separate 3D uncertainty maps for the different aspects of wind energy planning, for example, separate maps visualising the uncertainty relating to the potential energy of a site. Interviewee 2 commented that the 3D maps are useful but would be more useful if they were animated with the inclusion of a time variable in the 4th dimension. Interviewee 3 was of the opinion that 3D maps “are a good idea” as they indicate which areas should be further investigated early on in the planning process. Interviewee 4 commented that the visual representation makes the information easier to interpret and that such maps “reduce the number crunching” required. The different opinions indicate that the interviewed experts think that the 3D maps are helpful and would be more useful if adapted for their specific workflows.

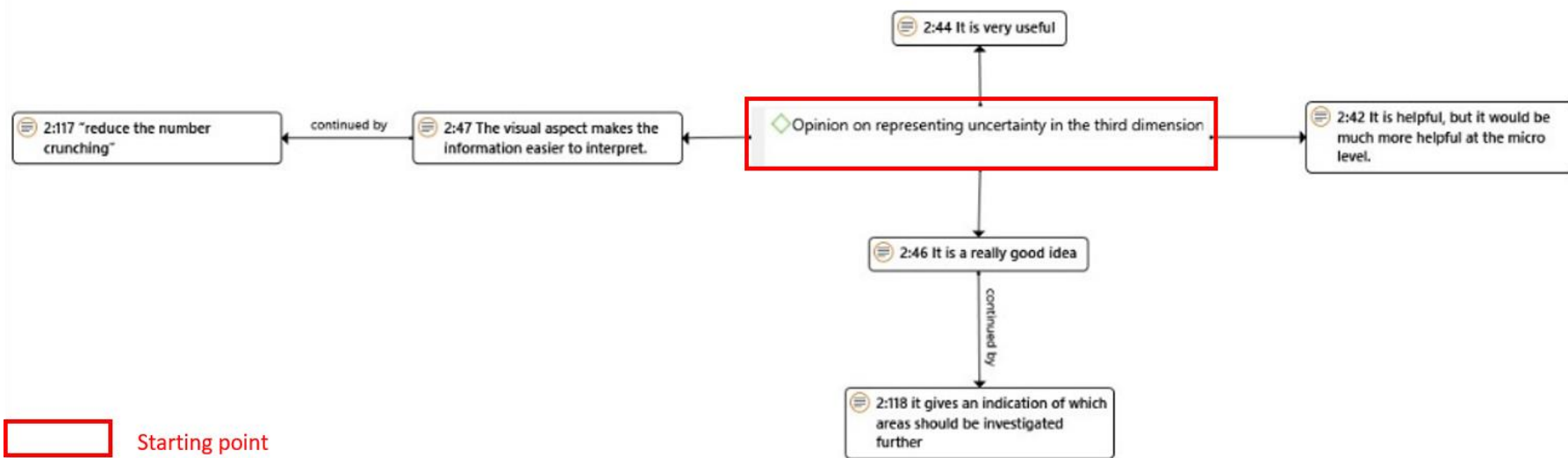


Figure 69: The Atlas.ti network of the responses to the question on the interviewee's opinion on representing uncertainty in the third dimension.

In question 7.2, interviewees were asked whether they would recommend uncertainty maps that visualise uncertainty. Figure 70 shows the network created based on the responses.

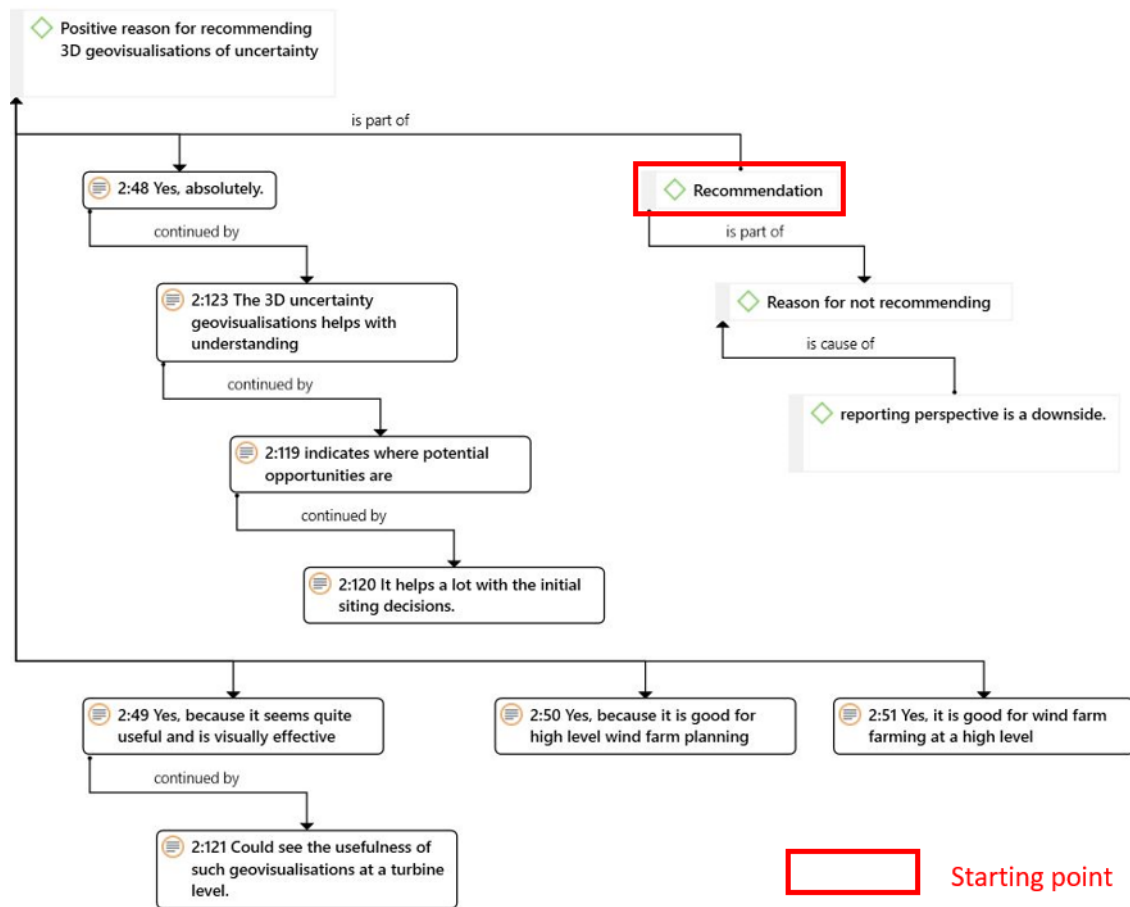


Figure 70: The Atlas.ti network of the responses to the question on whether the interviewee's would recommend 3D maps that visualise uncertainty.

All the interviewees responded that they would recommend 3D maps that visualise for a variety of reasons. Interviewee 1 said that the maps help with understanding and also provide a good indication of potential areas to focus on for new wind projects. He commented that “they would help a lot with the initial siting decisions”. Interviewee 2 specified that that the maps were useful as they were a visually effective way of communicating information. Many researchers have noted the benefits of the information communication potential of 3D maps (Royse et al. 2009; Wu et al. 2010; Li et al. 2013). Interviewee 2 could see the use of such maps at a wind turbine level. Interviewee 3 would recommend the 3D maps as he felt they would be useful for high level wind farm planning. Interviewee 4 noted that the maps would be helpful for regional planning of wind farm planning but he reiterated his concern about the reporting perspectives of such maps (see section 6.2.1.5).

The interviewee’s opinions presented in this section are substantially positive. This can be seen as an indication of the possible usefulness of 3D maps that visualise uncertainty. Based on opinions gathered in this interview it would appear that the interviewed experts feel that the maps would be useful and would recommend their use to others. There is evidence that the 3D maps would have to be modified to better meet the needs of the users for their specific workflows but overall the visualisation of uncertainty was received positively.

More evidence for the usefulness of 3D uncertainty maps are presented in section 6.2.1.7.

6.2.1.7 Usefulness of 3D maps which visualise uncertainty

Question 8 addresses the usefulness of visualising uncertainty in 3D maps. The usefulness of the 3D maps in the interviewees current workflow has already been established (section 6.2.1.4 and section 6.2.1.6). Question 8.1 asks interviewees to identify other planning scenarios or applications where 3D maps that visualise uncertainty would be useful. Figure 71 shows the network created based on the responses.

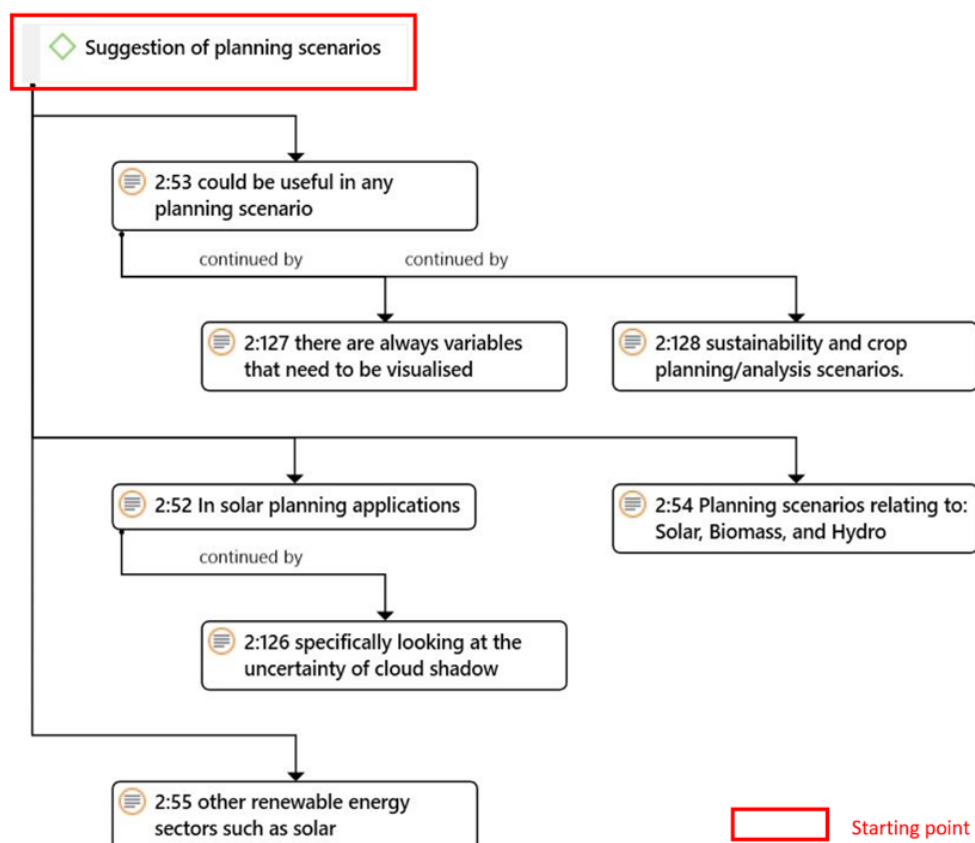


Figure 71: The Atlas.ti network of the responses to the question on suggestions for other planning scenarios.

All of the interviewees were able to think of other planning scenarios where 3D maps that visualise uncertainty would be useful. Interviewee 1 mentioned solar planning applications specifically looking at the uncertainty of cloud shadow. This could be because he indicated that he has work experience in the solar energy domain. Interviewee 3 and 4 listed other renewable energy sectors such as solar, biomass and hydro power. Interviewee 2 commented that the 3D maps would be useful in any planning application as “there are always variables to be visualised”. He then mentioned sustainability and crop planning scenarios as specific examples. The responses to this question imply that the 3D maps that visualise uncertainty would be useful in many other planning scenarios.

Question 8.2 addresses the topic of making 3D maps more useful by asking the interviewees which other variables they thought would be necessary for inclusion. Figure 72 shows the network created based on the responses.

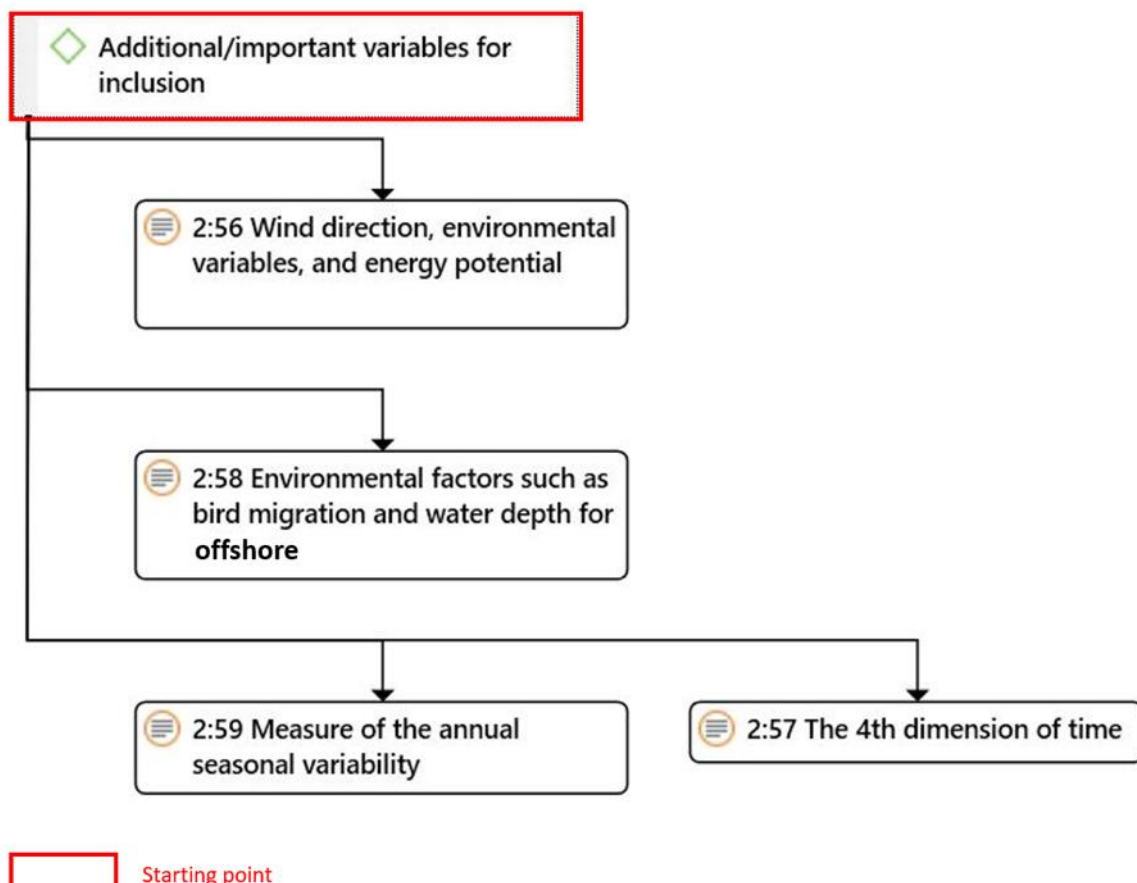


Figure 72: The Atlas.ti network of the responses to the question on additional variables for inclusion.

Interviewee 1 commented that uncertainty relating to wind direction and wind potential are important. He also mentioned that general other environmental variables could be included. In addition to the inclusion of time, interviewee 2 commented that the maps would be more useful if they were in real time so that there was a real time indication of the uncertainty. Regarding usefulness of the maps shown in the interview, interviewee 2 believed that a combination of the prism and pin maps would be useful for the analysis of existing wind if they were redesigned for a micro level of analysis. Interviewee 3 felt it was important to include annual bird migration paths into the map. He also commented that the water depth would be important to include for planning of offshore wind farms. Interviewee 4 felt the 3D maps could be more useful if they provided a measure of the annual seasonal variability. He also added that the 3D maps would only ever be as accurate as the input data.

The suitability information displayed in the trivariate map did take into account some of the additional variables requested by the experts. For example, water depth for offshore farming is a factor considered in the suitability calculation. Visualising more variables in the 3D uncertainty maps must be considered carefully as not to result in cognitive overload. Cognitive load is defined by Bunch & Lloyd (2006) as the amount of work needed to acquire and use information. All maps communicate a large amount of information and represent complex associations (Bunch & Lloyd 2006). According to Harper et al. (2009) the more information contained in a visualisation the more visually complex it is which results in imposing greater cognitive load on users. The additional variables mentioned by the experts give an indication of what they would find useful for their specific workflow. The prism technique for uncertainty representation would allow an additional variable to be visualised as proven by the trivariate map. The variable to be visualised could be changed depending on the use case for the 3D map.

6.3 Conclusion

In this section, South African experts' perception regarding usability and suitability of techniques for visualising uncertainty in 3D maps for regional level wind farm planning are presented. The expert perceptions are gathered from semi-structured expert interviews conducted with four experts in the field of wind energy generation.

It is evident from the expert's responses that uncertainty is a critical aspect of any wind farm planning project and is currently communicated as statistical values in tables and graphs. Expert perceptions suggest that the inclusion of 3D maps that visualise uncertainty into wind farm planning workflows will be useful and beneficial. The responses suggest that experts prefer a visual representation of uncertainty rather than statistical values in tabular format. However, it is likely that the two methods would possibly be used together in wind farm planning workflows.

Preference of technique seems to depend on the use case for the map in the workflow and on the experience of the user. Using the third dimension to represent the uncertainty as in the prism and trivariate map was the preferred technique for acquiring an overview of the information in the study area. This could possibly be because the height of the prisms is easier to interpret, as opposed to the pin and texture maps, when quickly scanning over a large geographic area. For more detailed analysis, such as, when comparing uncertainty between areas, the pin map is preferred. The additional wind speed data depicted on the pin map seems to be advantageous for comparison tasks. One possible reason is that the depiction of each wind speed prediction could be a factor in the assessment of the uncertainty. Although there is a preference for using the third dimension to represent uncertainty, it does not necessarily mean that the experts would be better at applying this technique to interpret uncertainty. It is possible for a person to prefer a technique, but not be successful at using it. One interviewee noted the importance of topography when evaluating areas for potential wind farm development and therefore preferred the texture map for such situations. This could indicate that for situations where topography is important, the texture map could be preferable as the topography is clearly visible. This should, however, be investigated further.

Based on the responses from the interviewees there is evidence to suggest that the preference of technique for representing uncertainty is largely dependent on the specific task for the map. It is clear that the pin map is preferred for more detailed analysis and precise tasks as it indicates the reason for the uncertainty. The prism map is preferred for more general analysis, such as, when acquiring an overview of the information in a study area.

Usefulness of the 3D uncertainty maps seems to depend on the preference of the interviewee. Experts who need to perform very detailed analysis prefer the pin map whereas

experts who need to see all of the information displayed in one map in order to make quicker decisions prefer the trivariate map. Overall, expert user opinion is positive which suggests that 3D maps that include uncertainty would be useful in wind farm planning projects. The experts were able to readily suggest other planning applications where 3D uncertainty maps would be useful indicating their usefulness in other renewable energy planning scenarios.

Including other necessary variables in the 3D maps, other than the suitability information shown in the trivariate map, would make the 3D maps more useful. The use case for the map would dictate what additional variables to include. Care must be taken, however, as to not clutter the map. The prism technique for representing uncertainty offers the flexibility to visualise an additional variable.

Although the experts identified drawbacks of the 3D maps the overall response is positive. The pin map seems to be the less user friendly but the most valuable in terms of information. The solution is to design a 3D map that shows the same information but which is more user friendly. The drawbacks identified could potentially be addressed in future studies.

The expert perceptions in this chapter contribute to the general understanding of the usability and suitability techniques to visualise uncertainty in 3D maps, specifically for regional-level planning of wind farms. Due to the small number of interviewees and the qualitative nature of the semi-structured interviews, general conclusions cannot be drawn. The perceptions and preferences of the experts could have been affected by numerous factors, such as, the background of the interviewee, the cognitive load, the misinterpretation of the map symbology, misinterpretation of the questions, and the nature of semi-structured interviews.

Chapter 7: Discussion and conclusions

7.1 Introduction

This dissertation explored the visualisation of uncertainty in 3D maps of wind speed models for use in regional level planning of wind farms. This final chapter provides both an overview of the main results, and recommendations on aspects that still need to be addressed in further research.

7.2 Discussion

The literature review revealed (see section 2.3.2) that characterising uncertainty in geospatial data is a current research challenge (Robinson et al. 2017) and new approaches to visualising uncertainty are needed. The results of this research address this challenge in the context of regional level wind farm planning.

Many of the German experts who were interviewed stated that they were intrigued by the idea of using 3D maps to represent uncertainty but in a few of them could not see the usefulness of such maps in their work. Most of the South African experts stated that they found the concept of using 3D maps to visualise uncertainty interesting.

Most of the German interviewees indicated when answering the background questions that they do consider uncertainty. It was not established how the uncertainty is represented which was a flaw of the interview. All of the South African interviewees indicated that they do consider uncertainty and based on the lessons learnt from the German interviews, they were also asked how the uncertainty is communicated. All of the interviewees indicated that the uncertainty is represented in the form of statistical values presented in tables and charts. Uncertainty does not seem to be visualised using 3D maps in wind farm planning applications that the interviewed experts are involved with. This does not seem like a common practice as identified by the gap in literature regarding using 3D maps for visualising uncertainty in wind farm planning.

Most of the German participants indicated that they do not have experience using 3D maps in their work. The interviewee's inexperience with using 3D maps might be a contributing factor to their preference in terms of usability for the texture map (task 10 in the first interview) which most closely resembles a traditional 2D map. The interviewee's lack of experience with 3D maps could possibly have led to them misunderstanding the information

communicated in the 3D map. Most of the South African experts indicated that they do have experience with using 3D maps. Although they stated that they have experience with 3D maps it is possible that the experts definition of a 3D map is different to the types of 3D maps discussed in this dissertation. It was established that common examples of 3D maps used in wind energy planning are physical landscape (terrain) models and 3D maps of individual wind farms which is consistent with what was identified in the literature review in section 2.5.

In terms of preference of technique for using the third dimension to visualise uncertainty the German experts preferred the prism map to the pin map. The reason provided for this preference is that, although the interviewees acknowledged that the pin map is more detailed, the prism is easier to interpret. When comparing the maps that make use of the third dimension to visualise uncertainty (the prism and pin map) to the 3D map that uses a 2D technique to represent uncertainty (the texture map), the experts preferred the texture map. It is possible that they are simply more comfortable with the texture map as it most closely resembles a traditional 2D map. Hegarty et al. (2009) found that people do have a preference for familiarity when it comes to map displays. This results corresponds with findings by Petrovič & Mašera (2005) who found that experienced map users prefer a draped topographic map over other types of 3D maps. The responses from the South African experts indicate that the preference of technique for representing uncertainty is largely dependent on the use case. This corresponds to past research on map displays that has suggested that users express different preferences in different situations (Levy et al. 1996; Hegarty et al. 2009). The pin map is preferred for more detailed analysis and precise tasks as it indicates the reason for the uncertainty. This result corresponds to findings by Slocum et al. (2003) that state that extrinsic techniques (as used in the pin map) are more useful for detailed analysis. The prism technique is preferred for more general analysis, such as when acquiring an overview of the information in a study area. This does not correspond to findings by Slocum et al. (2003) who state that intrinsic techniques, and not extrinsic techniques, are preferred by experts to get an overview of the information being depicted. The pin map was classified as extrinsic based on a similar map produced by Slocum et al. (2003) also being classified as extrinsic. However, it is possible that the prism technique could be classified as an intrinsic technique where the size visual variable is manipulated. In this case, the finding that the prim

map is preferred for getting an overview of the information in the stud area would correspond to Slocum et al's. (2003) finding.

There were a few positive outcomes from both sets of interviews. The first interview shows that using the third dimension to visualise uncertainty is effective as many of the interviewee's were able to interpret the uncertainty appropriately. The second interview showed that experts in the wind energy planning sector would welcome 3D map which visually portray uncertainty. This could indicate a need for further research on the topic as the literature review revealed a gap in existing knowledge related to using 3D maps to visualise uncertainty in the context of wind farm planning. A positive prospect for the usefulness of the pin map is that, with some changes, it could be used to look at the uncertainty associated with specific wind turbines.

There were also some negative outcomes from the interviews. The results of the first user study suggest that using the third dimension to represent uncertainty is not intuitive. Both user studies reveal that the pin map is the most difficult to interpret which is a significant negative reflection on the technique. Both sets of interviews also show that 3D maps which visualise uncertainty are not useful to all experts in the wind energy sector.

Both user studies show that most experts thought that the 3D maps are useful but more can be done to make them more useful. One observation that was echoed by many interviewee's in both sets of interviews was that the 3D maps that visualise uncertainty would be more useful for micro siting applications which focus on individual wind farms at larger geographic scales. Another common observation from both sets of interviews is that the 3D maps would be more useful if they were adapted for specific workflows.

7.3 Main results from dissertation

The main results are presented in terms of each objective as defined in chapter 1.

Objective 1: Perform an on-going literature review of existing theory and related work.

A literature review was conducted on the following topics: the current use of maps in regional planning of wind farms, uncertainty, 3D maps, and the current use of 3D maps in wind farm planning.

The literature review showed that 2D maps are used extensively in regional level planning of wind farms. These maps tend to focus on the communication of spatial analysis results for optimal siting. It is apparent from the literature that 3D maps are used in wind farm planning but these tend to be limited to specific sites at large geographic scales. These 3D maps are often a model of proposed or existing wind farms and tend to be quite photorealistic. 3D maps used at regional planning scales are not common.

There are many domains of uncertainty visualisation research and numerous studies have been conducted on various techniques to represent uncertainty. Many of these reported techniques are 2D techniques as opposed to 3D techniques. There is limited research on techniques used to visualise uncertainty in 3D maps.

The literature review helped to identify that visualising uncertainty in 3D maps and using these maps in regional level planning of wind farms is a gap in existing knowledge.

Objective 2: Design and produce 3D maps to visualise uncertainty and design semi-structured expert interviews to explore perceptions regarding such maps

Four 3D maps visually depicting uncertainty were designed and produced as part of this dissertation. Components of the ArcGIS platform (ArcGIS Pro, ArcGIS Server, and the ArcGIS API for JavaScript) were used to successfully create and display the 3D maps despite some technical limitations of the API and a few rendering issues in ArcGIS Pro.

Three different techniques for visualising uncertainty were utilised in the 3D maps: the height of prisms, the distance range between discs, and a pattern texture. The prism and texture patterns are existing techniques from the literature but no studies were found on using distance range between elements as technique for visualising uncertainty.

The maps were all presented in a two-dimensional media but were perceived as a representation of the 3D dimensional reality and therefore can, according to Häberling et al. (2008), be referred to as 3D maps.

Two expert interview questionnaires were designed as part of this dissertation. The second questionnaire was developed as an improvement of the first questionnaire. The interviews were semi-structured and the questions designed to elicit responses that would aid in

achieving the objectives set out in Chapter 1. The 3D maps produced as part of Objective 2 were presented to the experts as part of the interview.

Objective 3: Conduct expert interviews to ascertain expert preferences and perceptions regarding the use of 3D maps to visualise uncertainty

The expert perceptions gathered in the first interview suggest that prisms are an easy to understand technique to represent wind speed uncertainty, but a legend is necessary. The results of the first interview indicate a preference in terms of usability for 3D maps where uncertainty is represented using traditional 2D cartographic techniques, rather than using the third dimension, even though uncertainty seems to be represented less effectively.

It appears that the preference of technique for representing uncertainty is largely dependent on the use case. It is clear that the pin map is preferred for more detailed analysis and precise tasks as it indicates the reason for the uncertainty. The prism technique is preferred for more general analysis, such as when acquiring an overview of large geographic areas. Although there were mentioned drawbacks for all of the 3D maps, the pin map had the most number of mentioned drawbacks with the most popular comment being that it is difficult to interpret. Interpreting the pin map appears to be overwhelming for users at first but after studying the legend and spending a couple minutes interacting with the map, all of the experts seemed confident in their interpretation of the symbology. It would appear that the advantages of the pin map outweigh the drawbacks. A possible reason for this is that the pin map is the only map to give an indication of the reason for the uncertainty. Although the pin map seems to be difficult to interpret the information it conveys is valuable, and therefore the advantages outweigh the drawbacks.

The results from the semi-structured interviews suggest that representing the uncertainty of wind speed in the third dimension is suitable for getting a high-level overview of the trend of the uncertainty but a more detailed 3D uncertainty map is needed when working at larger scales (smaller geographic areas). In terms of 3D multivariate maps, there was consensus that the additional information helped to focus the user on specific geographic areas of interest which allowed decisions to be made more quickly.

Most of the interviewed experts were able to identify at least one of the 3D maps which would be beneficial in their current workflow. After seeing the 3D maps presented in this

dissertation, all of the South African experts were able to appreciate the value of visually representing uncertainty in a 3D map. Overall, the interviewed experts in the wind energy sector in South Africa would welcome 3D maps which visually portray uncertainty. There was consensus that 3D maps that include uncertainty could be useful but more work and research is needed to provide such maps that are useful for more focussed applications such as visualising the uncertainty of the wind energy potential of a specific wind farm. Most of the experts in both sets of interviews were able to recommend other planning scenarios where they thought such 3D maps would be useful. All of the South African experts indicated that they would recommend the use of 3D maps to visualise uncertainty to others.

Objective 4: Use the results from the expert interviews to draw conclusions

Although definitive conclusions cannot be drawn as a result of the small number interviewees, the following results are clear from the results of the expert interviews.

- 1) Representing uncertainty in the third dimension is not intuitive and a legend should always be provided.
- 2) Users who have no experience using 3D maps have a preference for 3D maps where the uncertainty is visualised using traditional 2D cartographic techniques as opposed to using the third dimension to represent uncertainty.
- 3) The prism technique for visualising uncertainty is better suited for 3D maps covering large geographic areas. The pin map is preferred for more detailed analysis that is needed for small geographic areas.
- 4) 3D maps that include uncertainty would be useful in regional planning of wind farms but they have the potential to be even more useful if they could be adapted for visualising uncertainty at a specific farm level.

The results from this dissertation show that it is possible to use 3D maps to visualise uncertainty in regional level wind farm planning, however more quantitative research should be conducted on the topic. When designing 3D maps to visualise uncertainty, the specific workflow followed by experts should be considered to ensure that the maps include information specific to their needs. It must be noted that the results are based on the specific 3D maps created for this research, and it is possible that other 3D maps might produce different results.

7.4 Recommendations for further research

Based on the interview results, the suitability of 3D maps to visualise uncertainty for micro-siting should be investigated. This would require data and visualisations at a much larger scale than those used in the research presented in this dissertation. It should also be established what type of uncertainty expert users would find useful to be represented in 3D maps. This could be established through other interviews. This would ensure that the uncertainty information that the expert users are familiar with are represented in the 3D maps.

A few improvements could be made to the study. 2D maps that visualise uncertainty should be included in order to investigate how the 3D maps compare to the 2D maps. The experts should not be limited to the field of renewable energy as experts in cartographic design could have useful insights into the 3D maps. The study could be further improved to include a training phase during the interviews so that the participants could familiarise themselves with the maps before answering questions on it.

As a next step, the results obtained from the expert interviews presented in this dissertation should be used to design and develop a follow-up quantitative user study that should be performed in a controlled environment that will evaluate the usability, efficiency and accuracy of using 3D maps for uncertainty representation. Other techniques for visualising uncertainty in 3D maps should also be investigated in order to extend the body of knowledge in this research area.

References

- Aerts, J., Clark, K. & Keuper, A. 2003. Testing popular visualization techniques for representing model uncertainty. *Cartography and Geographic Information Science*. 30(3):249–262.
- Afanasyeva, S., Saari, J., Kalkofen, M., Partanen, J. & Pyrhönen, O. 2016. Technical, economic and uncertainty modelling of a wind farm project. *Energy Conversion and Management*. 107:22–33.
- Altmaier, A. & Kolbe, T.H. 2003. Applications and Solutions for Interoperable 3d Geo-Visualization. In *Proceedings of the Photogrammetric Week 2003*. D. Fritsch, Ed. Stuttgart. 1–15.
- Azzellino, A., Ferrante, V., Kofoed, J.P., Lanfredi, C. & Vicinanza, D. 2013. Optimal siting of offshore wind-power combined with wave energy through a marine spatial planning approach. *International Journal of Marine Energy*. 3: 11–25.
- Bandrova, T., Zlatanova, S. & Konecny, M. 2012. Three-dimensional maps for disaster management. In *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. V. I. 245–250.
- Baseer, M.A., Rehman, S., Meyer, J.P. & Alam, M.M. 2017. GIS-based site suitability analysis for wind farm development in Saudi Arabia. *Energy*. 141:1166–1176.
- Bauer, J.R. & Rose, K. 2015. Variable Grid Method : An Intuitive Approach for Simultaneously Quantifying and Visualizing Spatial Data and Uncertainty. 19(3):377–397.
- Bektaş, K. & Çöltekin, A. 2011. An Approach to Modeling Spatial Perception for Geovisualization. *Procedia - Social and Behavioral Sciences*. 21:53–62.
- Benke, K.K., Pettit, C.J. & Lowell, K.E. 2011. Visualisation of spatial uncertainty in hydrological modelling. *Journal of Spatial Science*. 56(1):73–88.
- Berry, R., Higgs, G., Fry, R. & Langford, M. 2011. Web-based GIS Approaches to Enhance Public Participation in Wind Farm Planning. *Transactions in GIS*. 15(2):147–172.
- Bertin, J. 1983. *Semiology of graphics: Diagrams, networks, maps*. Madison, WI: University of Wisconsin Press.
- Bishop, I.D. & Stock, C. 2010. Using collaborative virtual environments to plan wind energy installations. *Renewable Energy*. 35(10):2348–2355.
- Bleisch, S. 2012. 3D geovisualization - definition and structures for the assessment of usefulness. In *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*. V. I-2. Melbourne, Australia. 129–134.
- Bleisch, S. & Nebiker, S. 2008. Connected 2D and 3D visualizations for the interactive exploration of spatial information. *Proc. of 21th ISPRS Congress, Beijing, China*. (1999):1037–1042.
- Bleisch, S., Dykes, J. & Nebiker, S. 2008. Evaluating the Effectiveness of Representing Numeric Information Through Abstract Graphics in 3D Desktop Virtual Environments. *The Cartographic Journal*. 45(3):216–226.
- Borah, K., Souvnik, R. & Harinarayana, T. 2013. Optimization in Site Selection of Wind Turbine for Energy Using Fuzzy Logic System and GIS — A Case Study for Gujarat. *Open Journal of Optimization*. 2:116–122.

- Bos, S., Bregt, A.K., Bulens, J.D. & Van Lammeren, R. 1998. Overdracht van ruimtelijke informatie door 2D-en 3D-visualisaties. *Kartografisch tijdschrift*. 24(4):18–24.
- Boukhelifa, N., Bezerianos, A., Isenberg, T., Fekete, J. & Evaluating, J.F. 2012. Evaluating Sketchiness as a Visual Variable for the Depiction of Qualitative Uncertainty To cite this version : Evaluating Sketchiness as a Visual Variable for the Depiction of Qualitative Uncertainty. *IEEE Transactions on Visualization and Computer Graphics*. 18:2769–2778.
- Brasebin, M., Perret, J., Mustière, S. & Weber, C. 2012. Measuring the impact of 3D data geometric modeling on spatial analysis: Illustration with Skyview factor. In *Usage, Usability, and Utility of 3D City Models – European COST Action TU0801*. V. 2001. EDP Sciences. 2001.
- Bunch, R.L. & Lloyd, R. 2006. The Cognitive Load of Geographic Information. *The Professional Geographer*. 58(October 2004):209–220.
- Chen, B., Huang, F. & Fang, Y. 2011. Integrating virtual environment and GIS for 3D virtual city development and urban planning. In *2011 IEEE International Geoscience and Remote Sensing Symposium*. IEEE. 4200–4203.
- Çöltekin, A., Lokka, I. & Zahner, M. 2016. ON THE USABILITY AND USEFULNESS OF 3D (GEO) VISUALIZATIONS -- A FOCUS ON VIRTUAL REALITY ENVIRONMENTS. In *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*. V. XLI-B2. XXIII ISPRS Congress. 387–392.
- Cowell, R. 2007. Wind power and 'the planning problem': The experience of Wales. *European Environment*. 17(5):291–306.
- Dalgarno, B. & Lee, M.J.W. 2010. What are the learning affordances of 3-D virtual environments? *British Journal of Educational Technology*. 41(1):10–32.
- Davis, T.J. & Keller, C.P. 1997. Modelling and visualizing multiple spatial uncertainties. *Computers & Geosciences*. 23(4):397–408.
- Deitrick, S. 2012. Evaluating implicit visualization of geographic uncertainty for public policy decision support. In *Proceedings of AutoCarto International Symposium on Automated Cartography*.
- Deitrick, S. & Edsall, R. 2006. The Influence of Uncertainty Visualization on Decision Making: An Empirical Evaluation. In *Progress in Spatial Data Handling*. A. Riedl, W. Kainz, & G.A. Elmes, Eds. Springer Berlin Heidelberg. 719–738.
- Demšar, U., Buchin, K., van Loon, E.. & J, S.-B. 2015. Stacked space-time densities : a geovisualisation approach to explore dynamics of space use over time. *Geoinformatica*. 19:85–115.
- Deren, L., Mi, W., Qingwu, H. & Fen, H. 2009. On three-dimensional visualization of geospatial information: graphics based or imagery based? *Annals of GIS*. 15(2):75–84.
- Dlamini, W.M. 2010. A Bayesian belief network analysis of factors influencing wildfire occurrence in Swaziland. *Environmental Modelling & Software*. 25(2):199–208.
- Department of Energy. 2015. *State of Renewable Energy in South Africa*. Pretoria.
- Drecki, I. 2002. Visualization of uncertainty in geographical data. In *Spatial Data Quality*. W. Shi, P.F. Fisher, & M.F. Goodchild, Eds. London/New York: Taylor & Francis. 140–159.

- Ducey, M.J. 2001. Representing uncertainty in silvicultural decisions : an application of the Dempster \pm Shafer theory of evidence. 150:199–211.
- Fisher, P. 1993. Visualizing uncertainty in soil maps by animation. *Cartographica*. 30(2 + 3):20–27.
- Fisher, D., Popov, I., Drucker, S.M. & Schraefel, M. 2012. Trust Me , I ’m Partially Right : Incremental Visualization Lets Analysts Explore Large Datasets Faster. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 1673–1682.
- Garlandini, S. & Fabrikant, S.I. 2009. Evaluating the Effectiveness and Efficiency of Visual Variables for Geographic Information Visualization. In *Cosit 2009*. 195–211.
- Golafshani, N. 2003. Understanding Reliability and Validity in Qualitative Research. *The Qualitative Report*. 8(4):597–606.
- Griethe, H. & Schuhmann, H. 2006. The Visualization of Uncertain Data : Methods and Problems. *SimVis 2006*. vi:143–156.
- Grigoryan, G. & Rheingans, P. 2004. Point-based probabilistic surfaces to show surface uncertainty. *IEEE Transactions on Visualization and Computer Graphics*. 10(5):564–573.
- Global Wind Energy Council. 2014. Global wind report: Annual Market Update 2013. Brussels.
- Häberling, C., Bär, H. & Hurni, L. 2008. Proposed Cartographic Design Principles for 3D Maps: A Contribution to an Extended Cartographic Theory. *Cartographica: The International Journal for Geographic Information and Geovisualization*. 43(3):175–188.
- Harper, S., Michailidou, E. & Stevens, R. 2009. Toward a definition of visual complexity as an implicit measure of cognitive load. *ACM Transactions on Applied Perception*. 6(2):1–18.
- Hedberg, J. & Alexander, S. 1994. Virtual reality in education: defining researchable issues. *Educational Media International*. 31(4):214–220.
- Hegarty, M., Smallman, H.S., Stull, A.T. & Canham, M.S. 2009. Naïve Cartography: How Intuitions about Display Configuration Can Hurt Performance. *Cartographica: The International Journal for Geographic Information and Geovisualization*. 44(3):171–186.
- Herbert, G. & Chen, X. 2015. A comparison of usefulness of 2D and 3D representations of urban planning. *Cartography and Geographic Information Science*. 42(1):22–32.
- Hernandez, T. 2007. Enhancing retail location decision support: The development and application of geovisualization. *Journal of Retailing and Consumer Services*. 14(4):249–258.
- Heuvelink, G.B. & Burrough, P.A. 2002. Developments in statistical approaches to spatial uncertainty and its propagation. *International Journal of Geographical Information Science*. 16:111–113.
- Hill, C.E., Thompson, B.J. & Nutt Williams, E. 1997. A Guide to Conducting Consensual Qualitative Research. *The Counseling Psychologist*. 25(4):517–572.
- Hope, S. & Hunter, G.J. 2007. Testing the effects of positional uncertainty on spatial decision-making. *International Journal of Geographical Information Science*. 21(6):645–665.
- Howard, D. & MacEachren, A.M. 1996. Interface design for geographic visualization: Tools for representing reliability. *Cartography and Geographic Information Science*. 23(2):59–77.

- Huk, T. 2006. Who benefits from learning with 3D models ? the case of spatial ability. *Journal of Computer Assisted Learning*. 392–404.
- Hunter, G.J. & Goodchild, M.F. 1993. Managing uncertainty in spatial databases: Putting theory into practice. In *Papers from the Annual Conference-Urban and Regional Information Systems Association*. Urisa Urban And Regional Information Systems. 55–62.
- Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Braun, A., Colette, A., et al. 2014. EURO-CORDEX: New high-resolution climate change projections for European impact research. *Regional Environmental Change*. 14(2):563–578.
- Jacobson, M. 2006. Empirical research into learning in 3D virtual and game environments: selected review of the literature [working paper]. Singapore.
- Jankowski, J.M. 2010. A European Legal Perspective on Wind Energy. *Journal of Energy & Natural Resources Law*. 28(2):265–297.
- Jiang, H. & Eastman, J.R. 2000. Application of fuzzy measures in multi-criteria evaluation in GIS. *International Journal of Geographical Information Science*. 14(2):173–184.
- Jones, C.E., Haklay, M., Griffiths, S. & Vaughan, L. 2009. A less-is-more approach to geovisualization – enhancing knowledge construction across multidisciplinary teams. *International Journal of Geographical Information Science*. 23(8):1077–1093.
- Khatib, J.M. 2007. Antecedents and benefits of 3D and 4D modelling for construction planners. *Journal of Engineering, Design and Technology*. 5(2):159–172.
- Kinkeldey, C., MacEachren, A.M. & Schiewe, J. 2014. How to Assess Visual Communication of Uncertainty? A Systematic Review of Geospatial Uncertainty Visualisation User Studies. *The Cartographic Journal*. 51(4):372–386.
- Kinkeldey, C., Mason, J., Klippel, A. & Schiewe, J. 2014. Evaluation of noise annotation lines: using noise to represent thematic uncertainty in maps. *Cartography and Geographic Information Science*. 41(5):430–439.
- Koletsis, I., Kotroni, V., Lagouvardos, K. & Soukissian, T. 2016. Assessment of offshore wind speed and power potential over the Mediterranean and the Black Seas under future climate changes. *Renewable and Sustainable Energy Reviews*. 60:234–245.
- Kraak, M. 2003. Geovisualization illustrated. *ISPRS Journal of Photogrammetry & Remote Sensing*. 57:390–399.
- Krivoruchko, K. & Gotway Crawford, C.A. 2005. Assessing the Uncertainty Resulting from Geoprocessing Operations. In *GIS, Spatial Analysis, and Modeling*. D.J. Maguire, M. Batty, & M.F. Goodchild, Eds. Redlands, California: ESRI Press.
- Kunz, M., Gret-Regamey, A. & Hurni, L. 2011. Visualization of uncertainty in natural hazards assessments using an interactive cartographic information system. *Natural Hazards*. 59:1735–1751.
- Kwan, M.P. 2000. Interactive geovisualization of activity-travel patterns using three-dimensional geographical information systems: A methodological exploration with a large data set. *Transportation Research Part C: Emerging Technologies*. 8(1–6):185–203.

- Kwan, M.-P. & Kotsev, A. 2015. Gender differences in commute time and accessibility in Sofia, Bulgaria: a study using 3D geovisualisation. *The Geographical Journal*. 181(1):83-96.
- van Lammeren, R., Houtkamp, J., Colijn, S., Hilferink, M. & Bouwman, A. 2010. Affective appraisal of 3D land use visualization. *Computers, Environment and Urban Systems*. 34(6):465–475.
- Lange, E. & Hehl-Lange, S. 2005. Combining a participatory planning approach with a virtual landscape model for the siting of wind turbines. *Journal of Environmental Planning and Management*. 48(6):833–852.
- Lange, M., Waldl, H. & Oldenburg, D.-. 2001. Assessing the Uncertainty of Wind Power Predictions. In *Proceedings of the European Wind Energy Conference*.
- Leitner, M. & Buttenfield, B.P. 2000. Guidelines for the Display of Attribute Certainty. *Cartography and Geographic Information Science*. 27(1):3–14.
- Levy, E., Zacks, J., Tversky, B. & Schiano, D. 1996. Gratuitous graphics? Putting preferences in perspective. In *Proceedings of the SIGCHI conference on human factors in computing systems*. ACM. 42–49.
- Li, J., Jiang, Y., Yang, C., Huang, Q. & Rice, M. 2013. Visualizing 3D/4D environmental data using many-core graphics processing units (GPUs) and multi-core central processing units (CPUs). *Computers and Geosciences*. 59:78–89.
- Liao, H., Dong, W., Peng, C. & Liu, H. 2016. Exploring differences of visual attention in pedestrian navigation when using 2D maps and 3D geo-browsers. *Cartography and Geographic Information Science*. 44(6):474–490.
- Longley, P., Goodchild, M., Maguire, D. & Rhind, D. 2005. *Geographic Information Systems and Science*. 2nd editio ed. West Sussex, UK: Wiley & Sons.
- Lu, Y. & Fang, T. 2014. Examining Personal Air Pollution Exposure, Intake, and Health Danger Zone Using Time Geography and 3D Geovisualization. *ISPRS International Journal of Geo-Information*. 4(1):32–46.
- MacEachren, A.M. & Kraak, M. 2001. Research Challenges in Geovisualization. *Cartography and Geographic Information Science*. 28(1):3–12.
- MacEachren, A.M., Brewer, C.A. & Pickle, L.W. 1998. Visualizing georeferenced data: representing reliability of health statistics. *Environmental and Planning A*. 30:1547–1561.
- MacEachren, A.M., Robinson, A., Hopper, S., Gardner, S., Murray, R., Gahegan, M. & Hetzler, E. 2005. Visualizing Geospatial Information Uncertainty: What We Know and What We Need to Know. *Cartography and Geographic Information Science*. 32(3):139–160.
- MacEachren, a. M., Roth, R.E., O'Brien, J., Li, B., Swingley, D. & Gahegan, M. 2012. Visual Semiotics & Uncertainty Visualization: An Empirical Study. *IEEE Transactions on Visualization and Computer Graphics*. 18(12):2496–2505.
- Mason, J.S., Retchless, D., Klippel, A., Smith, J., Retchless, D. & Domains, A.K. 2016. Domains of uncertainty visualization research : a visual summary approach. *Cartography and Geographic Information Science*. 44(4):296-309.

- Mentis, D., Hermann, S., Howells, M., Welsch, M. & Siyal, S.H. 2015. Assessing the technical wind energy potential in Africa a GIS-based approach. *Renewable Energy*. 83:110–125.
- Messac, A., Chowdhury, S. & Zhang, J. 2012. Characterizing and mitigating the wind resource- based uncertainty in farm performance. *Journal of Turbulence*. 13(13): 1-26.
- Métral, C., Ghoula, N. & Falquet, G. 2012. An ontology of 3D visualization techniques for enriched 3D city models. *Usage, Usability, and Utility of 3D City Models – European COST Action TU0801*. 2005:2005.
- Mohr, S.H., Wang, J., Ellem, G., Ward, J. & Giurco, D. 2015. Projection of world fossil fuels by country. *Fuel*. 141:120–135.
- Morton, P.J., Horne, M., Dalton, R.C. & Thompson, E.M. 2012. Virtual City Models : Avoidance of Obsolescence. *Education and Research in Computer Aided Architectural Design in Europe-eCAADe*. 1(June 2015):213–224.
- Mourmouris, J.C. & Potolias, C. 2013. A multi-criteria methodology for energy planning and developing renewable energy sources at a regional level : A case study Thassos , Greece. *Energy Policy*. 52:522–530.
- Mülder, J., Säck-da Silva, S. & Bruns, D. 2007. Understanding the role of 3D visualisation: The example of Calden Airport expansion, Kassel, Germany. In *Imaging the future: Geo-visualisation for participatory spatial planning in Europe*, Mansholt publication series 3. R. van Lammeren, A. Van den Brink, S. Däne, & R. van der Velde, Eds. Wageningen: Wageningen Academic publishers. 267–286.
- Mytilinou, V., Kolios, A.J. & Lorenzo, G. Di. 2015. A comparative multi-disciplinary policy review in wind energy developments in Europe. *International Journal of Sustainable Energy*. 36(8): 754 - 774.
- Newman, T.S. & Lee, W. 2004. On visualizing uncertainty in volumetric data: techniques and their evaluation. *Journal of Visual Languages & Computing*. 15(6):463–491.
- O'Brien, R. 2008. Visualising uncertainty in spatial decision support. *Proceedings of the 8th International Symposium on Spatial Accuracy Assessment in Natural Resources and Environmental Sciences, Vol I*. 335–340.
- Ohl, C. & Eichhorn, M. 2010. The mismatch between regional spatial planning for wind power development in Germany and national eligibility criteria for feed-in tariffs-A case study in West Saxony. *Land Use Policy*. 27(2):243–254.
- Pang, A.T., Wittenbrink, C.M. & Lodha, S.K. 1997. Approaches to uncertainty visualization. *The Visual Computer*. 13(8):370–390.
- Panwar, N.L., Kaushik, S.C. & Kothari, S. 2011. Role of renewable energy sources in environmental protection: A review. *Renewable and Sustainable Energy Reviews*.15(3):1513-1524
- Patrizi, P. 2005. Deviant Action and Self-Narration : A Qualitative Survey through ATLAS . ti. *Journal for the Theory of Social Behaviour*.35(2):171-188.
- Patton, M. 2002. *Qualitative evaluation and research methods*. 3rd ed. ed. Thousand Oaks,CA: Sage Publications, Inc.
- Petrova, V. 2014. *Intro to Atlas.ti: Qualitative Data Analysis Software*. Center for Social Science Computation and Research. University of Washington. Seattle.

- Petrovič, D. & Mašera, P. 2005. Analysis of user's response on 3D cartographic presentations. In Proceedings of the 22nd ICA international cartographic conference, A Coruna, Spain.
- Potter, K., Rosen, P. & Johnson, C.R. 2012. From quantification to visualization: A taxonomy of uncertainty visualization approaches. *IFIP Advances in Information and Communication Technology*. 377:226–247.
- Rautenbach, V., Bevis, Y., Coetzee, S. & Rautenbach, V. 2015. Evaluating procedural modelling for 3D models of informal settlements in urban design activities Study area : Slovo Park settlement. *South African Journal of Science*. 111(11):161-170.
- Rautenbach, V., Coetzee, S. & Coltekin, A. 2016. Investigating The Use Of 3D geovisualizations for urban design in informal settlement upgrading in South Africa. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*. 41(July):425–431.
- Retchless, D.P. & Brewer, C. A. 2016. Guidance for representing uncertainty on global temperature change maps. *International Journal of Climatology*. 36(3):1143-1159.
- Richards, D. & Taylor, M. 2015. A Comparison of learning gains when using a 2D simulation tool versus a 3D virtual world: An experiment to find the right representation involving the Marginal Value Theorem. *Computers and Education*. 86:157–171.
- Robinson, A.C., Moore, A.B. & Buckley, A. 2017. Geospatial big data and cartography : research challenges and opportunities for making maps that matter. *International Journal of Cartography*. 3(Supplement 1): 32 - 60.
- Roth, R.E., 2013. Interactive maps: what we know and what we need to know. *The Journal of Spatial Information Science*, 6, pp.59–115.
- Royse, K.R., Rutter, H.K. & Entwisle, D.C. 2009. Property attribution of 3D geological models in the Thames Gateway , London : new ways of visualising geoscientific information. *Bulletin of engineering geology and the environment*.68(1):1.
- Sanyal, J., Member, S., Zhang, S., Bhattacharya, G., Amburn, P., Moorhead, R.J. & Member, S. 2009. A User Study to Compare Four Uncertainty Visualization Methods for 1D and 2D Datasets. *IEEE Transactions on Visualization and Computer Graphics*. 15(6):1421–1430.
- Scott, M. & O'Neill, E. 2013. Displacing wind power across national boundaries or eco-innovation ? Spatial planning implications of UK-Ireland renewable energy trading. *Planning Theory & Practice*. 14(3):418–424.
- Senaratne, H., Gerharz, L., Pebesma, E. & Schwering, A. 2012. Bridging the Geographic Information Sciences. J. Gensel, D. Josselin, & D. Vandenbroucke, Eds. (Lecture Notes in Geoinformation and Cartography). Berlin, Heidelberg: Springer Berlin Heidelberg.
- Shafiee, S. & Topal, E. 2009. When will fossil fuel reserves be diminished? *Energy Policy*. 37(1):181–189.
- Shepherd, I.D. 2008. Travails in the third dimension: A critical evaluation of three-dimensional geographical visualization. In *Geographic visualization: concepts, tools and applications*. V. 36. M. Dodge & M. Turner, Eds. Chichester: John Wiley & Sons. 199–222.

- Sheppard, S.R.J. & Cizek, P. 2009. The ethics of Google Earth: Crossing thresholds from spatial data to landscape visualisation. *Journal of Environmental Management*. 90(6):2102–2117.
- Slingo, J. & Palmer, T.N. 2011. Uncertainty in weather and climate prediction. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*. 369(1956):4751–67.
- Slocum, T.A., Cliburn, D.C., Feddema, J.J. & Miller, J.R. 2003. Evaluating the Usability of a Tool for Visualizing the Uncertainty of the Future Global Water Balance. *Cartography and Geographic Information Science*. 30(4):299–317.
- Smallman, H., Cook, M. & Cowen, M. 2007. Naïve realism in terrain appreciation. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. 1–6.
- Smit, B. 2002. Atlas . ti for qualitative data analysis. *Perspectives in Education*. 20(3):65–76.
- Thomson, J., Hetzler, E., Maceachren, A. & Gahegan, M. 2005. A Typology for Visualizing Uncertainty. In *Visualization and Data Analysis*. V. 5669. 146–157.
- Tsoutsos, T., Tsitoura, I., Kokologos, D. & Kalaitzakis, K. 2015. Sustainable siting process in large wind farms case study in Crete. *Renewable Energy*. 75:474–480.
- Turner, A.K. 2006. Challenges and trends for geological modelling and visualisation. *Bulletin of Engineering Geology and the Environment*. 65(2):109–127.
- Uusitalo, L., Lehtikoinen, A., Helle, I. & Myrberg, K. 2015. Environmental Modelling & Software An overview of methods to evaluate uncertainty of deterministic models in decision support. *Environmental Modelling and Software*. 63:24–31.
- Vasileiou, M., Loukogeorgaki, E. & Vagiona, D.G. 2017. GIS-based multi-criteria decision analysis for site selection of hybrid offshore wind and wave energy systems in Greece. *Renewable and Sustainable Energy Reviews*. 73(January):745–757.
- Wise, J.A., Thomas, J.J., Pennock, K., Lantrip, D., Pottier, M., Schur, A. & Crow, V. 1995. Visualizing the Non-Visual: Spatial analysis and interaction with information form text documents. In *Information Visualization, 1995. Proceedings*. 51–58.
- Wróżyński, R., Sojka, M. & Pyszny, K. 2016. The application of GIS and 3D graphic software to visual impact assessment of wind turbines. *Renewable Energy*. 96:625–635.
- Wu, H., He, Z. & Gong, J. 2010. A virtual globe-based 3D visualization and interactive framework for public participation in urban planning processes. *Computers, Environment and Urban Systems*. 34(4):291–298.
- Zamyadi, A., Pouliot, J. & Bédard, Y. 2014. Towards 3D Metadata for Discovering 3D Geospatial Models. In *Innovations in 3D Geo-Information Sciences*. Springer International Publishing. 267–290.
- Zhang, J. & Goodchild, M. 2002. *Uncertainty in geographical information*. London: CRC press.
- Zhang, Y., Zhu, Q., Liu, G., Zheng, W., Li, Z. & Du, Z. 2011. GeoScope: Full 3D geospatial information system case study. *Geo-Spatial Information Science*. 14(2):150–156.
- Zuk, T. & Carpendale, S. 2006. Theoretical analysis of uncertainty visualizations. In *Proceedings of SPIE*.6060:66-79.

Annex A. Acronyms and abbreviations

2D	Two - dimensional
3D	Three - dimensional
API	Application Programming Interface
DoE	Department of Energy
EURO-CORDEX	World Climate Research Program Coordinated Regional Downscaling Experiment Initiative for Europe
GCM	Global Climate Model
GIS	Geographic Information Systems
GWEC	Global Wind Energy Council
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SAWEP	South African Wind Energy Programme

Annex B. Ethical approval



UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Natural and Agricultural Sciences
Ethics Committee

E-mail: ethics.nas@up.ac.za

Date: 9 June 2016

ETHICS SUBMISSION: LETTER OF APPROVAL

Prof S Coetzee
Department of Geography, Geoinformatics and Meteorology
Faculty of Natural and Agricultural Sciences
University of Pretoria

Reference number: EC160406-012R
Project title: Assessing the effectiveness of 3D uncertainty geovisualisations

Dear Prof Coetzee,

The submission conforms to the requirements of the NAS ethics committee.

You are required to submit annual progress reports no later than two months after the anniversary of this application as indicated by the reference number. The progress report document is accessible on the NAS faculty's website: Research/Ethics Committee.

You are also required to notify the NAS ethics committee upon the completion or ending of the project using the form Project Completed. Completion will be when the data has been analysed and documented in a postgraduate student's thesis or dissertation, or in a paper or a report for publication.

The digital archiving of data is a requirement of the University of Pretoria. The data should be accessible in the event of an enquiry or further analysis of the data.

If you want to submit an amendment to the current project, please use the Amendment form accessible on the NAS faculty's website: Research/Ethics Committee.

Yours sincerely,

A handwritten signature in black ink, appearing to read 'M. P. ...'.

Chairperson: NAS Ethics Committee