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Multi-Criteria GIS Analysis for Siting of Small Wind Power Plants - A Case Study from Berlin

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Supervisors:
Dr. Per Schubert, Lund University

Declaration

I hereby declare that this is my own work, except where otherwise acknowledged, and that it has not been submitted for a degree at this, or any other university.

Laura V. Drews

Data source declaration

Datengrundlage: Informationssystem Stadt und Umwelt (ISU) der Senatsverwaltung für Stadtentwicklung Berlin

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Abstract

One of the main issues to be solved for the 21st century is the energy generation from renewable sources. In particular, wind energy has a large potential and is one of the most advanced technologies currently available. However, in many cases wind energy is restricted to large wind parks with wind power plants often reaching heights greater than 100 m. In areas with high population density such as cities, where many obstacles like buildings are present, the construction of large wind power plants is often problematic. In such areas, small wind power plants are an alternative due to their lower starting wind speeds and higher flexibility in terms of logistics, costs and space-demand. However, small wind power plants are mainly used on roof tops of buildings in European cities, if at all. The capital of Germany, Berlin, can serve as a typical example of this issue's large wind power plants have been declared as unsuitable for the Berlin area. The present study attempts to contribute to small wind power site assessment in Berlin by performing a GIS-based overlay analysis for small wind power plants on free space and in addition on electric power poles, which can serve as supporting towers for small wind power plants. The focus of the GIS-based overlay analysis lies on a safety and performance point of view, including factors such as wind speed for three different power plant heights (10, 20 and 30 m), land use, distance to power line network, safety distance to buildings and wind shed/turbulences distance to buildings. The latter two depend on the regarded wind power plant height. Even though the overlay analysis technique and associated weight criteria (rank and ratio scale based weights) and decision rules (simple additive weighting) used in this study are chosen to be transparent and simple, they have been proven to be useful to investigate the influence of the included assessment factors on suitability.

As a result of the study, we show that up to 9% of the total area of Berlin is suitable for small wind power plants with a height ≥ 20 m. Interestingly, the suitable areas are very scattered throughout the Berlin's area. Furthermore, up to 28% of Berlin's power poles are suitable to serve as constructional bases for small wind power plant rotors. This result is a pointer for other communities to utilise power poles and other pole type structures, such as telephone poles, antennas, etc for the erection of small wind power plant rotors. Finally, the results of this study emphasise the flexibility and potential of unconventional, decentralized wind power generation in cities such as Berlin, especially when compared to large wind power plant farm installations.

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1 Introduction

Carbon dioxide free renewable energy generation is getting more and more important recently, due to on-going climate change by carbon dioxide air pollution as well as decreasing conventional energy resources like fossil fuels. Renewable energy can be generated by using e.g. sun warmth, wind power, geothermal fluid flow, water power, or biochemical crops. In many cases, these renewable energy forms are combined (Angelis-Dimakis et al. 2011).

Wind energy is the fastest growing energy resource worldwide (Balat 2010; Oğulata 2003). Wind energy possesses many advantages which makes it very interesting for the future energy production (GWEC Global wind energy council 2012): First, it does not produce carbon dioxide during its operation, and only produces small amounts of carbon dioxide during manufacture and construction phases. Second, it does not pollute the air compared to fossil fuels, which contribute to air pollution during their combustion. Third, it does not use any water resources, which is important in times when water resource is becoming rare in many regions of the world. In contrast, many techniques helping to generate fossil energy consume lots of water.

In relation to other renewable energy resources, wind energy stands out because of several reasons (Balat 2010): One main advantage is that wind energy is available globally, as wind blows potentially everywhere around the world. Another advantage is that wind energy is relatively cheap in its production and implementation costs. For example, compared to biomass energy (Field et al. 2008), wind energy has the advantage that it does not consume much agricultural space, which is needed for solving other main world problems like food crops production.

Wind energy was one of the first energy sources used in history. Simple wind energy devices were already employed thousands of years ago, which can be proven by archaeological and historical findings like vertical-axis windmills found at the borders between Persia and Afghanistan around 200 BC and horizontal-axis windmills of the Netherlands and the Mediterranean dating back to 1300-1875 AD (Fleming and Probert 1984; Kaldellis and Zafirakis 2011; Musgrove 2010; Pasqualetti et al. 2004). Early civilizations devoted the wind energy resource for sailing ships at sea, for grinding grain in windmills, and for pumping water (Angelis-Dimakis et al. 2011). In 1887-1888, the American engineer Charles F. Brush (1849-1929) invented the first automatically operating wind turbine for electricity generation (Danish Wind Industry Association 2011) in Cleveland, Ohio. Today, the use of wind energy for generating electrical energy is widely spread and many new wind power plants are installed each year worldwide (e.g. Dincer 2011; EWEA The European Wind Energy Association 2009).

In countries with many areas covered by settlements, not much space is available for the construction of large wind power plant parks. Therefore, alternatives are researched and assessed. An example is the implementation of offshore wind power parks at the North Sea (Breton and Moe 2009). The erection of wind power plants at sea is not only a good alternative to searching for free sites on land, but also a good choice in terms of power reliability, as wind speed is higher offshore. In addition to already researched areas for large wind power parks offshore (e.g. Breton and Moe 2009) and onshore (BWE Bundesverband WindEnergie e. V. 2012), more alternatives are needed in order to implement more wind power plants in the upcoming years in Germany.

Cities are densely populated areas, with not much space for implementation of conventional large wind power plants. In large cities like the capital Berlin, only very few areas could be assigned as suitable for siting of large wind power plants (BWE Bundesverband WindEnergie e. V. 2012). An approach to solve these problems in cities is the implementation of small wind power plants (e.g. Ayhan and Sağlam 2012; Free Energy 2012e). Even though small wind power plants are less effective in terms of power production compared to large wind power plants due to their smaller rotor size (Gasch and Twele 2011), they can be a valuable addition (e.g. Free Energy 2012a) to large wind power plants and wind power parks in these areas. Small wind power plants can be erected including bearing substructures, but the small wind rotors can also be placed directly on roofs (Free Energy 2012e), electric power poles (Frey architects 2011; Free Energy 2012b) or in some cases even on trees (Free Energy 2012c). A major advantage of using existing substructures is that their use can reduce construction cost up to 60% and cut down resource consumption (e.g. Free Energy 2012d).

The aim of this study is assessing Berlin's area in terms of potential sites for small wind power plants built on ground or on electric power poles, in order to find out additional possibilities for siting wind power plants in Berlin. The present study is a case study based on Geographical Information Systems (GIS), using weighted and Boolean overlay analysis for a first assessment of potential sites for small wind power plants in Berlin, Germany. To do so, three different ranking scenarios were conducted, and apart from sites for erecting complete small wind power plants, a small sub-study assessing the potential use of already existing overhead electric power poles was included in the present study, too.

2 Background

2.1 Wind power

Wind energy makes up an important part of the energy sources. The increasing importance of wind power is for example depicted in the high increased share of wind energy of total installed power capacity in Europe in the past years. From 2000 to 2011, the partition of wind energy of Europe's total installed power capacity increased from 2% to 10% (EWEA The European Wind Energy Association 2012) (Figure 2.1).

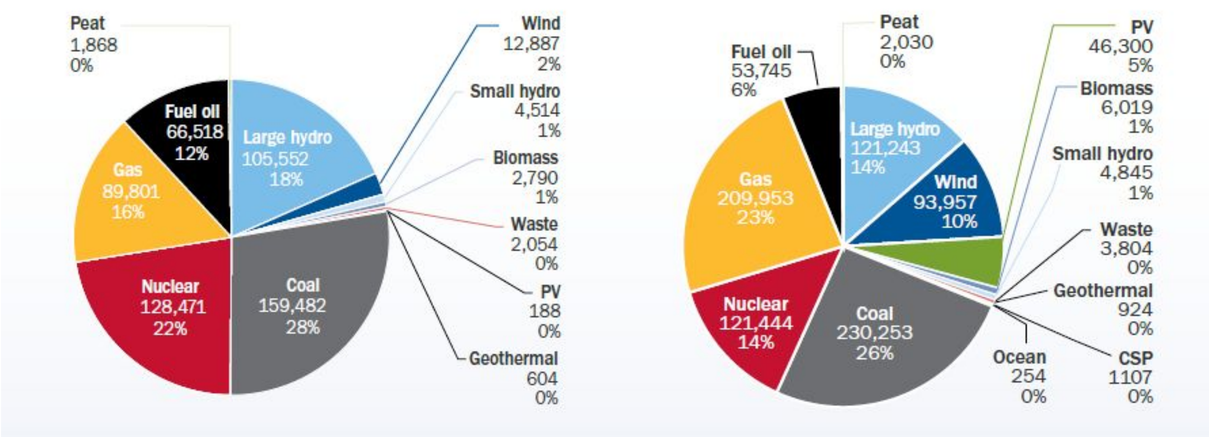

Figure 2.1: Share of wind power of European power capacity for 2000 (on the left) and 2011 (on the right) (EWEA The European Wind Energy Association 2012).

In 2010, Germany was the third strongest wind power nation worldwide, with around 27215 MW total installed wind power and 14% of the market share (BWE Bundesverband WindEnergie e. V. 2011a) (Table 2.1; Figure 2.2).

Table 2.1: Countries with highest total installed wind power (middle table column) and percentage of market share (right table column) (after BWE Bundesverband WindEnergie e. V. 2011a).

Country	Total installed wind power[MW]	Market share [%]
China	42287	21.8
USA	40180	20.7
Germany	27215	14.0
Spain	20676	10.6
India	13065	6.7
Italy	5797	3.0
France	5660	2.9
Great Britain	5204	2.7
Canada	4009	2.1
Denmark	3752	1.9
Rest of the World	26546	13.6
Total	194390	100.0

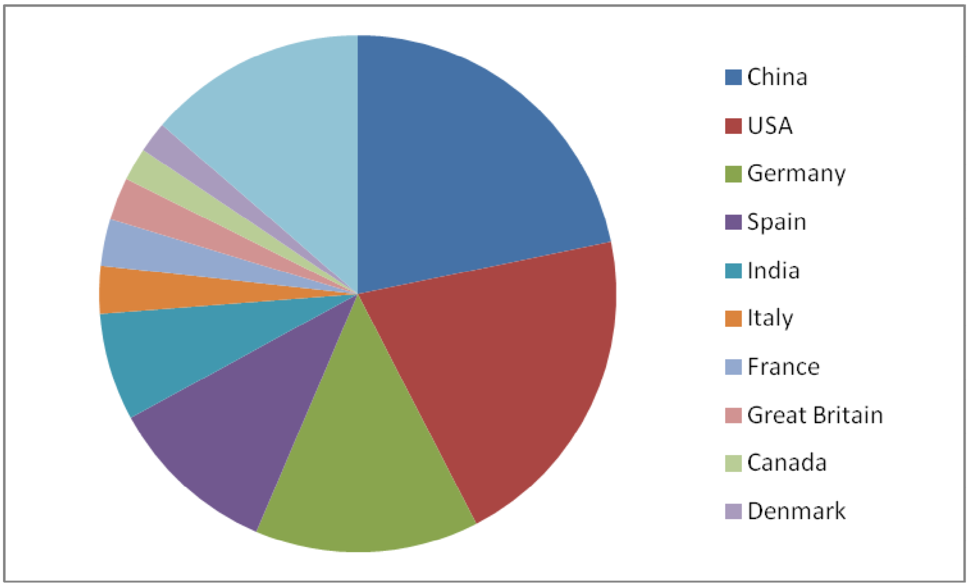

Figure 2.2: Pie chart showing wind power market share of the countries with highest total installed wind power (BWE Bundesverband WindEnergie e. V. 2011a).

Insight into German wind power numbers is given by many international and national wind power associations (Table 2.2) (e.g. BWE Bundesverband WindEnergie e.V. 2011b; EWEA The European Wind Energy Association 2009).

Table 2.2: Wind statistics for Germany 2011(after BWE Bundesverband WindEnergie e.V. 2011b).

Property	**Value**
Total installed power	29060 MW
Newly installed power	2086 MW
Number of plants	22297
Repowering (removed)	123 MW
Repowering (added for removed installations)	238 MW
Newly installed plants	895
Energy yield from plants	48 billion kWh
Share on energy consumption	7.8% (primary assumption)
Potential yearly application of energy	50.7 billion kWh
Avoided CO_2 emissions	36.1 million t

In 2011, 29060 MW total installed wind power existed in Germany. Out of this, 2086 MW were newly installed in 2011. In total, 22297 wind power plants existed in Germany, from which 895 were implemented in 2011. Thereby, 48 billion kWh of power were produced by wind energy devices. The proportion of wind energy on the general energy consumption was 7.8%. A potential annual energy yield of 50.7 billion kWh was designated. Finally, the number of carbon dioxide emissions avoided due to the use of wind power plants was estimated to be 36.1 million tons. In the first half year of 2011, 356 wind power plants were additionally implemented in Germany. The total power of these newly installed wind power plants summed up to about 793 MW of performance (DEWI Deutsches Windenergie Institut 2011).

While the overview above dealt with wind power in general, the following thesis section will highlight some numbers related to small wind power plants in particular. The most important market for small wind power plants is the US. More than 100000 small wind power plants have been in operation in the US in 2009 (EWEA The European Wind Energy Association 2009), ranging from 90 W to 25 kW size, and generating more than 35 MW electrical power (EWEA The European Wind Energy Association 2009). Furthermore, the US market for small wind power plants is growing by around 15% to 20% per year (EWEA The European Wind Energy Association 2009). The UK is the European market leader for small wind power plants. According to the British Wind Energy Association (BWEA), enough small sized wind power plants could be constructed in the UK by 2020 for generation of up to 1300 MW electrical power (Renewable UK 2010). Other upcoming European markets for small wind energy devices and countries contributing much to research and development are e.g. the Netherlands and Portugal.

In Germany, the small wind power plant market is rather small compared to the leading markets. However, no official statistics about small wind power plants in Germany could be made available. Total units installed are estimated to range somewhere between 4000 and 10000 (Kühn 2010). Small wind power projects are performed and applied in several cities like e.g. Freiburg (e.g. Free Energy 2012e) and Berlin (e.g. Berliner Morgenpost 2011a; htw Hochschule für Technik und Wirtschaft Berlin 2012).

Overall, the small wind power economic market sector is promising, with an increasing number of minor companies all around the world. Major companies are also already beginning to enter this wind power market sector (EWEA The European Wind Energy Association 2009).

2.2 Wind power plants

Wind power plants can be divided into large and small wind power plants according to their size (EWEA The European Wind Energy Association 2009). While larger wind power plants are more often and conventionally used, the use of small wind power plants is becoming more important (e.g. BWE Bundesverband WindEnergie e.V. 2011c; EWEA The European Wind Energy Association 2009; Walker 2011). Large and small wind power plants have different fields of applications. Large wind power plants are preferred in many settings, as they are able to generate higher power rates and are therefore more economically viable than smaller wind power plants (EWEA The European Wind Energy Association 2009). However, small wind power plants also possess some advantages compared to larger wind power plants. A main advantage is their ability to generate power at lower wind speeds (Rodman and Meentemeyer 2006).

2.2.1 Small wind power plants

In the present study, the siting of small wind power plants in Berlin is analyzed. This is why small wind power plants will be treated more deeply in the following, while large wind power plants will not be characterized in detail. However, many basic wind power issues are similar for large wind power plants. While large wind power plants are convenient for application in commercial wind power parks (EWEA The European Wind Energy Association 2009), due to their higher energy yield caused by larger rotor size and/or height (see above); small wind power plants are useful devices in remote areas without grid connection (e.g. Fleck and Huot 2009; Renewable UK 2011a, 2012a), on mobile devices like boats (EWEA The European Wind Energy Association 2009) or in areas like cities, where large wind power plants are unsuitable (e.g. BWE Bundesverband Windenergie e.V. 2010). Small wind power plants are also often applied in combination with other energy generation systems (usually solar energy systems), in form of “hybrid systems” (EWEA The European Wind Energy Association 2009). In cities or areas of built settlement, small wind turbines are well applicable e.g. because of their easier logistics compared to larger wind turbines and their higher flexibility in terms of construction area. Small wind power plants “consume” less space and are constructed in settlements near buildings, on buildings' rooftops, and sometimes they are building-integrated (EWEA The European Wind Energy Association 2009). Moreover, it is easier to take safety aspects for small wind power plants into account, as they are smaller in size. Above all, small wind power plants have lower starting wind speeds and can generate power in areas where wind speed is much too low for application of large wind power plants (Rodman and Meentemeyer 2006).

No unique small wind power plant definition does exist, which makes it sometimes difficult to clearly distinguish small wind power plants from larger ones. A summary of small wind power plant definitions in use is given by a German web page focusing on small wind power plants (Das Portal für Kleinwindkraftanlagen 2012).

The most prominent definition criterion of small wind power plants is the output power or capacity. The threshold value, which separates small wind power plants from larger wind power plants, is an output power of 100 kW. Installations with capacities less than 100 kW are therefore called “small” wind power plants. This definition is represented by the wind power associations in Germany, Great Britain and the US (AWEA American Wind Energy Association 2012a; BWE Bundesverband Windenergie e. V. 2011c; Das Portal für Kleinwindkraftanlagen 2012; Renewable UK 2011c).

For the division of small wind power plants into sub-categories, many different definitions do exist (e.g. AWEA American Wind Energy Association 2002; BWE Bundesverband Windenergie e. V. 2011c; Renewable UK 2011c). According to a study published by the German Federation for Wind Energy (Bundesverband Windenergie e.V.), the following classification of small wind power plants according to their output power is proposed (BWE Bundesverband Windenergie e. V. 2011c; Das Portal für Kleinwindkraftanlagen 2012): “Micro wind power plants” are power plants with a performance between 0 and 5 kW, “mini wind power plants” are wind power plants with a performance of 5 to 30 kW, and “middle wind power plants” are defined by their performance between 30 and 100 kW (see Table 2.3).

Table 2.3: Definitions of small wind power plants after BWE (after BWE Bundesverband Windenergie e. V. 2011c).

Name	**Performance**	**Application and network connection**
Micro wind power plant	0 to 5 kW	Private applicants and single family houses; connected to power line network or battery-based insular system
Mini wind power plant	5 to 30 kW	Trade firms and farmers
Middle wind power plant	30 to 100 kW	Trade firms and farmers connected to middle voltage power line network

The German Federation for Small Wind Power Plants (Bundesverband Kleinwindanlagen) argues for another definition, which utilizes the rotor area as main definition criterion. Hereby, installations with up to 200 m^2 rotor area are defined as small wind power plant installations (Bundesverband Kleinwindanlagen 2012; Das Portal für Kleinwindkraftanlagen 2012). This definition is also used in the respective German technical norm (Bundesverband Kleinwindanlagen 2012; Das Portal für Kleinwindkraftanlagen 2012).

Another criterion for the definition and classification of small wind power plants is the height of the installation (Das Portal für Kleinwindkraftanlagen 2012). Combinations of rotor size and tower height for small wind power installations are very variable, as Figure 2.3 shows. In this study the height of a wind power plant is determined as the height above ground at its rotor centre.

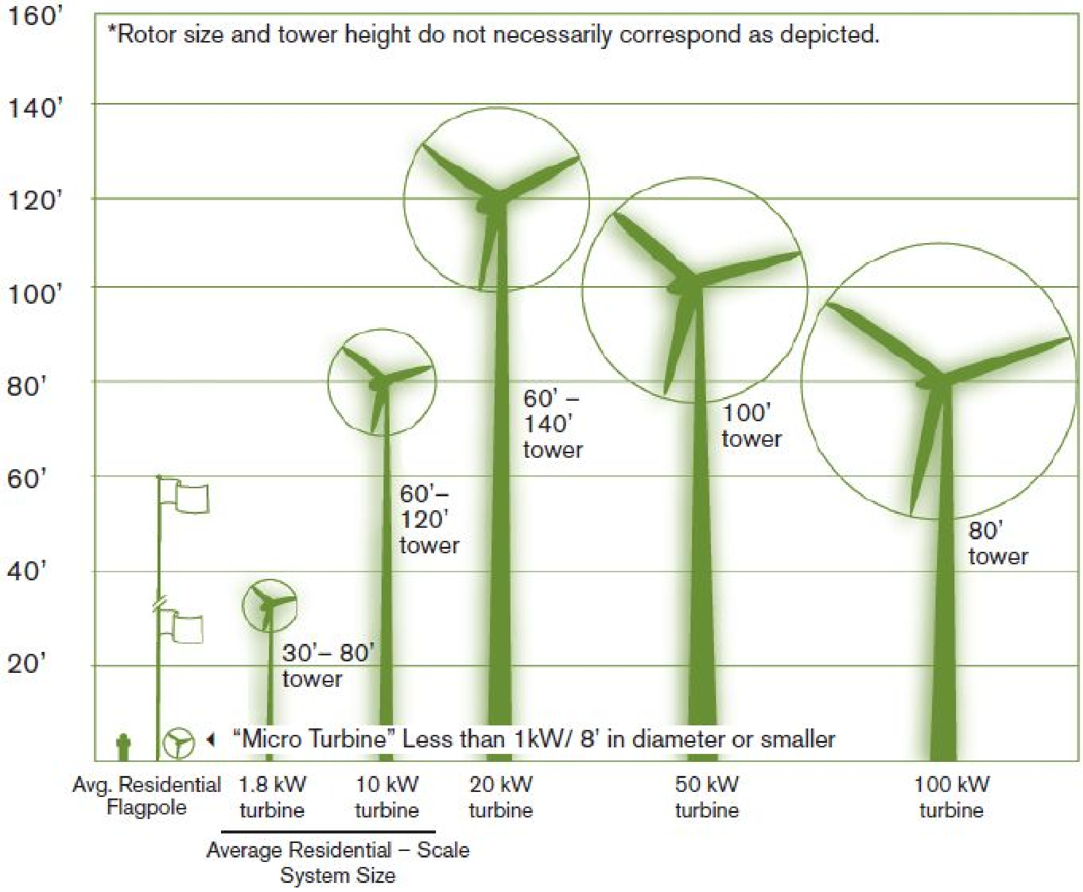

Figure 2.3: Combinations of different wind power pole heights and rotor sizes. Unit: feet (AWEA American Wind Energy Association 2012b).

The main idea driving the design of small wind power plants is the same as for large wind power plants. Electrical power can be generated in many different ways. In every case, a "fuel" or "energy" from a power source is caught by a system, which drives a generator, and the generator feeds the electrical grid. The system that is designed to "catch" the energy is adapted to suit the particular energy or fuel characteristics. In wind-generated electricity, the wind is the fuel, which drives a turbine as catching system, which drives a generator, which generates electrical energy and feeds it into the electrical grid (EWEA The European Wind Energy Association 2009). Hence, an installation for generating wind power usually consists of a wind rotor, a generator for converting mechanical energy into electrical energy, and a supporting structure to which the rotor and generator are attached (e.g. EWEA The European Wind Energy Association 2009). The rotors of most small wind power plants possess three blades. The typical length of the blades is 2-15 feet (AWEA American Wind Energy Association 2012b).

Many different structures can serve as the supporting element of a wind turbine. Classically, tubular steel structures carry the turbine. Not as widely spread, but also in use, are concrete towers, concrete bases with steel upper sections, and lattice towers (AWEA American Wind Energy Association 2012b; EWEA The European Wind Energy Association 2009). Small wind power turbine tower heights are typically 12 to 24 m (EWEA The European Wind Energy Association 2009). Although, small wind power plants can be built including a supporting structure, they can also be installed on already existing structures. Small wind power plants are for example sometimes constructed on rooftops (e.g. Ayhan and Sağlam 2012; Chong et al. 2011; Grant et al. 2008; Ledo et al. 2011; Van Bussel and Mertens 2005).

A relatively new idea is the utilization of already existing supporting structures like power poles (Free Energy 2012b; Frey architects 2011) (Figure 2.4). An advantage of the use of already existing supporting structures compared to "complete" wind power plant architectures are the reduced construction costs (Free Energy 2012d; Frey architects 2011) due to the redundancy to build supporting structures, which normally make up around 60% of construction costs (Free Energy 2012d).

Figure 2.4: Small wind power rotors on power pole (Spiegel Online 2011).

Apart from classification of small wind power plants based on performance, rotor size and tower height, other types of distinctions for small wind power plants do exist. Architectural type distinctions are for example based on orientation of rotor compared to ground. A common small wind power type distinction is the one between horizontal axis and vertical axis small wind power type (e.g. Ayhan and Sağlam 2012; Renewable UK 2010). The horizontal axis small wind power type follows the classical wind power plant scheme with a propeller-shaped rotor rotating horizontally to the ground (e.g. Ayhan and Sağlam 2012). The horizontal axis small wind power type is the most common small wind power type (Ayhan and Sağlam 2012) (Figure 2.5).

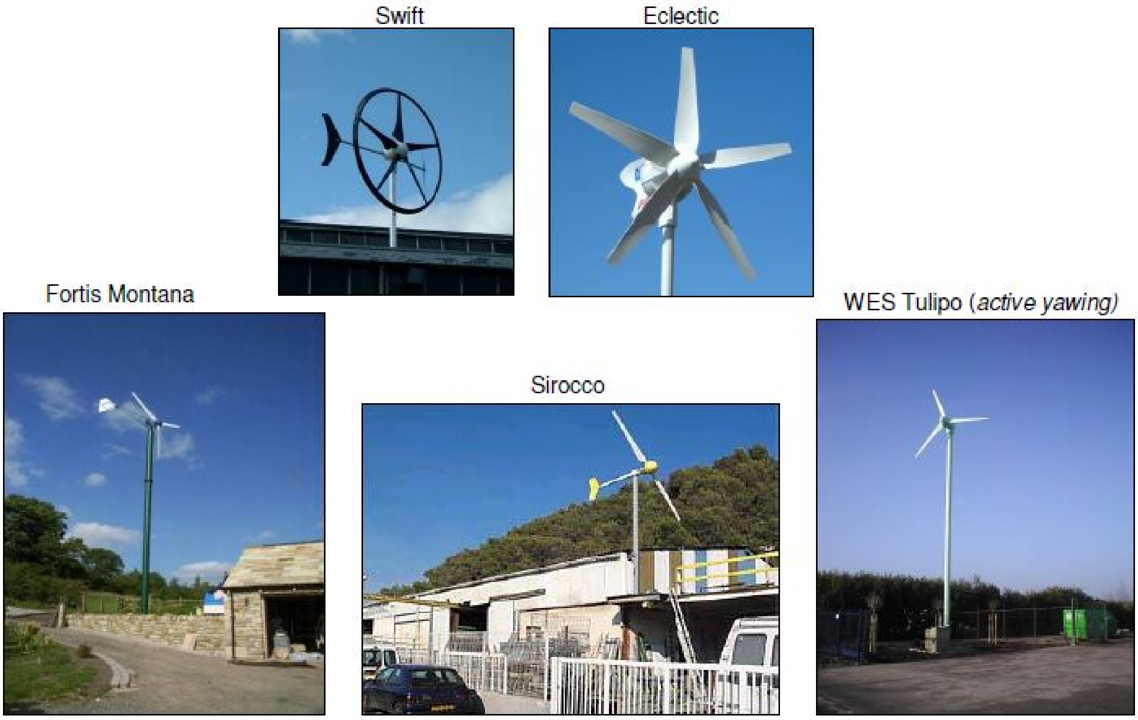

Figure 2.5: Some examples of horizontal axis small wind turbines (Wineur Wind Energy Integration in the Urban Environment 2007).

In the vertical axis small wind power type, the plane of the turbine's rotation is situated vertical to the ground. Instead of the traditional propeller-shaped blade design, vertical axis turbines feature a cylinder-like component (Figure 2.6). The design of this component can be compared to a barbershop pole or to a corkscrew (AWEA American Wind Energy Association 2012b).

Figure 2.6: Some examples of vertical axis small wind turbines (Wineur Wind Energy Integration in the Urban Environment 2007).

However, even more types of small wind power plants do exist (e.g. Wineur Wind Energy Integration in the Urban Environment 2007).

In the present study, it is assumed to use a traditional three-bladed horizontal axis type of small wind power plant as reference. This small wind power plant is representing a very common, traditional type of small wind power plants. Furthermore, it was decided to perform the calculations assuming a rotor diameter of 5 m and a start wind speed of 2.5 m/s. The rotor height is kept variable at 10, 20 and 30 m, respectively (e.g. wind power plant “Fortis Montana” in Figure 2.5; Wineur Wind Energy Integration in the Urban Environment 2007).

2.3 Wind power planning

Planning of sites suitable for erecting wind power plants is a complex procedure, involving the consideration of many different factors and constraints. To name some criteria groups which need to be considered: performance and security, environmental, economic, social, legal and land use criteria. The focus of the present study, however, lies on the consideration of performance and security criteria.

Many studies concern themselves with a range of wind energy development aspects (e.g. Leung and Yang 2012; Ouammi et al. 2012; Saidur et al. 2011; Tegou et al. 2010), from which information about relevant aspects can be obtained. Unfortunately, most of the studies deal with impacts of large wind power plants, and do not estimate impacts of small wind power plants on the environment. Wind power planning case studies based on GIS are a valuable source of background information for GIS planning methodologies and for planning criteria (e.g. Aydin et al. 2010; Baban and Parry 2001; Mari et al. 2011; Ouammi et al. 2012; Rodman and Meentemeyer 2006; Simões et al. 2009; Tegou et al. 2010; van Haaren and Fthenakis 2011).

It is not within the scope of this study to provide an introduction to all wind power planning aspects, but an overview of the most commonly used criteria groups will be given (performance and security, environmental, economic, social, legal and land use criteria). However, there exist other criteria, like e.g. the altitude criterion (e.g. Zhou et al. 2011). Also, other criteria groups are possible. Zhou et al. (2011) for example subsume the distance to roads criterion under the accessibility criteria group, together with the altitude criterion, and not under the economic criteria group, which was used in the present study. Wind resource is often interpreted as an economic criterion (e.g. van Haaren and Fthenakis 2011), but in the present study, it is treated as a performance criterion, as energy output of wind power plants strongly depends on available wind.

2.3.1 Performance and security aspects

In the following, performance and security aspects will be treated in greater detail than the remaining aspects, as these are the main criteria included in this study. In this study, wind speed, wind power plant height and distance to obstacles were the included performance and security aspects into the wind power plant site assessment.

2.3.1.1 Wind speed and power yield

Energy yield of wind power plants depends on wind speed. The sensitivity of energy yield from wind power plants is highly dependent on wind speed variation. Low speed wind sites show greater sensitivity than high speed wind sites (EWEA The European Wind Energy Association 2009). The relationship of power yield and wind speed is not a linear, but a cubic function. Therefore, the power output from the turbine will increase eight times, if the wind speed is doubled (Renewable UK 2012c). Wind power plants usually start their performance at certain “starting wind speeds”, and there are also maximal wind speed thresholds, where wind power plants shut down, because of security reasons (Renewable UK 2012b). For small wind power plants, starting wind speeds are considerably lower than for large wind power plants (e.g. Rodman and Meentemeyer 2006). An example threshold where a large wind power plant would shut down is a wind speed of 25 m/s (EWEA The European Wind Energy Association 2009).

2.3.1.2 Wind speed and height of wind power plants

Wind speed is the most important characteristic for wind power planning (EWEA The European Wind Energy Association 2009; Renewable UK 2012c). For wind power plants to function well, it is also crucial that a certain minimal wind speed is guaranteed most of the time in order to start and maintain wind rotor rotations. In cities, wind speed is considerably lower than in most less densely populated areas, due to turbulences caused by the presence of many obstacles. A factor which influences available wind speed positively is the height of wind power rotors or the wind power plant pole height, as wind speed increases significantly with height.

The change of wind speed with height is documented in the “wind speed height profile” (e.g. Gasch and Twele 2011). The average wind profile can be described by the power law equation after Hellmann like in equation 1 (e.g. Gasch and Twele 2011):

$$\frac{v_1(z_1)}{v_2(z_2)} = \left(\frac{z_1}{z_2}\right)^{\alpha} \qquad \text{Eq. 1}$$

Where $v_1(z_1)$ and $v_2(z_2)$ are the wind speeds at the heights z_1 and z_2. α is the height exponent, which depends on the height z, the roughness, atmospheric layering and topology. Thus, α is only valid for a particular location with respective measured heights z_1 and z_2. A more general description of the wind speed profile, which accounts for the roughness by introducing the roughness length z_0, is given by the logarithmic wind profile (e.g. Gasch and Twele 2011). The logarithmic wind profile can be applied in its usable form (equation 2):

$$v_2(z_2) = v_1(z_1) \cdot \frac{\ln\left(\frac{z_1}{z_0}\right)}{\ln\left(\frac{z_1}{z_0}\right)} \qquad \text{Eq. 2}$$

The logarithmic wind profile allows for calculation of the wind speed v_2 in height z_2 as a function of the measured wind speed v_1 in height z_1 and the roughness length z_0, which is a measure of the roughness structure of the surface. Table 2.4 gives an overview of roughness lengths of the most common surface structures. Other roughness length schemes can be obtained from literature, too (e.g. Tong 2010). The complex behaviour of wind flow and related wind speed in cities has to be kept in mind, and therefore the use of logarithmic wind profile including roughness lengths for a densely built area can only be an approximation. Additionally to the factor that wind speed increases with height, higher situated rotors can be necessary sometimes because of nearby obstacles, in whose wind shadow the rotors would otherwise be placed. A higher supporting structure can help to avoid this constraint and can guarantee better wind speed conditions.

Table 2.4: Typical roughness length z_0 variations for the most common land use surface structures. (after Gasch and Twele 2011).

Land use	**z_0 [m]**
Smooth water bodies	0.0001-0.001
Agricultural land or farmland	0.03
Heather with few bushes and trees	0.1
Forest	0.3-1.6
Suburb, flat building	1.5
City cores	3

2.3.1.3 Wind speed and distance to obstacles

Turbulences and diminished wind speeds caused by obstacles, such as buildings and sharp topological boundaries can have a significant influence on wind power plant performance. Figure 2.7 shows the development of wind turbulences, which can be induced by obstacles. Thus, certain zones around natural obstacles (EWEA The European Wind Energy Association 2009), buildings (e.g, Baban and Parry 2001) or even residential areas and settlements (e.g. Krewitt and Nitsch 2003; van Haaren and Fthenakis 2011) should be avoided in wind power planning.

In addition to the constraint of diminished wind speed or wind shadowing, security aspects can demand for the compliance of wind power plant free zones around high and low obstacles like buildings, roads, railway or airports (e.g. Aydin et al.2010; Hansen 2003; Ouammi et al.2012; Phuangpornpitak and Tia 2011; Voivontas et al.1998). The free areas guarantee that e.g. people living in buildings are not in danger if e.g. ice falls down from rotors in winter (e.g. van Haaren and Fthenakis 2011).

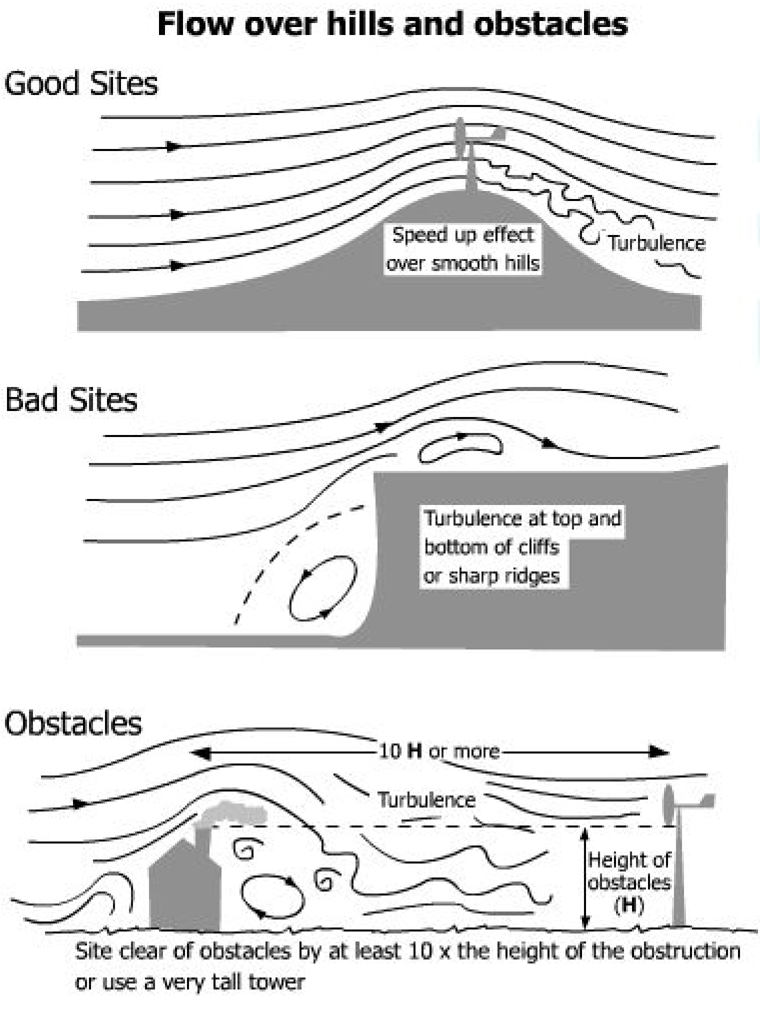

Figure 2.7: Wind turbulences caused by wind flow over hills and obstacles (Renewable UK 2011b).

2.3.1.4 Wind direction

At any site, wind blows from a certain (main) direction more often than from other directions, which is sometimes taken into consideration in wind power siting studies (e.g. van Haaren and Fthenakis 2011; Gasch and Twele 2011). This is especially interesting for planning of wind power parks, as single plants can be better sited in a way that they do not lessen the performance of other wind power plants. Knowing wind direction helps to avoid wind shadowing effects caused by wind turbines (Gasch and Twele 2011).

2.3.1.5 Slope

Underlying ground should not be too steep, in order to guarantee securely positioned wind power plants. Consequently, many planners try to avoid steep slopes in their wind power planning process (e.g. Ouammi et al. 2012; Voivontas et al. 1998). Slope is not included in this study.

2.3.2 Environmental aspects

Wind power plants are not only showing many positive environmental impacts, but do also possess some negative environmental influence (e.g. Leung and Yang 2012), such as noise, visual impact, shadowing caused by rotors and electromagnetic interference. Good overviews over environmental aspects in wind power planning and erection are given e.g. by Tegou et al. (2010) and Saidur et al. (2011). Much research and development is performed in order to assess and minimize the negative environmental aspects of wind power plants, and much progress has been attained (e.g. EWEA The European Wind Energy Association 2009).

Acoustic noise effects caused by moving wind power plant rotors (e.g. Kaldellis et al. 2012; Saidur et al 2011; Son et al.2010) are considered in many wind power planning studies (e.g. Cavallaro and Ciraolo 2005). A good summary of acoustic noise aspects in wind power planning is given by Leung and Yang (2012). Two different sorts of noise effects can be caused by wind power plants: mechanical and aerodynamic noise (Leung and Yang 2012; Torrance and Goff 2009). Some authors consider aerodynamic noise to be a critical aspect, causing stress symptoms like headaches (Leung and Yang 2012; Pedersen 2011), or sleep disturbances and hearing loss (Leung and Yang 2012; Punch et al. 2010). Son et al. (2010) think that noise effects are reduced by obstacles in the propagation path, which could be a positive aspect for reduced noise effects with small wind power plants in obstacle-rich areas like cities. In order to minimize acoustic noise effects, wind power plants can be implemented at certain distances from areas sensitive to loud noise, e.g. by the means of drawing isophones (lines marking zones of certain acoustic noise) around areas with wind power devices (Gasch and Twele 2011).

The negative visual impact of wind power plants on landscapes, city skylines, or cultural heritage like archaeological sites is a problem dealt with in many wind power planning studies (e.g. Bishop and Miller 2007; Jerpåsen and Larsen 2011; Möller 2006; Molina-Ruiz et al. 2011; Voivontas et al. 1998). If possible, wind power planning should aim to keep visibility of wind power plants as low as possible, especially close to heritage sites (Voivontas et al.1998).

Negative impact of wind power plants on birds is discussed. While many researchers conclude a negative impact of wind power plants on birds (e.g. Carrete et al. 2012; Dahl et al. 2012), others question this influence (e.g. Farfán et al. 2009 for birds mortality; Marris and Fairless 2007). Typical negative effects of wind power plants related to birds are: collision of birds with power plant architectural elements causing death or injury; displacement of birds from their preferred habitat which can lead to reduced breeding success; interference with birds' movements e.g. for wintering; as well as reduction or loss of overall habitat (Dahl et al. 2012; EWEA The European Wind Energy Association 2009; Farfán et al. 2009). Apart from negative impact of wind power plants on birds, the influence of wind power plants on other animal habitats and migration routes is also considered in some studies concerned with environmental impact of wind power (e.g. Saidur et al. 2011).

Wind power plants can generate “shadow flickering“-effects, caused by rotating rotors and/or reflected sunlight, that negatively influence nearby living people (EWEA The European Wind Energy Association 2009; Saidur et al. 2011). It is possible to plan wind power plant single devices or parks by drawing isolines (lines of same value) of shadowing duration in hours per year around the power plants, in order to trying to avoid nearby living people being affected by shadow flickering effects (Gasch and Twele 2011).

Electromagnetic interference (EMI) is a criterion sometimes considered when it comes to wind power planning (e.g. Baban and Parry 2001). EMI is any type of interference, which is able to disrupt, interfere with or degrade the effective performance of electronic devices (EWEA The European Wind Energy Association 2009). Wind power can create EMI e.g. by obstructing, reflecting or refracting electromagnetic waves (EWEA The European Wind Energy Association 2009). An example for application of EMI criterion in wind power planning is siting of wind turbines away from the line-of-sight of broadcaster transmitter, in order to diminish TV interference (EWEA The European Wind Energy Association 2009).

In terms of the planning of wind power plants in nature reserves, it is recommended to investigate nature reserves including site-specific and species-specific criteria, in order to find out whether the reasons for which the nature reserve was defined are not affected by negative impact of the wind power plants (EWEA The European Wind Energy Association 2009).

In this study, natural reserves and water bodies have been accounted for as environmental aspects.

2.3.3 Economic aspects

Economic aspects have to be treated or integrated in more or less every wind power planning procedure at some time of the process, and a variation of economic criteria can be assessed in power planning (e.g. Arnette and Zobel 2011). Typical economic aspects dealt with in wind power site assessments are access to roads and access to power line network (e.g. van Haaren and Fthenakis 2011). A good access to nearby located roads can reduce power plants logistics and construction costs, and a good access to power line network diminishes costs for cable connections from power plant to energy distribution network (van Haaren and Fthenakis 2011). Access (distance) to power line networks has been included as an economic aspect in this study.

2.3.4 Social aspects

In populated areas, wind power with all its positive and negative contributions is a controversially discussed issue and wind power planners have to pay attention to people's opinion (e.g. Graham et al. 2009; Jobert et al. 2007; Jones and Eiser 2009, 2010; Meyerhoff et al. 2010; Musall and Kuik 2011; Pasqualetti et al. 2011; Warren and Birnie 2009; Wolsink 2000). A good overview of social aspects in (general) power planning is given by Ribeiro et al. (2011), who derive from their literature review that quantitative methods are predominant choice of methodology when assessing social criteria. In terms of assessing social criteria, the objective is finding out how people's opinion towards implementation of wind power devices can be changed for the better, either by avoiding negative aspects, or by implementing positive aspects. Typical aspects influencing peoples opinion on wind power planning are e.g. wind power device's impact on view or landscape (e.g. Meyerhoff et al. 2010), land ownership-participation (Brannstrom et al. 2011) or community co-ownership (Musall and Kuik 2011). The perceived visual impact of wind power plants on landscape view has been identified as the most influential factor influencing people's opinion towards wind energy implementation (after Musall and Kuik 2011; Toke et al. 2008; Warren et al. 2005). As a social aspect, cemetery locations have been considered in this study.

2.3.5 Legal aspects

Legal aspects are also important when it comes to wind power planning (Gasch and Twele 2011). For construction of more than two large wind power plants with heights above 50m, German national emission law "Bundes-Immissionsschutzgesetz" (Bundesministerium der Justiz and juris GmbH 2012) dictates in most cases an inspection of environmental influence like noise emissions (e.g. Gasch and Twele 2011).

In contrast, no consistent legal framework for small wind power planning does exist in Germany. For small wind power plants, German federal states give legal recommendations, which are not obligatory, but it is better to take them into consideration (e.g. Gasch and Twele 2011). No legal recommendations for small wind power plants in Berlin were accessible from usual sources like literature. However, from Berlin's building code, a regulation covering the construction of buildings or built structures close to buildings was obtained (Senatsverwaltung für Stadtentwicklung Berlin: Oberste Bauaufsicht 2011). This regulation can be found in § 6 and says that the distance of buildings or built structures to other buildings should be at least 0.4 times the height of the building or built structure, which yields to equation 3:

$$0.4 \cdot (h_{structure}) = 0.4 \cdot (h_{wpp}) = 0.4 \cdot (h_{pole} + r_{rotor}) \quad \text{Eq. 3}$$

Where $h_{structure}$ is the height of any built structure named in the Berlin building code, h_{wpp} is the height of the wind power plant to be erected, which is calculated by the sum of the wind power plant pole h_{pole} the rotor radius r_{rotor}.

Because of the complex nature of this issue and little accessible information related to small wind power regulations in Berlin, legal aspects will only be dealt with by inclusion of the safety distance to buildings in the present study.

2.3.6 Land use aspects

Land use aspects are treated separately, as they interfere with more than one of the above listed aspect groups. Land use aspects include nature reserves which can be subsumed under environmental aspects, while other land use classes like cemeteries and the ethical motivated choice of not building wind power plants there can be subsumed under social aspects.

2.4 Planning tools and methodologies

2.4.1 GIS as wind power planning tool

Recently, GIS have become more and more popular as a assessment tool in renewable energy management and planning (e.g. Janke 2010; Mondal and Denich 2010; Tiba et al. 2010). Apart from their visualization possibilities, GIS are also useful system tools for geographical analysis. A GIS consists of hardware and software. The system facilitates the acquisition, management, manipulation, analysis, modelling and visualization of spatially referenced data. By the means of GIS systems, available information can easier be accessed, and various input data can be combined for generating new information. Thereby, GIS help endorsing complex planning and management problems by supporting problem-solving in complex environments where many spatially referenced data have to be integrated (Carrion et al. 2008; Tegou et al. 2010; Tiba et al. 2010). In some GIS studies, wind power planning issues are investigated together with other renewable energy resources, mostly for getting an overview of the general renewable energy potential of an area (e.g. Arnette and Zobel 2011; Belmonte et al. 2009). In other GIS publications, wind power planning issues are analyzed alone without any other renewable energy resource (e.g. Tegou et al.).

GIS are useful for assessing areas in terms of suitable locations for constructing wind power plants. GIS manage to integrate many aspects in the wind power planning process. GIS systems help to bring a range of spatial criteria together, in order to define locations where wind power plants could be successfully implemented. The appropriateness of GIS systems for locating wind power plants has been shown e.g. by Baban and Parry (2001). In studies investigating wind power only, GIS are either applied with focus on spatial wind characterization in wind energy potential studies (e.g. Hillring and Krieg 1998; Palaiologou et al. 2011), or for site assessments using given wind values (e.g. Baban and Parry 2001). Combinations of these two main study types are also possible. Zhou et al. (2010), for example, first construct a wind power map using meteorological data and then use GIS for performing a site assessment combining the wind power map with additional information. The majority of GIS studies related to wind power planning deal with finding suitable locations for wind power implementation (Baban and Parry 2001; Lejeune and Feltz 2008; Tegou et al. 2010), either for large-scale implementations like wind power parks, or for single wind power plants.

GIS are very often applied in wind power site investigations as “(spatial) decision support systems” ((S)DSS) (e.g. Aydin et al. 2010; Lejeune and Feltz 2008; Malczewski 1999; Mari et al. 2011), or even "environmental decision support systems" (EDSS) (e.g. Ouammi et al.2012). DSS describe systems that help in finding a decision in a problem solving process. In DSS, different "what-if" planning scenarios can be investigated, each focusing on other wind power planning aspects and interests (e.g. Mari et al. 2011). EDSS are a special application of DSS with focus on environmentally relevant decisions (e.g. Ouammi et al. 2012). Furthermore, "multi-criteria analysis" (=MCA) or "Multi-criteria decision making" (=MCDM) and "overlay analysis" are GIS-based strategies often applied in wind power planning site assessments (Aydin et al. 2010; Malczewski 1999; Tegou et al. 2010). All three strategies concern themselves with the integration of multiple criteria in a GIS analysis process.

2.4.2 Overlay analysis

In an overlay analysis, several datasets are "overlaid", in order to produce one output raster. Overlay analysis in GIS can be compared to an overlay of paper maps with the motivation to draw one resulting map combining criteria from the input paper maps. Thereby, overlay can serve for identifying specific locations or areas that possess a certain set of attribute values—that is, match the specified criteria. Overlay approach is often employed for finding locations which are suitable for a particular use, such as wind power generation, or which are susceptible to some risk (ArcGIS Resource Center 2012).

In general, two methods of overlay analysis do exist: feature overlay (overlaying points, lines, or polygons) and raster overlay (overlaying raster datasets). For certain types of overlay analysis, one or the other of the two overlay methods is more suitable. Overlay analysis for identifying locations meeting certain criteria is in many cases best done using raster overlay (but it can also be done using feature data) (ArcGIS Resource Center 2012).

In raster overlay, the fact that each cell of each layer references the same geographic location is used. Raster overlay is well suited for combining characteristics of numerous layers into one single layer. Normally, numeric values are assigned to each characteristic. This is allowing a mathematical combination of the layers and an assignment of a new value to each cell in the resulting output layer (ArcGIS Resource Center 2012). An example of raster overlay performing an addition can be found below (Figure 2.8). Two input raster datasets were added together for creation of an output raster. In the output raster, the values for each cell are summed.

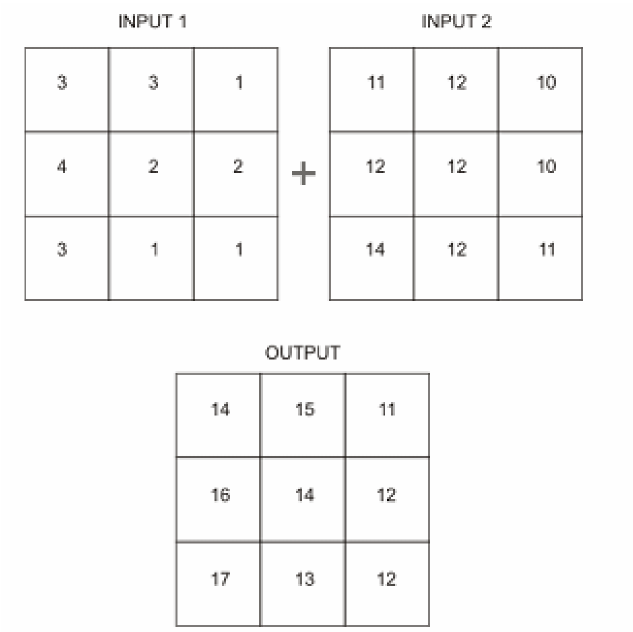

Figure 2.8: Raster overlay operation scheme. Two input raster datasets (INPUT 1 and INPUT 2) are overlaid to generate one output raster (OUTPUT) (ArcGIS Resource Center 2012).

The overlay methodology approach often includes ranking attribute values by suitability or risk and then summarizing these attributes. Since the input criteria layers are likely to possess different numbering systems with different ranges, to combine them in a single analysis, each cell for each criterion must be reclassified into a common preference scale. A common reference scale can e.g. be a scale reaching from 1 to 10, with 10 being the most favourable range, or e.g. 0 to 1, with 1 being the most favourable range. The preference value scale can be a linear scale. In this case, a preference of 10 is twice as preferred as a preference of 5 (ArcGIS Resource Center 2011).

In addition, the preference values should not only be allocated relative to each other within the layer, but also between the layers. To give an example: if a location for one criterion is allocated a preference of 5, then this criterion will have the same influence as another criterion with a preference of 5 (ArcGIS Resource Center 2011). However, it is possible to assign a relative importance to each of the various ranked layers of a "simple" overlay analysis, in order to create a weighted ranking. The ranks in each layer are then multiplied by that layer's weight factor before being added to the other layers. This special overlay analysis variant, where relative weights are assigned to each of the various layers, is called "weighted overlay analysis" (ArcGIS Resource Center 2011)¸ "weighted linear combination" (WLC) (Malczewski 1999), or "simple additive weighting" (SAW) (Malczewski 1999). The steps of the simple additive weighting method (Malczewski 1999) are as follows:

- Definition of a set of evaluation criteria (map layers) and a set of the feasible scenario alternatives.
- Standardization of each criterion map layer.
- Definition and assignment of criterion weights that are reflecting the relative importance of each criterion map.
- Construction of weighted standardized map layers by multiplying standardized map layers by the corresponding weights.
- Generation of overall score for each location (ranked raster cell) using overlay operation for summarizing the weighted standardized map layers.
- Ranking of the locations according to their overall performance score: the location with the highest score rank is the best location (alternative).

Equation 4 shows, how each alternative *A* can be evaluated (Malczewski 1999):

$$A_i = \sum_j w_j x_{ij} \qquad \text{Eq. 4}$$

Where x_{ij} is the score of the i^{th} location with respect to the j^{th} attribute. The weight w_j is a normalised weight, so that $\sum w_j = 1$. The weights are representing the relative importance of the attribute criteria. The most preferred location is selected by figuring out the maximum value of A_i with $i = (1,2,\ldots,m)$. Thereby, m is the number of locations. Various methodologies to estimate weights are available. In this study two methods were chosen, namely the ranking (by rank sum weights) and the rating method. The ranking method requires straight ranks which are assigned to the respective parameters of the overlay operation based on their importance. Hereby, the most important criterion receives the rank 1, where the least important criterion receives the rank n, where n is the number of criteria (equation 5). The weight for each criterion is then obtained by:

$$w_i = \frac{n - r_i + 1}{\sum (n - r_j + 1)} \qquad \text{Eq.5}$$

Where w_i is the normalised weight for the i^{th} criterion, n is the number of criteria with ($j = 1,2,\ldots,n$) and r_i is the rank of the criterion (Malczewski 1999).

The rating method follows the same procedure as the ranking method with an intermediate step, where ratio scales (e.g. integer values from 0-100) are assigned according to rated ranks. Hereby, the most important criterion receives the highest ratio scale and the least important criterion receives the lowest ratio scale. The final weights are then received by normalization (Malczewski 1999). The difference to the ranking method is that the importance of different criteria is not confined by straight or linear ranks (1,2,3,...), but can be assigned with respect to the importance of the particular criteria (e.g. 1, 15, 30, 100). Other methods to estimate weights, such as the pair-wise comparison method, which utilizes a comparison matrix of the individual parameters to compute weights (Malczewski 1999), involve more sophisticated, but also more complex procedures.

Also, different overlay operation types, or decision rules, than the SAW method have been developed (see Malczewski 1999 for a comprehensive review). One example, which is similar to the SAW method is the fuzzy additive weighting method (FSAW). As in the SAW method, weighted average is utilized as the aggregation operator in FSAW, but in contrast to SAW, FSAW operates on fuzzy data. Hence, the entries of the decision matrix and weights are specified using fuzzy numbers in FSAW (Malczewski 1999). Thereby, FSAW allows for transferring linguistic terms like "moderately important" into fuzzy numbers. Therefore, FSAW can be especially useful, when complex criteria need to be analyzed that cannot easily be converted into crisp scores. In addition, FSAW can cover a range of weights, which are defined by the fuzzy set membership function, for each regarded parameter.

Nevertheless, it is not guaranteed that other weight estimation methods and decision rules, such as pair-wise comparison method and FSAW, provide a significantly more accurate estimate of the weights than ranked and ratio scale based weights together with SAW. Ranked and ratio scale based weight estimation methods allow for high flexibility (e.g. changing importance of criteria) and are relatively simple to be employed. The same is valid for SAW, which has been used in this study. FSAW might have given a more comprehensive view on the influence of individual parameters, but would have required a complex setup of a decision matrix to estimate weights. In wind power planning site assessment, a typical criterion translated into a ranked raster is wind speed criterion, where lower wind speed values are usually ranked lower than higher wind speed values, as they are less suitable (e.g. Rodman and Meentemeyer 2006).

Apart from weighted overlay analysis, "Boolean overlay" is a commonly applied GIS multicriteria decision analysis method (Figure 2.9) (Malczewski 1999). Weighted and Boolean overlay analysis are often combined in order to detect sites for wind power developments (e.g. Griffiths and Dushenko 2011). Boolean overlay is a methodology based on Boolean algebra. The presence of a criterion is denoted by 1, and the absence of a criterion is denoted by 0. There are three basic Boolean or logical operators (Malczewski 1999):

- Intersection: the logical AND
- Union: the logical OR
- Complement: the logical NOT

The logical AND can be applied as multiplication in overlay analysis, and the logical OR can be translated to addition operations in overlay analysis. The NOT operation is an inversion, and can be translated for overlay analysis by generating a layer containing values of 1s and then performing a subtraction (Malczewski 1999). If two Boolean raster datasets are combined using an AND operator by multiplying the layers, the resulting layer will contain values of 1 where both input layers contain values of 1, and values of 0 where either one or both of the input layers contain a 0, as the product of a number unequal 0 with 0 is always 0 (Malczewski 1999).

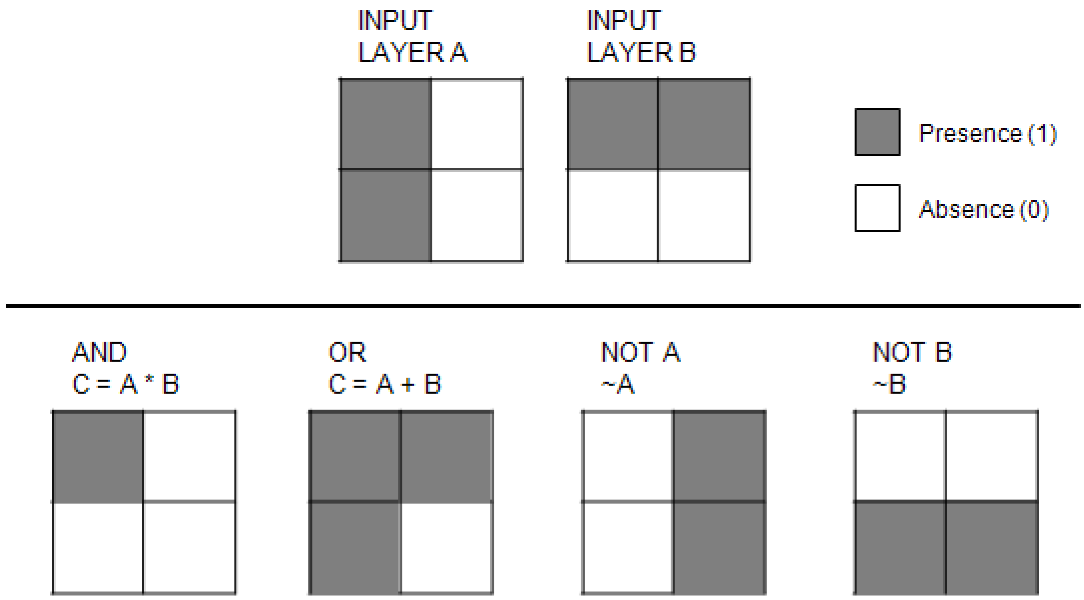

Figure 2.9: Boolean overlay operations scheme for two input layers (after Malczewski 1999).

Boolean overlay analysis is a useful methodology for assessing areas in terms of suitability for wind power development (e.g. Griffiths and Dushenko 2011). Boolean raster datasets are used for clipping away overall unsuitable areas (Boolean value = 0) from the study area

(Griffiths and Dushenko 2011). The resulting raster of the Boolean AND overlay multiplication only includes suitable areas, that means areas which do not possess the respective unsuitability criterion. An example for a criterion typically translated into a Boolean raster with criterion value equal to 0 in wind power planning site assessment is the criterion of nature conservation area (e.g. Krewitt and Nitsch 2003).

Before being able to assign the ranks or Boolean values, data often have to be processed and some data preparation steps have to be conducted. The data preparation steps can be simple, like conversions from vector to raster data, but they can also be more complex, like e.g. view shed analysis, which is utilized for estimating impact of wind power plants influence on landscape view (e.g. Möller 2006). In many cases, buffer zones are created during data preparation, in order to transmit e.g. distances to obstacles or security zones into data layers (e.g. Lejeune and Feltz 2008). These buffer zones can then be converted to Boolean rasters, in order to exclude certain areas from the study area in the overlay process. Among safety and wind shadow zones around obstacles like buildings, safety zones for protecting birds using buffers (e.g. van Haaren and Fthenakis 2011) are also a common wind power planning constraint, as well as zones around wild animal migration routes, which also can be translated into buffer zones (e.g. Ouammi et al. 2012).

2.5 GIS wind power planning studies

The following chapter aims to give an overview over what GIS wind power planning studies can be composed of, which choice of criteria and criteria combinations they contain, and also which methodologies can be combined. To do so, some relevant publications are reviewed.

A GIS-based environmental assessment of wind energy systems applied in Western Turkey has been presented by Aydin et al. (2010). The focus of this study lies on the assessment of environmental objectives related to wind power plant performance using weighted combination of fuzzy sets in a multi-criteria decision process. Thereby, crisp environmental criteria were transferred to fuzzy sets (Aydin et al. 2010). Some examples of the crisp criteria used in Aydin et al. (2010) are: 1000 m away from areas of ecological value; 400 m away from water bodies; 250 m away from ecologically sensitive areas; 2000 m away from large settlements; 2000 m away from cities or urban centres; at least 500 m away from wildlife conservation area; 300 m from nature reserves to reduce risk to birds.

The article "A Methodology for the Identification of the Sustainable Wind Potential. A Portuguese Case Study" by Simões at al. (2009) is interesting for the present study, as it is a

GIS case study dealing with site assessment for wind power sites. It is especially useful because of the methodology of site assessment for wind power planning using GIS that is described. The methodology is transferable to other countries and regions. The article deals with the development of planning tools for the siting of wind power plant parks in Portugal. The methodology presented can be described as follows: The first part is the spatial continuous mapping of the wind resource, usually named "wind atlas". The second part contains the identification of relevant constraints to wind power construction in certain areas, like e.g. land use classification, environmental restrictions, electric grid capacity and its voltage level, terrain slope, roads, railways and other communication networks. The third and final step is the application of GIS to combine the wind atlas and constraints in order to produce a geo-referenced map of regions adequate for wind power plant deployment. Concerning the datasets used for the methodology, the "wind energy resource" dataset can be differentiated from the "classes of criteria for terrain". According to the methodology described, classes of criteria for terrain are excluded from the wind energy resource dataset during the workflow.

The article "Developing and applying a GIS-assisted approach to locating wind farms in the UK" by S. M. J. Baban and T. Parry (Baban and Parry 2001) is also useful for the present study as the methodology applied is very similar to the standard methodology of weighted overlay analysis (ArcGIS Resource Center 2012). A lack of coherent national criteria for locating wind farms in the UK has been diagnosed by the use of a questionnaire targeting public and private sectors. The questionnaire and available published literature have been used for the development of simple GIS-assisted wind farm location criteria for the UK. These criteria have been applied in a GIS performing two different methods of combination of layers for a site in Lancashire, UK. In the first method, all layers have been considered as equally important and consequently, all layers have been given the same weight in the overlay analysis. In the second method, the layers have been grouped and weighted according to perceived importance (weighted overlay analysis). The outputs have been composed of classes from 0 to 10, where 0 represents the most suitable and 10 represents the least suitable location.

The article "A geographic analysis of wind turbine placement in Northern California" by Rodman and Meentemeyer (2006) was chosen, because of the methodology applied. The methodology is again close to the “classical” weighted overlay analysis (for example: ArcGIS Resource Center 2012). The article is similar to the former article by Baban and Parry (2001). Additionally to conventional large wind power plants, small wind power plants are included in the analysis, too. This has been done by developing three separate Boolean raster datasets, one for a large wind turbine with a average annual/starting wind speed of 7 m/s, and two raster datasets for small wind turbines with starting wind speeds of 4.5 m/s and 3 m/s respectively.

3 Study area

The study area is Berlin, the capital city of Germany. Berlin is not only a city, but as a city-state it is also a federal state of Germany. Berlin is the centre of the metropolitan region Berlin-Brandenburg and is located in North-Eastern Germany (52°31’N, 13°24’E) (Figure 3.1).

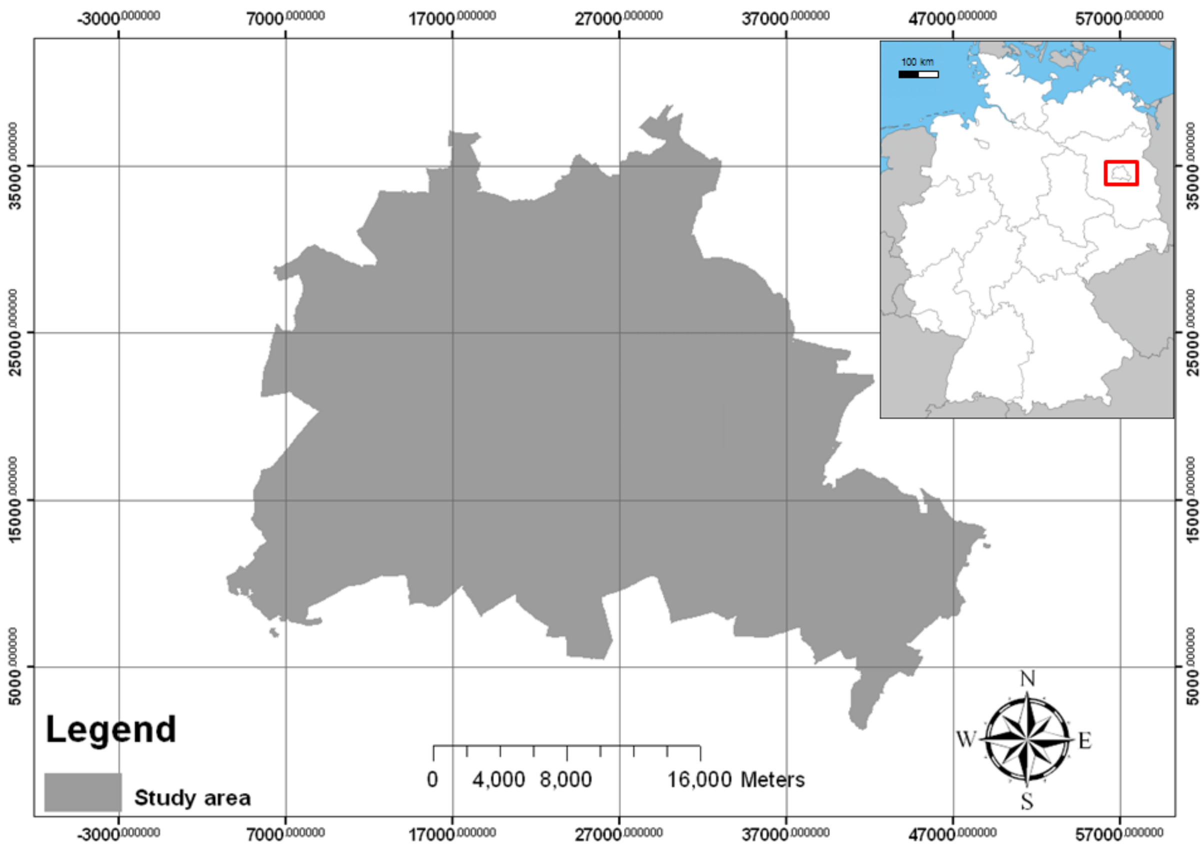

Figure 3.1: Berlin study area and location of Berlin in North-Eastern Germany (small figure; after Dalet, 2012). Here, the study area is referenced with a grid relative to the study area extent.

In 2010, Berlin comprised 892 km^2, had a population of 3460725 people, resulting in a population density of 3880 people per square kilometre in 2010 (Amt für Statistik Berlin-Brandenburg 2012). As a metropolitan centre, Berlin is a densely built area. Thus, the general wind potential is low to average because of turbulences and wind shadows caused by buildings and other obstacles.

A study analyzing onshore wind power plant potential in different federal states of Germany (BWE Bundesverband WindEnergie e. V. 2012) shows that only very few Berlin areas are assigned as suitable or usable for constructing conventional wind power plants (Figure 3.2). Compared to other regions in Germany, for example Bavaria or Niedersachsen, only a very little area has been assigned as suitable for implementation of large wind power plants, even in relation to the overall available area (Figure 3.2).

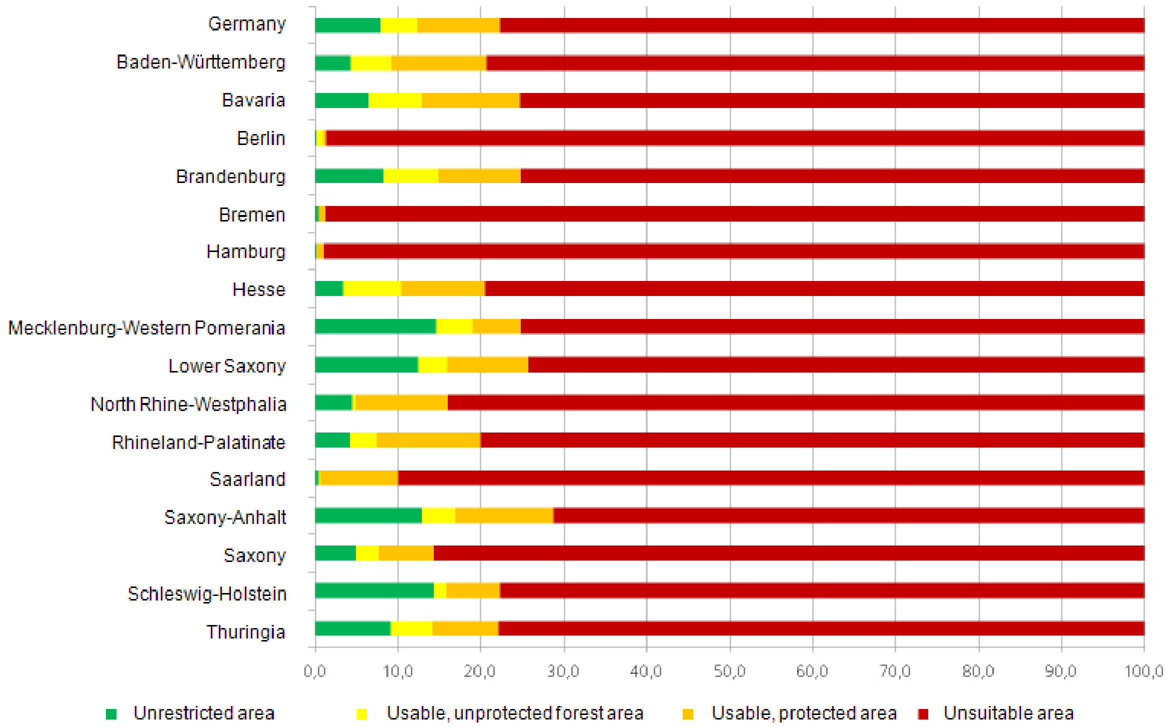

Figure 3.2: Relative areas useable for wind power implementation for each German county in percent (modified after BWE Bundesverband WindEnergie e. V. 2012).

Only one single large wind power plant has been implemented in Berlin so far, and for a second one, it is not clear, whether it will be implemented or not (Berliner Morgenpost, 2011b). In contrast, around 50 small wind power plants have been implemented in Berlin until 2010 (BWE Bundesverband Windenergie e.V. 2010). There are several reasons, why Berlin is rated to be unsuitable for the implementation of large wind power plants:

- Large wind power plants need a relatively high wind speed in order to function well (EWEA The European Wind Energy Association 2009).
- Due to dense building, population and infrastructure enough safety distance of large wind power plants to obstacles cannot be guaranteed.
- The high density of buildings and other infrastructure (e.g. underground rail ways) makes it very difficult and expensive to erect large wind power plants, as these need strong fundaments (Gasch and Twele 2011).

On the opposite, small wind power could be an alternative mean for the generation of renewable energy in cities like Berlin:

- Small wind power plants can be built closer to obstacles and still have a good functionality, because they need lower wind speed to function well (Rodman and Meentemeyer 2006). Small wind rotors are even often built on top of roofs in settlements (e.g. Grant et al. 2008; Ledo et al. 2011).
- Small wind power plants are much more flexible and do not need high logistic effort to be erected, replaced or moved to more suitable or newly available areas.

4 Data

Data from the Berlin City and Environmental Information System (Berlin Informationssystem Stadt und Umwelt) have been used in this study. The data have been provided by department for geo-information of Berlin's administrative city office (Senatsstadtverwaltung des Landes Berlin, Abteilung Geoinformation), mainly by Mr. Jörn Welsch.

The data are depicted in the data catalogue of the Berlin City and Environmental Information System (Informationssystem Stadt und Umwelt (ISU) der Senatsverwaltung für Stadtentwicklung Berlin 2011). Many of the city and environmental information system's data are created, administrated and displayed with a common reference to space. The spatial reference frame is generated by the so-called "bloc map ISU 5" or "bloc map ISU 50". "ISU 5" is the abbreviation for a map with the scale 1:5000, whereas "ISU 50" constitutes a map with the scale 1:50000. While the bloc maps serve as reference frames and basis of data creation, the data acquisition and maintenance takes place in databases. In a five-year turn, the geometries are adapted and modified according to changing bloc structures and changing land use. The altered bloc structures are allocated by Berlin's department of statistics.

From the available subject areas of the Berlin City and Environmental Information System, the following ones have been chosen for the study: bloc map ISU 5, land use and wind speeds. In addition, a building and a nature and land reserves dataset was utilized, which was not initially constructed based on bloc map ISU 5. The source of this dataset was mainly the ALK (Allgemeines Liegenschaftskataster = Germany's general land survey register) (FIS Broker Berlin 2012b; personal communication with Mr. Holger Brandt and Mr. Jörn Welsch).

In the present study, most of the data were initially related to bloc map ISU 5 as the spatial reference frame (FIS Broker Berlin 2012a). If data were initially not related to bloc map ISU 5 (e.g. the nature and land reserves dataset), they were still compatible with the other data, because they were allocated the same projected coordinate system.

Additional information and metadata related to the bloc map dataset can be found in the FIS Broker system, a web map server, which helps accessing maps, plans and other geodata of Berlin and Brandenburg. In the FIS Broker system, geodata can be researched, presented and combined. FIS Broker was developed by Department of Geo-information of Berlin's Administrative City Office (Senatsstadtverwaltung Berlin) together with the commercial partner SRP GmbH (Berlin.de: Senatsverwaltung für Stadtentwicklung und Umwelt 2012).

4.1 Spatial reference frame: Bloc Map ISU 5

Vector data polygon bloc map ISU 5 consists of statistical blocs, including sub-blocs and areas (Figure 4.1). The blocs of the map are congruent with statistical blocs, which were created by the Administrative Office of Statistics of the federal state Berlin Brandenburg (Amt für Statistik Berlin Brandenburg). Borders of sub-blocs referring to land use were established by the team of Berlin's City and Environmental Information System (Informationssystem Stadt und Umwelt (ISU)) based on digital aerial orthophotos allocated by the archive of aerial photography, as well as based on land surveys. Table 4.1 gives an overview over main metadata related to bloc map ISU 5.

Table 4.1: Main metadata of bloc map ISU 5 (FIS Broker Berlin 2012a).

Scale of data entry	1:5000
Scale range	1:100 to 1:50000
Projected coordinate system	DHDN Soldner Berlin
Created on	30.06.2010

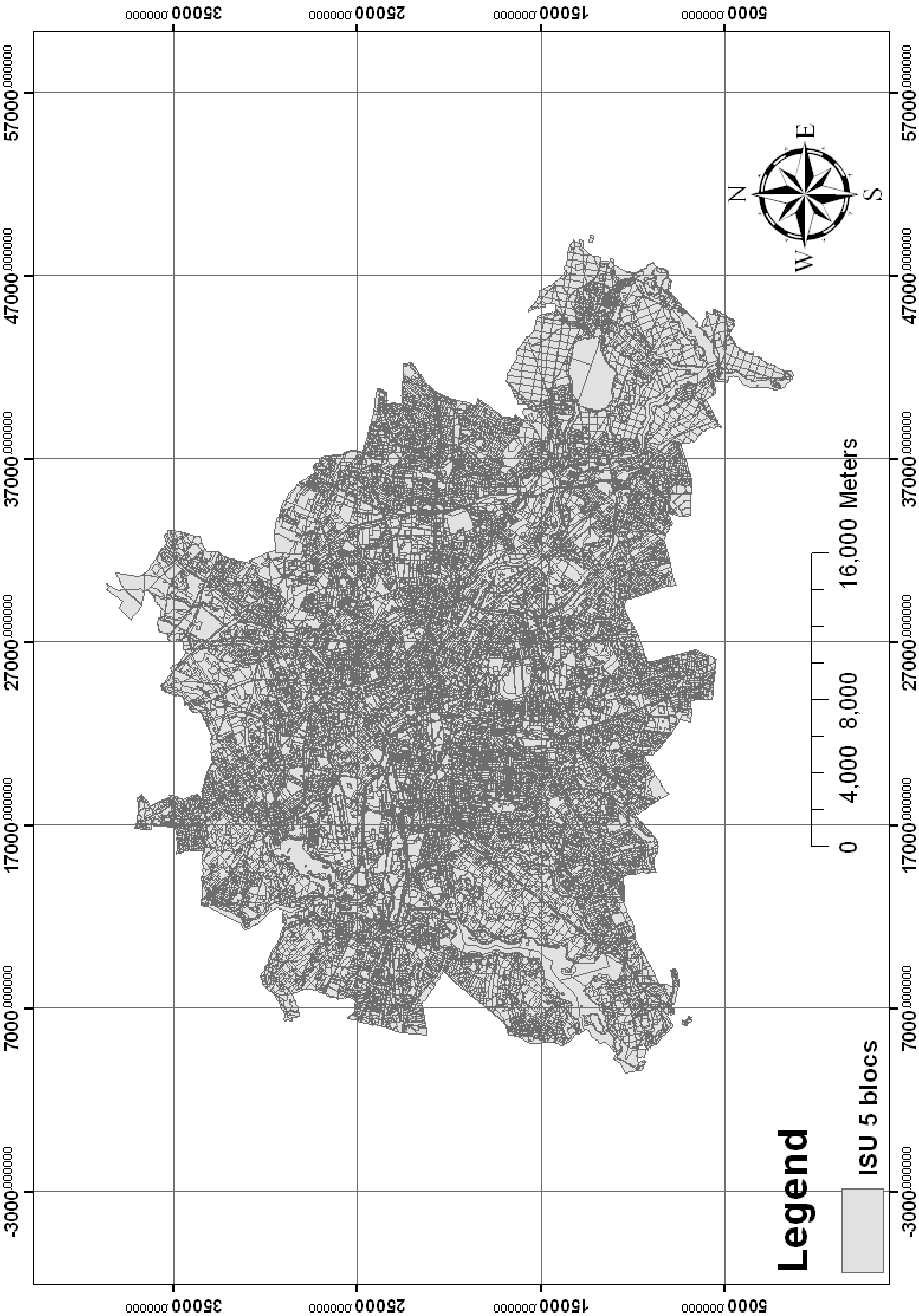

Figure 4.1: Bloc map ISU 5 (Informationssystem Stadt und Umwelt (ISU) der Senatsverwaltung für Stadtentwicklung Berlin 2011).

4.2 Land use database

A land use database referring to the ISU 5 bloc map has been used for creating a land use map (Informationssystem Stadt und Umwelt (ISU) der Senatsverwaltung für Stadtentwicklung Berlin 2011). In addition to the database, metadata with detailed explanations of the database data were allocated. The land use database consists of several data sets saved in tables depicting information related to land use with different focuses, but a certain degree of overlap. The four tables included in the land use database are (Table 4.2):

- A general information database table, which includes, amongst other information, key codes for linking the database table to blocs of the ISU 5 bloc map.
- A general land use information database table, which contains traditional land use attribute data (e.g. forests and forestry, water bodies). In detail, the table depicts 22 different land use classes, saved as numerical codes between 10 and 200 and land use names.
- A land use type table focussing on constructional features, information about 52 different surface area types is saved among other information. In contrast to the general land use information table, the focus lies on a differentiated exposure of constructional use with focus on city structure (settlement type, age etc.).
- A city structure land use table mainly describing structural attributes of the different ISU 5 bloc map blocs and sub-blocs. The city structure land use table focuses on structural attributes of land use in a city. Information about the differentiation of the ISU 5 blocs and sub blocs in 16 city structure types is saved. Data is saved as numerical codes and names for the city structure types.

Table 4.2: Land use database tables (after Informationssystem Stadt und Umwelt (ISU) der Senatsverwaltung für Stadtentwicklung Berlin 2011).

Table	Table function
1) General information database table	Key codes for link to ISU 5 bloc map
2) General land use database table	Traditional land use types (forest, etc.)
3) Constructional land use database table	Focus on constructional land use types
4) City structure land use table	Focus on city structure land use types

In detail the general land use, constructional land use and the city structure land use database tables are listed next to each other in Table 10.1.

4.3 Wind speed table

The wind speed table for Berlin (Table 4.3) contains nightly and daily average annual wind speed data as absolute values in m/s and relative values in percentages with reference to the former airport Berlin Tempelhof (Informationssystem Stadt und Umwelt (ISU) der Senatsverwaltung für Stadtentwicklung Berlin 2011). The wind speeds have been measured at a height of 2.7 m above ground in the year 1995. Additionally, the wind speed table incorporates structural (land use) data of Berlin in the year 1995. The structural classes are associated to the wind speeds, in order to allow linking to a Berlin bloc map from 1995, similar to the ISU 5 bloc map used in this study.

Table 4.3: Wind speed table of Berlin (after Informationssystem Stadt und Umwelt (ISU) der Senatsverwaltung für Stadtentwicklung Berlin 2011).

Wind ID	Structural types of Berlin	Average wind speed			
		Wind speed (day)		Wind speed (night)	
		m/s	%	m/s	%
1	Reference station Airport Tempelhof	3.60	100.00	2.30	100.00
2	Core area	1.60	44.40	1.10	47.80
3	Garden court	0.80	22.20	0.50	21.70
4	Closed inner court	0.30	8.30	0.20	8.70
5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	2.00	55.60	1.10	47.80
6	"Unsorted" rebuilding , post-war perimeter block developments	1.40	38.90	0.90	39.10
7	Large housing estates/large residential areas	2.80	77.80	1.10	47.80
8	Houses in rows	2.10	58.30	1.10	47.80
9	Village type	1.40	38.90	0.80	34.80
10	Public facilities, waste management and maintenance/supplying utilities, special utilities, sealing below 50%	1.00	27.80	0.80	34.80
11	Garden ranks type, garden type, park-like garden type, gardens and semi-private surrounding greens	1.50	41.70	0.50	21.70
12	Farmland, ruderal/fallow land with or without grassland like vegetation	2.60	72.20	1.30	56.50
13	Allotments, weekend home area, cemetery, tree nursery, camping, parking area, city plaza with high amount of vegetation	1.60	44.40	0.70	30.40
14	Forest, ruderal/fallow land with forest like vegetation	0.80	22.20	0.50	21.70
15	Green area, park, ruderal/fallow land with bushes/tree vegetation	1.00	27.80	0.40	17.40

4.4 Electric energy dataset

The electric energy dataset consisted of vector data, in form of point shapefiles, line shapefiles and polygon shapefiles (Informationssystem Stadt und Umwelt (ISU) der Senatsverwaltung für Stadtentwicklung Berlin 2011). The dataset equals the electric energy map that can be found online in FIS Broker (FIS Broker Berlin 2012e). For the visual presentation of the electric energy dataset in the present work, an English adaption of the map was chosen (Figure 4.2), as the electric energy dataset was delivered as a complex mixture of digitized data and digitized legend, and full map reconstruction of the original electric energy map was not possible. Also, only parts of the extensive electric energy dataset were used in our analysis work.

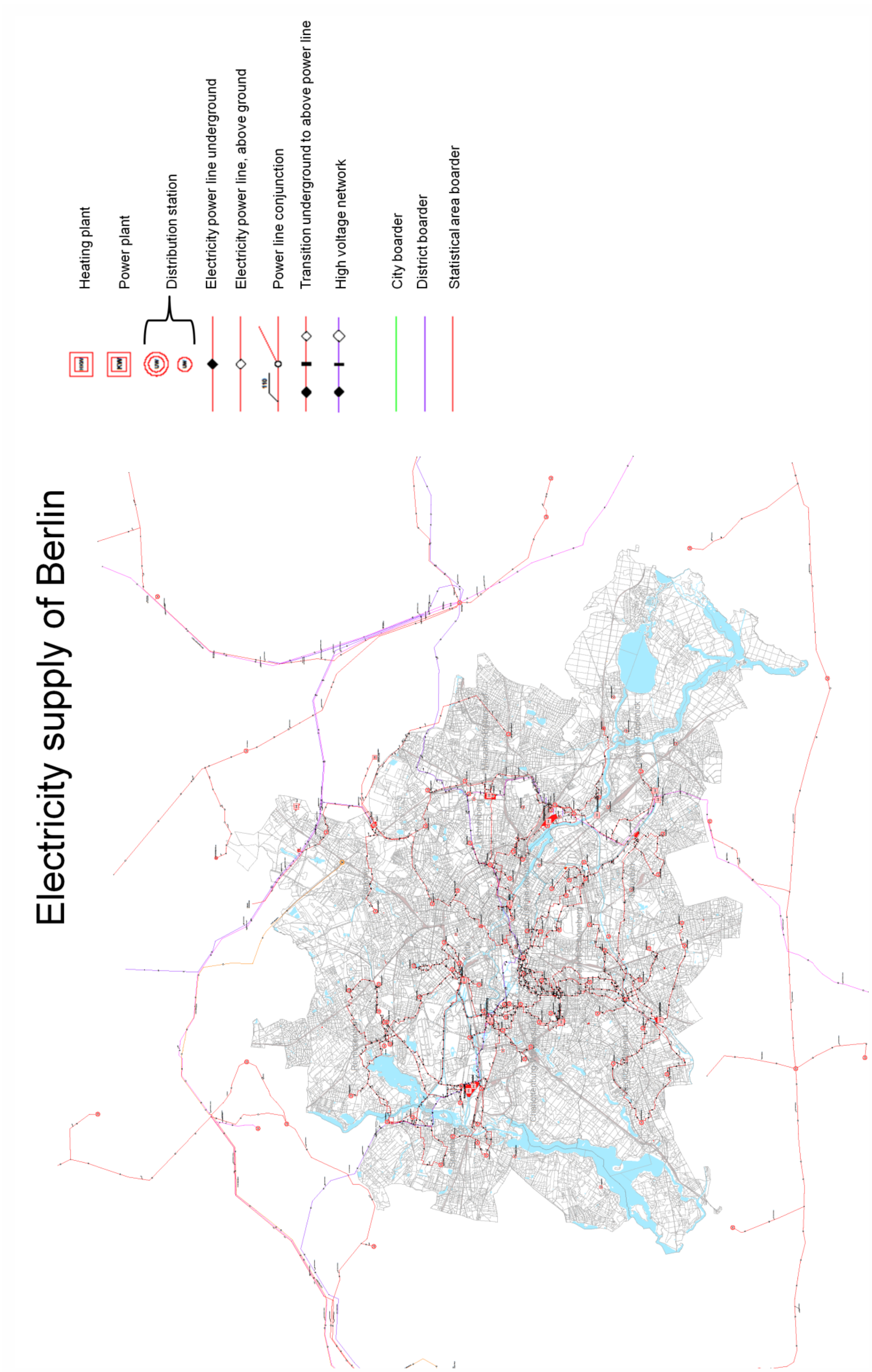

Figure 4.2: Electricity supply of Berlin (after Informationssystem Stadt und Umwelt (ISU) der Senatsverwaltung für Stadtentwicklung Berlin 2011). The map shows above ground and underground power networks and power poles/nodes among other electricity network features.

The electric energy map (Figure 4.2) presents power lines of high voltage level 110kV, power lines of high voltage level 220 kV and power lines of high voltage level 380kV, in addition to an overhead rail power line, as well as electrical generating stations and electric power transformation substations of the city of Berlin. Source of information for the map construction were supply and disposal companies of Berlin (FIS Broker Berlin 2012e). Table 4.4 presents main metadata related to electric energy map.

Table 4.4: Metadata of the electricity supply of Berlin map (FIS Broker Berlin, 2012e).

Scale of data entry	1:10000
Scale range	1:600 to 1:210000
Projected coordinate system	DHDN Soldner Berlin
Created on	01.05.2007

From the whole electric energy dataset, only data referring to above ground power poles (point vector data), as well as data presenting information on parts of the power line network, were utilized in the present study.

4.5 Buildings dataset

The buildings of Berlin dataset was delivered in QSI data format. QSI data format allows the saving of information of 3D data. Geometrical data are defined as 3D-point, 3D-polyline and 3D-polygon vector data with defined absolute heights above sea level in this data format (Informationssystem Stadt und Umwelt (ISU) der Senatsverwaltung für Stadtentwicklung Berlin 2011). In our case, the buildings were saved as 3D-polygon data (Figure 4.3). The corresponding attribute table contains, amongst other information, also information about absolute buildings heights (without incorporation of heights above sea level).

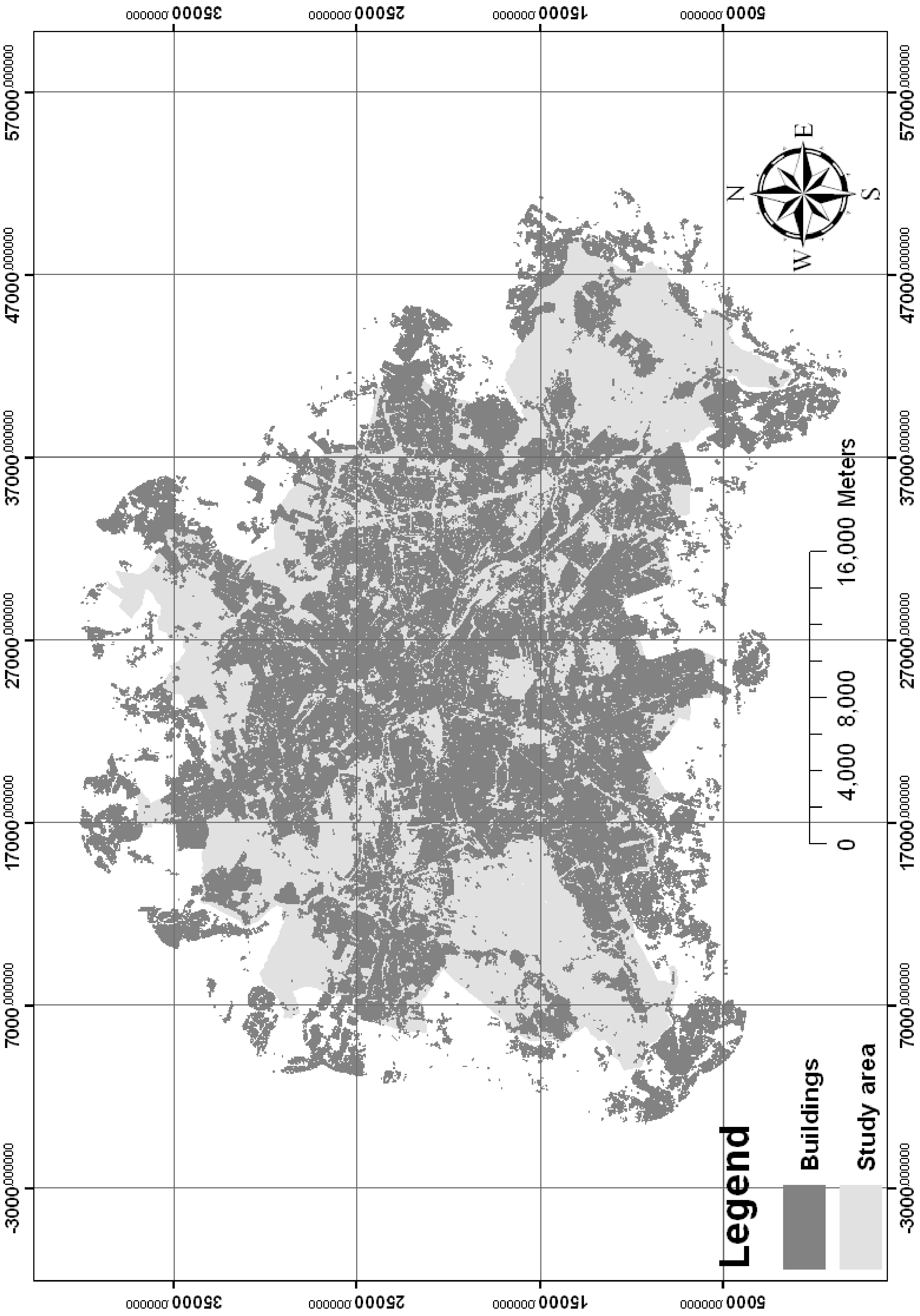

Figure 4.3: Buildings dataset map (Informationssystem Stadt und Umwelt (ISU) der Senatsverwaltung für Stadtentwicklung Berlin 2011). Note that the buildings dataset is covering an area larger than the study area.

The buildings of Berlin dataset had been produced based on the ALK-Berlin (personal communication with Mr. Jörn Welsch). ALK-Berlin is a digital map containing cadastral land register information for Berlin (Berlin.de: Das offizielle Hauptstadtportal 2012). For the present study, from the building dataset, only information about the building ground plans (polygon vector data) and information describing absolute building heights was of interest.

4.6 Nature and land reserves

Source of the nature and land reserves dataset was Mr. Holger Brandt from Berlin's administrative city office (Informationssystem Stadt und Umwelt (ISU) der Senatsverwaltung für Stadtentwicklung Berlin 2011; see also FIS Broker Berlin 2012d). In the nature and land reserves dataset, areas protected on the basis of Berlin's nature protection law, as well as areas protected based on EU birds protection policy (Natura 2000 areas) are included (FIS Broker Berlin 2012b). The geodata are stored as vector data in the form of a polygon shapefile, and were provided together with a database table containing related attribute data information (Figure 4.4). Metadata information for the nature and land reserves dataset can be found in Table 4.5.

The data are not based on the ISU 5 bloc map. Instead, the spatial basis of the map has been digital raster data of map K5 of Berlin, as well as data derived from the ALK (FIS Broker Berlin 2012b). K5 is another base map of scale 1:5000 than ISU 5 bloc map and can be accessed via FIS Broker (FIS Broker Berlin 2012c). The main difference between K5 and ISU 5 bloc map is that K5 is not a bloc map. K5 has in turn been produced based on information of the ALK (FIS Broker Berlin 2012c).

Table 4.5: Metadata for the nature and land reserves dataset (FIS Broker Berlin 2012d).

Scale of data entry	1:1000
Scale range	1:250 - 1:1000000
Projected coordinate system	DHDN Soldner Berlin
Actualized on	01.04.2011

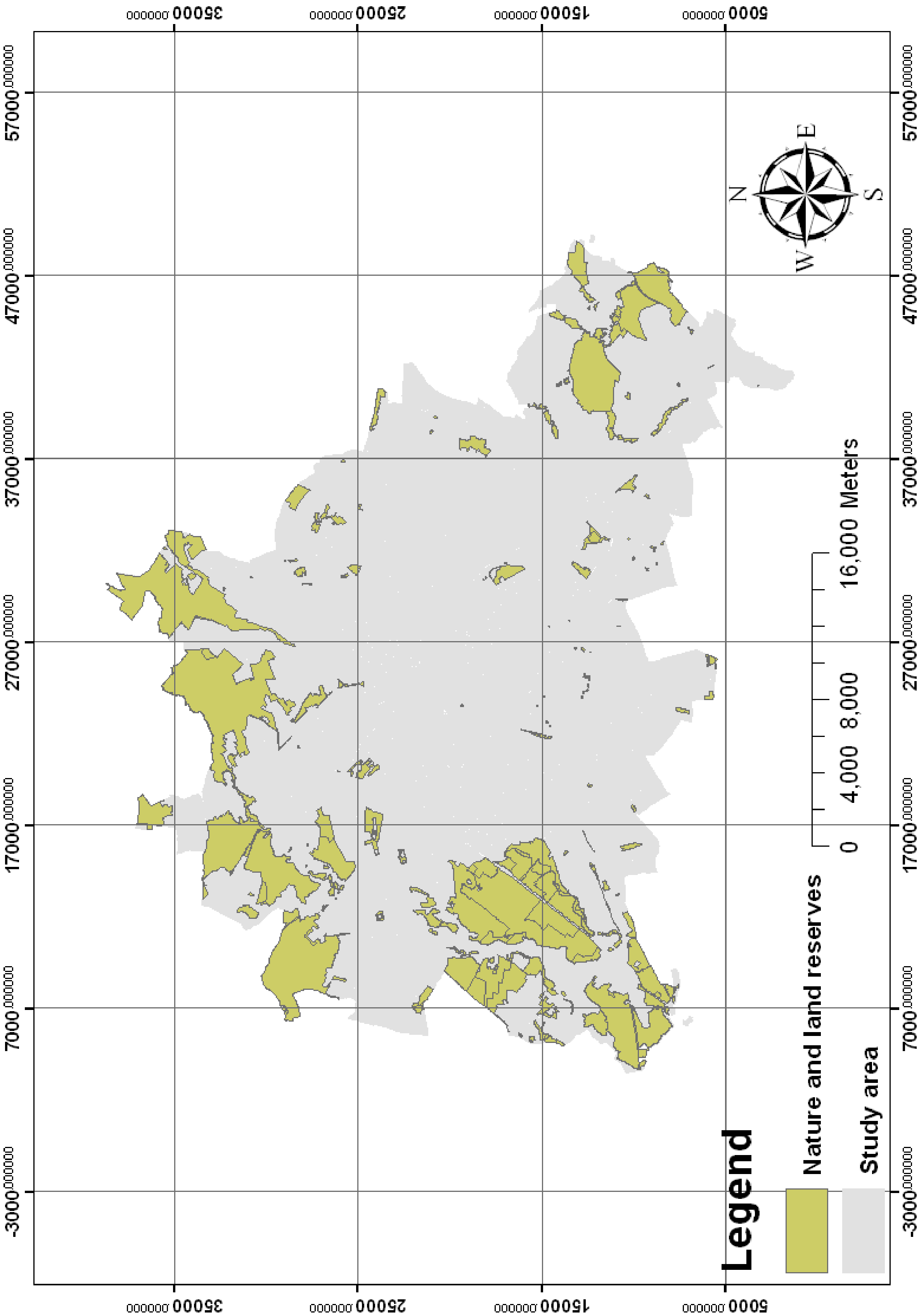

Figure 4.4: Nature and land reserves map (Informationssystem Stadt und Umwelt (ISU) der Senatsverwaltung für Stadtentwicklung Berlin 2011).

5 Methodology

The methodology can be divided into two parts. In the first part (Part I), overlay operations were made between weighted factors and Boolean constraints in order to gain suitability maps showing how suitable certain areas of Berlin are for the construction of small wind power plants (including supporting structures). To do so, weighted and Boolean raster datasets were produced for aspects important for the siting of wind power plants. Table 5.1 summarizes, which criteria were translated into weighted raster datasets and which aspects were translated into Boolean raster datasets.

In the second part (Part II), an additional Boolean overlay is performed in order to find out how suitable locations of already existing above-ground power poles are for the positioning of small wind power rotors and generators on them. To do so, an additional Boolean raster dataset was created to clip all data but the electric power poles.

Weighted overlay analysis, combined with Boolean overlay analysis, is the methodology of choice in this study. Weighted overlay is a well known methodology for combining multiple criteria for identifying a suitable site. While weighted overlay procedure helps including criteria together with certain ranking or rating factors, Boolean overlay can be utilized for excluding areas that are not suitable at all for the construction of unconventional wind power plants.

Table 5.1: Overview of the weighted and Boolean overlay data sets.

Weighted overlay data (factors)	Boolean overlay data (constraints)
Land use raster	Nature and land reserves, water bodies and cemetery raster
Distance to power line network raster	Buffers around buildings
3 Wind speed raster datasets (for 10, 20 and 30 m wind power plant height respectively)	3 Wind speed < 2.5 m/s raster datasets (for 10, 20 and 30 m wind power plant height respectively)

The choice of raster datasets for the weighted and Boolean overlays was mainly motivated and influenced by former conventional wind power planning siting studies, and by data availability. Criteria of environmental aspects of wind power plants like the ones assessed in Aydin et al. (2010) have not been considered in this study due to data inaccessibility. Instead, the main focus of the present study laid on basic safety and performance criteria like wind speed and distance to buildings. However, environmental, social and economic aspects are also included by means of natural reserves, cemeteries and assumed general population acceptance and distance to power line network, respectively. The assumed general population acceptance is included by rating highly populated areas less than lower populated areas based on the land use dataset. In the following the assignment of the projected coordinate system is dealt with, then, the data preparation for construction of criteria maps is treated, and finally, the overlay analysis steps are depicted.

5.1 Assignment of projected coordinate system

All data were projected in the projected coordinate system of the ISU 5 base map, EPSG:3068 Soldner Berlin. The system is also called “DHDN-Soldner-Berlin”. The parameters of DHDN-Soldner-Berlin are outlined in Table 5.2 (ESRI ArcMap 9.3 2008).

Table 5.2: Summary of the parameters of the projected coordinate system EPSG:3068 Soldner Berlin (ESRI ArcMap 9.3 2008).

Projection	Cassini
False easting [m]	40000
False northing [m]	10000
Central meridian [deg]	13.627204
Scale factor	1
Latitude of origin [deg]	52.418648
Linear unit	Meter (1.0)
Geographic coordinate system	GCS-Deutsches-Hauptdreiecksnetz
Angular unit	Degree (0.0174532925199433299)
Prime meridian	Greenwich
Datum	D-Deutsches-Hauptdreiecksnetz
Spheroid	Bessel-1841
Semi-major axis [m]	6377397.1550000003
Semi-minor axis [m]	6356078.9628181886
Inverse flattening	299.15281279999999

5.2 Data Preparation

In the following, the practical preparation steps for creating criteria maps are described. Hereby, five raster datasets were prepared for the weighted overlay analysis: land use dataset, three wind speed datasets (for 10, 20 and 30 m wind power plant height, respectively) and a distance to power line network dataset. Three Boolean raster datasets were prepared for the

Boolean overlay analysis (nature and land reserves, water bodies and cemeteries, and three wind speeds below 2.5 m/s raster datasets). Finally an additional Boolean dataset has been generated to analyse suitability of existing power poles as pre-existing structures for wind power plant rotors.

5.2.1 Preparation of land use dataset

In this raster, land use suitability for small wind power plant construction is reflected. Land use is a common criterion included in wind power siting GIS analysis (e.g. Rodman and Meentemeyer 2006; Tegou et al. 2010; Baban and Parry 2001). For the ranking of land use classes, a decision basis was necessary. As no detailed studies for Berlin on land use suitability for wind power plant construction have been available, a simple numerical classification scheme with four options was applied to the land use dataset based on common experiences and experience from other studies (Rodman and Meentemeyer 2006, Simões et al. 2009, Zeit Online 2011). The suitability values can take on numerical values of 0.0, 0.25, 0.5, 0.75 and 1.0 for impossible, difficult, medium and good suitabilities. Table 5.4 shows how these suitability values have been applied to each land use data type. Thereby, it was decided to take population density and possible opinion aspects, as well as the presence of physical constraints (e.g trees) as decision base. On the one hand, population density aspects of land use classes were incorporated, as siting of wind power plants is not widely accepted in many parts of Germany (e.g. Zeit Online 2011). Especially when it comes to the construction of wind power plants in a neighbourhood, people often react with resistance. It was therefore assigned a higher suitability value to less populated land use classes than to higher populated ones, which can receive a maximum suitability of 0.5. The influence of population density was taken into consideration in other studies, too (e.g. T. Simões et al. 2009). On the other hand side, physical constraints make some land use classes less suitable for construction of small wind power plants. This approach was applied for example in the case of forests. They were assigned a very low suitability value (0 or 0.25) due to the trees that would possibly need to be chopped in case of constructing small wind power plants here. The incorporation of negative effect of many trees or forested areas into the GIS siting analysis process can be also found in Rodman and Meentemeyer (2006). Here, forest was treated as an obstacle, with no forest being most suitable and very dense forest being least suitable. The final land use classes will be included as ranked raster in the weighted overlay operations. To do so, the general land use data table is connected to the ISU 5 bloc map. The resulting land use polygon feature dataset is then converted into a land use raster dataset with a resolution of 1 m x 1 m.

5.2.2 Preparation of wind speed maps

As in many studies concerned with wind power plant siting (e.g. Baban and Parry 2001; Rodman and Meentemeyer 2006), it was necessary to incorporate wind speed as a criterion in the present analysis. In contrast to the methodology applied in some case studies (e.g. Sliz-Szkliniarz and Vogt 2011; Simões et al. 2009), in the present study no wind data has been measured, but a wind speed bloc map was generated from an already existing wind speed dataset of Berlin acquired at 2.7 m above ground in 1995. Similar methodologies using already existing wind speed data have also been employed by other authors in the past (e.g. Tegou et al. 2010). As a result of the age of the wind speed dataset, a reassignment of the structural types of the wind speed dataset to up-to-date structural types of Berlin was required.

In order to convert the wind speed dataset to be compatible with various sizes of small wind power plants, wind speeds were calculated for 10, 20 and 30 m height on the basis of the original dataset. Hereby, the following considerations were included:

- First of all, it is known from literature that many small wind power plants need a certain minimal wind speed before they can start working properly (e.g. Rodman and Meentemeyer 2006; Wineur Wind Energy Integration in the Urban Environment 2007), or need a certain wind speed input in order to work economically viable (Baban and Parry 2001).
- Second, the negative influence of obstacles like high buildings or other obstacles on wind speed could be diminished by incorporating the idea of higher wind turbine heights in the study.

The extrapolation of wind speed data in vertical direction is a commonly applied approach in GIS wind power planning studies (e.g. Sliz-Szkliniarz and Vogt 2011). The logarithmic wind profile is often applied for extrapolating wind speeds in vertical direction, in order to obtain wind speeds at greater heights (Gasch and Twele 2011; Hossain et al. 2011; Mostafaeipour 2010; Sliz-Szkliniarz and Vogt 2011). The higher the wind speed, the more wind power can be produced by the small wind power plants (EWEA The European Wind Energy Association 2009; Renewable UK 2012c). Thus, three wind speed maps at 10, 20 and at 30 m height, respectively, were produced in two steps from the wind speed table and the ISU 5 bloc map.

5.2.2.1 Matching of structural types in the wind speed table with structural feature types in the land use table

The original wind speed table has been produced on the basis of structural land use types of Berlin in the year 1995. In contrast, the ISU 5 bloc map and the linked land use data table used in this study are updated versions from the year 2010. This difference in production year and the resulting time span between the production times of both datasets causes problems, as location and definition of structural types of Berlin have changed during that period. In order to overcome this issue and to generate a wind speed map based on the recent structural land use types and the recent ISU 5 bloc map, a matching between the structural land use types of the wind speed table from 1995 with the recent structural land use types had to be conducted.

To do so, a table including all unique combinations of general land use, constructional land use, and city structural land use, was constructed, using joining operations. The unique combinations were then assigned to the structural land use types from 1995. The assignment was performed following the workflow and criteria depicted below:

- If one classification type of either of the three land use tables (traditional land use; constructional land use; city structural land use) is found literally within the wind speed of Berlin structural types, the according wind speed type class and value will be assigned.
- If more than one classification type of either of the three land use tables (traditional land use; constructional land use; city structural land use) is found literally within the wind speed of Berlin structural types, all suitable wind speed classes will be allocated in a first step. In all cases, not more than two wind speed classes were allocated. In a second step, a decision was made based on the structural land use elements that had the strongest influence on wind speed. One example is a case where "camp site" and "forest" wind speed of Berlin structural types were both found in the land use database tables. In this case, it was decided to assign the wind speed value of the structural type "forest", as it was assumed that a forest with all its trees has a greater influence on wind speed than e.g. tents or lightly cultivated land of a camp site.
- In the case that none of the classification types literally matches the wind speed of Berlin structural types, the decision had to be made on the basis of the classification type which best fits the wind speed of Berlin structural type. This assignment incorporates the highest uncertainty and source of error due to false assignment.

The complete assignment can be reviewed in Table 10.1, which has been saved in Appendix A, due to its great extent.

For reasons of simplicity, the daily and nightly average annual absolute wind speed values of the wind speed table were combined by arithmetic averaging to a single average annual absolute wind speed data set. The resulting table linking wind speed to recent land use data was assigned to the ISU 5 bloc map to generate the wind speed bloc map at a height of 2.7 m.

5.2.2.2 Roughness class assignment and calculation of wind speed values at 10, 20 and 30 m

The newly generated wind speed map shows wind speeds for a height of 2.7 m only. A rotor height of 2.7 m only seemed to be very low for the construction of small wind power plants, when assuming a rotor diameter of 5 m. Furthermore, wind speed and therefore wind power plant performance maximize with greater height (Gasch and Twele 2011; Tegou et al. 2010). For many applications, a pole height of 10 m or even more is utilized (Wineur Wind Energy Integration in the Urban Environment 2007). Another reason for the calculation of wind speeds at greater heights was the fact that Berlin is a densely built city with many buildings and high constructions. The inclusion of greater wind speed heights allows diminishing the negative effect of these obstacles by making it possible to plan wind rotors at heights greater than these obstacles. Therefore, the next step was the calculation of wind speed values at additional heights. It was decided to choose values of 10, 20 and 30 m height. The motivation for this choice was mainly that these values cover the range of common heights recommended for small wind power rotor positioning (Wineur Wind Energy Integration in the Urban Environment 2007).

For the calculation of additional wind speed datasets, the logarithmic wind profile was utilized (Gasch and Twele 2011). This formula allows the estimation of wind speed values at certain heights, if a wind speed value at a known height is available, together with a structural roughness type of the land below. Each structural roughness type of land is assigned a certain numerical factor, namely the roughness length. The roughness length adapts the wind speed calculation in a way that wind deceleration due to the roughness of the underground are included in the result. Consequently, different wind speed values result from calculations with different roughness lengths z_0. In this study, roughness lengths have been allocated to the newly assigned structural types of the wind speed dataset on the basis of the proposed roughness length vs. structural type definition from Gasch and Twele (2011). Table 5.3 shows the assignments of roughness lengths to the structural types used in this study based on the structural types proposed by Gasch and Twele (2011). Calculated wind speed values are also included in the table.

Table 5.3: Assignments of roughness lengths compared to the structural types used in this study based on the structural types in Gasch and Twele (2011). Calculated wind speed values are also shown in the table (Gasch and Twele 2011; Informationssystem Stadt und Umwelt (ISU) der Senatsverwaltung für Stadtentwicklung Berlin 2011).

Wind ID	Structural types of Berlin	Average wind speed	After Gasch und Twele (2011): Windkraftanlagen, page 129		Wind speed [m/s]		
		m/s	Structural types of terrain	z0 [m]	10 m height	20 m height	30 m height
1	Reference station Airport Tempelhof	2.95	Farmland	0.03	3.81	4.26	4.53
2	Core area	1.35	City cores	2.00	7.24	10.36	12.18
3	Garden court	0.65	Suburb, flat building	1.50	2.10	2.86	3.31
4	Closed inner court	0.25	City cores	2.00	1.34	1.92	2.26
5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	1.55	Suburb, flat building	1.50	5.00	6.83	7.90
6	"Unsorted" rebuilding, postwar perimeter block developments	1.15	City cores	2.00	6.17	8.82	10.38
7	Large housing estates/large residential areas	1.95	City cores	2.00	10.46	14.96	17.60
8	Houses in rows	1.60	City cores	2.00	8.58	12.28	14.44
9	Village type	1.10	Suburb, flat building	1.50	3.55	4.85	5.61
10	Public facilities, waste management and maintenance/supplying utilities, special utilities, sealing below 50%	0.90	Suburb, flat building	1.50	2.90	3.97	4.59
11	Garden ranks type, garden type, park-like garden type, gardens and semi-private surrounding greens	1.00	Suburb,flat building	1.50	3.23	4.41	5.10
12	Farmland, ruderal /fallow land with or without grassland like vegetation	1.95	Farmland	0.03	2.52	2.82	2.99
13	Allotments, weekend home area, cemetery, tree nursery,camping, parking area, city plaza with high amount of vegetation	1.15	Suburb, flat building	1.50	3.71	5.07	5.86
14	Forest, ruderal/fallow land with forest like vegetation	0.65	Dense forest	1.60	2.28	3.14	3.64
15	Green area, park, ruderal/fallow land with bushes/tree vegetation	0.70	Loose forest	1.00	1.62	2.11	2.40

Subsequently, the table with the generated wind speed data for all four heights (2.7 m; 10 m; 20 m; 30 m) was joined to a copy of the ISU 5 bloc map. While 2.7 m height was the wind speed of the wind speed base tables and was only used for producing and linking the other three wind speed heights tables, wind speeds at heights of 10, 20 and 30 m height were produced for the overlay operation. Thus, three new wind speed maps at 10, 20 and 30 m height, respectively, were produced by raster conversion. A resolution of 1 m x 1 m was selected for each conversion, in order to obtain raster datasets of a good accuracy that were still computationally manageable.

5.2.3 Preparation of distance to power line network raster

Distance to power line network criterion is a commonly used economical criterion in studies concerned with GIS-based wind power plant planning analysis (e.g. Simões et al. 2009; Tegou et al. 2010; van Haaren and Fthenakis 2011). This criterion is not as much important for small wind power plants as for conventional wind power plants, as small wind power plants can also be used independently to a close power line network (Fleck and Huot 2009; Renewable UK 2011a, 2012a), for example by using battery-based decentralized systems to store the produced power. In this case, the distance between small wind power plants and buildings or machines is more important than how close to the power line network the small wind power plant is. However, there are benefits of being close to the power line network.

Thereby, the following rule was employed: The closer a wind power plant is sited to the power line network, the more suitable it is, as less cable connecting the wind power plant to the network is needed, which is cheaper. In addition, more energy can be preserved if the connection to the network is short (van Haaren and Fthenakis 2011).

In order to construct the distance to power line network raster, line features of the electric network dataset were used. To do so, the line features were selected from the electric network dataset and exported to a new map, whereas line features belonging to German rail were excluded. In the next step, a Straight Line Distance operation was performed on the line feature dataset. A Straight Line Distance operation calculates distances from given features for given increments (resulting raster resolution) and saves the resulting dataset as a raster dataset (ESRI ArcGIS 9.2 Desktop Help 2007c). In this case an increment size of 2 m x 2 m had to be chosen, because a smaller increment size exceeded the computational capacity. The resulting raster dataset was then refined to a raster resolution of 1 m x 1 m, in order to make it compatible with the other datasets of the overlay operation.

5.2.4 Preparation of distance to buildings datasets

In many GIS wind power planning studies, distances to buildings, or even settlements are an important criterion for siting of wind power plants (Baban and Parry 2001; EWEA The European Wind Energy Association 2009; Krewitt and Nitsch 2003; van Haaren and Fthenakis 2011). The choice of including a distance to buildings dataset to the analysis was mainly motivated by performance and safety reasons, as well as legal reasons. A certain distance of wind power plants to buildings helps to diminish safety risks on the one hand side and to augment performance on the other hand side. For example, distances to obstacles like buildings also help to avoid wind power plants being negatively influenced by wind turbulences caused by these obstacles. Additionally, people will be kept safer, if a certain distance to houses is kept. Finally, environmental impact on nearby living people will be kept to a minimum, if wind power plants are not built too close to buildings.

Safety distances of obstacles to buildings as described in § 6 of Berlin's building code (Berlin.de: Senatsverwaltung für Stadtentwicklung Berlin: Oberste Bauaufsicht 2011) were used for setting the minimum distances to be kept. Accessorily, recommendations for performance distances of small wind power plants to buildings from British Wind Energy Association webpage (Renewable UK 2011b) were utilized.

In order to create datasets which contain information about distances to buildings, where small wind power plants should not be built due to both, safety and performance reasons, a dataset with buildings in Berlin and close surroundings was used. The generation of buffer zones around the buildings lead to a polygon feature datasets describing the distances to buildings. On the one hand side, this distance must honour safety reasons, while on the other hand side it must guarantee minimum influence of wind shed and turbulences induced by buildings on the performance of the small wind power plants. To do so, a safety buffer zone had to be created around buildings by using the buffer tool. Hereby, the Berlin building code (Berlin.de: Senatsverwaltung für Stadtentwicklung Berlin: Oberste Bauaufsicht 2011) was employed. The safety zone depends on the total height of the wind power plant. Thus, for each of the three investigated wind power plant heights (10, 20 and 30 m), a safety zone has to be calculated, which is reflected in equation 6:

$$S_h = 0.4 \cdot (h_{WR} + r_{Rot}) \qquad \text{Eq. 6}$$

Where S_h is the safety zone for the wind power plant rotor centre height h_{WR} and r_{Rot} is the rotor radius (2.5 m).

To calculate the buffer zone for allowance of minimum building influence on wind power plant performance, the recommendations of the British Wind Energy Association (BWEA) were followed, which state (Renewable UK 2011b): ”*Ideally, stand-alone turbines should be sited as far away as possible from buildings or trees, which may block the wind and cause turbulence. As a guide, the wind turbine should be about twice the height of obstructions in the immediate front of it (for at least the prevailing wind direction). In general, the turbine should be above the height of nearby obstructions that are within a distance of 10 to 20 meters* [15 m were chosen in this study] *of the tower heights.*” In addition the BWEA recommends a distance to buildings or obstacles of 10 times the building or obstacle height. Together with the safety zone, the BWEA scheme results in 3 buffer zones BZ_A, BZ_B, BZ_C (Figure 5.1). In zone A, the obstructing building has to be less than half the size of the wind power plant, yielding a buffer zone equal to the safety zone (equation 7). In zone C the obstructing building covers at least parts of the wind turbine rotor, requiring a buffer zone of ten times the building height (equation 9). Zone B is a transition zone with building heights in between of those present in zones A and C. Zone B thus is a flexible buffer zone, which linearly increases from 15 m to ten times of the building height (equation 8):

A: if $h_{Building} \leq 0.5 \cdot h_{WR}$ → $BZ_A = S_h = (h_{WR} + r_{Rot}) \cdot 0.4$ Eq. 7

where $S_h \leq 15$ m

B: if $0.5 \cdot h_{WR} < h_B \leq h_{WR} - r_{Rot}$ → $BZ_B = \frac{h_B - 0.5 \cdot h_{WR}}{h_{WR} - r_{Rot} - 0.5 \cdot h_{WR}}$ Eq. 8

where 15 m < $BZ_B < 10 \cdot h_B$

C: if $h_B > h_{WR} - r_{Rot}$ → $BZ_C = 10 \cdot h_B$ Eq. 9

Where S_h is the safety zone belonging to wind turbine height h_{WR}, r_{Rot} is the radius of the wind turbine rotor and h_B is the building height. The 15 m are derived from the average of the “*10 to 20 meters of distance between nearby obstructions and the turbine, which should then be above the height of these obstructions*” (Renewable UK 2011b). S_h is always less than 15 m as the maximum wind turbine height h_{WR} is 30 m in this study.

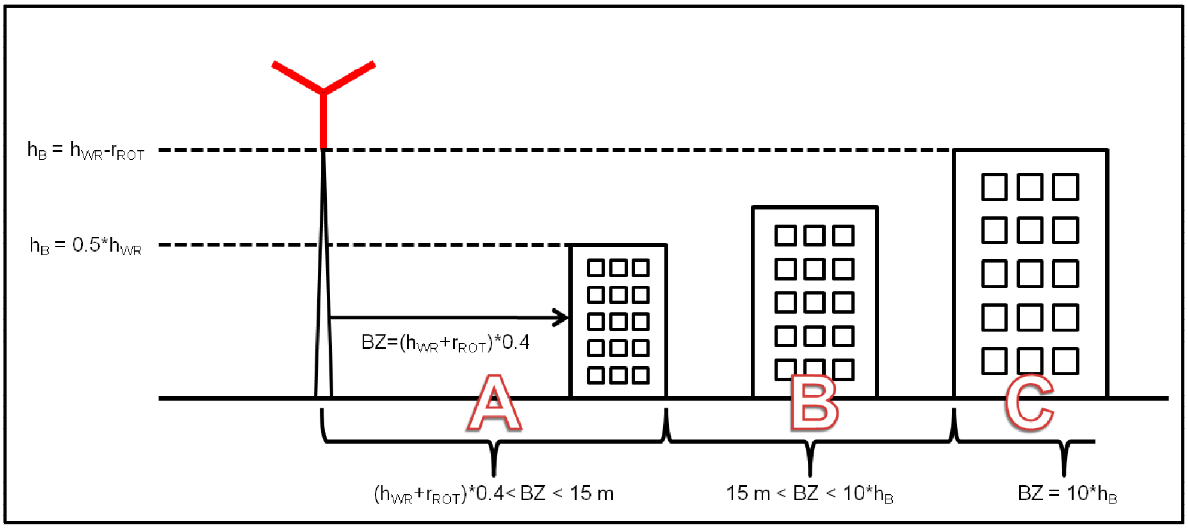

Figure 5.1: Schematic explaining the buffer zone generation around buildings.

For calculation of buffer zone values, those conditions need to be applied on the building dataset.

The resulting three attribute table field columns were used for generating three vector buffer zone layers (for 10, 20 and 30 m wind power plant height, respectively). In the next step, the three vector buffer zone layers were each converted to a raster, with a resolution of 1 m x 1 m. Then, each of the three raster datasets was reclassified such that the buffer zone was set equal to NoData and all other values to 1. The final results were three Boolean raster datasets (for 10, 20 and 30 m wind power plant height, respectively), where buffer zones around houses were set to NoData.

5.2.5 Preparation of a Boolean raster combining nature and land reserves, water bodies, cemeteries and areas with wind speeds below 2.5 m/s (combined Boolean)

The choice of excluding nature and land reserves from the output study area was mainly motivated by environmental and ethical reasons. In Germany, the installation of wind power plants in areas signed as nature or land reserves is not forbidden, but mostly not applied (BWE Bundesverband WindEnergie e. V. 2012). Birds and other species need nature and land reserves as protection zones, and some studies show that birds are negatively influenced by wind power plants (e.g. Carrete et al. 2011). Simões et al. (2009) also excluded areas assigned as “natural reserves” from their study area, because of environmental reasons, even though they include less protected areas usable for wind energy exploitation according to Portuguese environmental authorities. Krewitt and Nitsch (2003) reduce the study area by stepwise nature conservation categories like nature protection areas and landscape conservation areas. Other authors go even further, by introducing safety zones around nature reserves, because of environmental reasons (e.g. Aydin et al. 2010; Sliz-Szkliniarz and Vogt 2011).

In this study, cemeteries were excluded from the output study area in addition to natural reserves, because of pure ethical reasons. Water bodies are assigned as non suitable areas in our study, because it is assumed in this study that many of them are used for e.g. shipping or swimming activities. In contrast to offshore sites, most water streams or lakes in Berlin are smaller and restricted in size. Additionally, construction of small wind power plants in water areas would be much more complex and cost-intensive, considering the necessity of building a base, which is resistant against water flow induced erosion and corrosion. Finally, it can also be argued that water bodies can be excluded for environmental reasons. In many GIS wind power planning studies, water bodies are assigned as non-suitable (e.g. Aydin et al. 2010; Baban and Parry 2001; Sliz-Szkliniarz and Vogt 2011; van Haaren and Fthenakis 2011). Water bodies are often environmentally sensitive zones and provide habitats for many animals (van Haaren and Fthenakis 2011). In many studies, even additional safety zones were implemented as Boolean criterion around water bodies (e.g. Aydin et al. 2010; Baban and Parry 2001; Sliz-Szkliniarz and Vogt 2011). However, additional safety zones around water bodies were not implemented, as it can be assumed that water bodies outside of nature and land reserves in a city area like Berlin are not as environmentally sensitive areas as water bodies in open landscape, where many threatened animals have their habitats and where ground at waterfronts might be not solid enough to carry constructions.

As small wind power plants need a certain minimal wind speed in order to be able to start their performance, a starting wind speed need to be considered in the workflow. Therefore, an assumed minimal wind speed was used, which was set to a value of 2.5 m/s, which is a common value for small wind power plants (Wineur Wind Energy Integration in the Urban Environment 2007). The exclusion of too small wind speeds for wind power plants performance is a common criterion in wind power planning studies (e.g. Rodman and Meentemeyer 2006). In our case the exceedance of the starting wind speed at any location in Berlin depends on the height for which the wind speed was calculated (10, 20 or 30 m, respectively).

As nature and land reserves, water bodies, cemeteries, as well as areas with wind speeds below 2.5 m/s are all regarded as unsuitable areas for implementation of small wind power plants in the present study, Boolean raster datasets had to be constructed to exclude these unsuitable areas. For computational reasons, the individual Boolean raster datasets of the unsuitable areas were combined into three Boolean raster datasets (for 10, 20 and 30 m wind power plant height respectively). Thereby, nature and land reserves, water bodies, cemeteries and areas with wind speeds below 2.5 m/s were set to a value of NoData and all other raster cells are set to 1. The resolution of the raster datasets was set to 1 m x 1 m. To do so, the nature and land reserves data were derived from a polygon to raster transformation of the nature and land protection reserves polygon feature dataset. To restrict the nature and land reserves data to the Berlin area (setting the area outside Berlin to NoData), a multiplication with the land use dataset was necessary. Water body and cemetery data were selected from the land use polygon dataset. Hereby, water bodies and cemeteries were set to NoData, NoData remained NoData and all other values were set equal to 1 and the polygon dataset was then converted to a raster dataset.

The exclusion of areas with wind speeds < 2.5 m/s required the generation of three Boolean raster datasets (one for each wind power plant height). Thereby, wind speeds ≥ 2.5 m/s were assigned a value of 1 and wind speeds < 2.5 m/s were allocated a value of No Data.

In a final step, the nature and land reserves and the water bodies and cemeteries Boolean raster datasets were combined with the respective Boolean wind speed below 2.5 m/s raster datasets by performing a raster multiplication, in order to obtain a single Boolean raster dataset. This allowed for obtaining three combined Boolean raster datasets for 10, 20 and 30 m wind power plant height, where areas outside Berlin's borders, nature and land reserves, cemeteries, water bodies and areas with wind speed below 2.5 m/s were set to NoData and all other values are set to 1.

5.2.6 Preparation of an above ground level power poles dataset (Part II only)

The motivation for including this raster in the analysis was the idea of architect Frey to use existing poles or other supporting structures for the mounting of wind power plants, in order to minimize cost and/or construction restrictions (e.g. Free Energy 2012b, 2012d; Frey architects 2011). Locations of already existing overhead power poles in Berlin was used together with the other datasets for finding overhead power poles that are suitable for implementing small wind power rotors on them No similar assessment was found in literature. However, the implementation of small wind power plants on power poles is already tested in Germany (Frey architects 2011).

The above ground level power poles dataset is a Boolean raster dataset containing above ground power poles not belonging to German National Rail, not in planning and not in dismounting process, situated in the area covered by the Berlin ISU 5 bloc map (note: power poles situated in the area of Berlin between the blocs of the ISU 5 bloc map were not included because only bloc area was considered in the calculations of this study). In a first step, electro energy data were generalized in order to separate above ground power poles from the rest of electro energy data features. To do so, from the electro energy point feature dataset, all above ground level power poles were selected and exported to generate a new dataset. In a second step, only those above ground power poles not belonging to German National Rail not in planning or in disassembling were chosen from the new dataset. The reason for this selection is that it is likely that German National Rail power poles cannot be used as supporting structures for small wind turbines because of the underlying rail tracks. In a third step, all above ground level power poles covered by Berlin's ISU 5 bloc map were selected from the dataset using the land use feature map. In addition, the land use feature map served as a template for Berlin’s area. The performance of this step was necessary, because the electrical power grid dataset included not only data from the geographical area of Berlin. Instead, also parts of electrical power grid features from Berlin’s surrounding area were part of the electrical power grid dataset. It is important to note the bloc structure of the land use feature map, which lead to the exclusion of above ground power poles situated outside of the blocs (streets and plazas in most cases). In a fourth step, the point feature dataset (Figure 5.2) was converted to a raster dataset, choosing a resolution of 1 m x 1 m for the conversion operation. Finally, a reclassification of the raster dataset was performed setting all power poles to a value of 1 and NoData to NoData, in order to obtain a Boolean raster dataset.

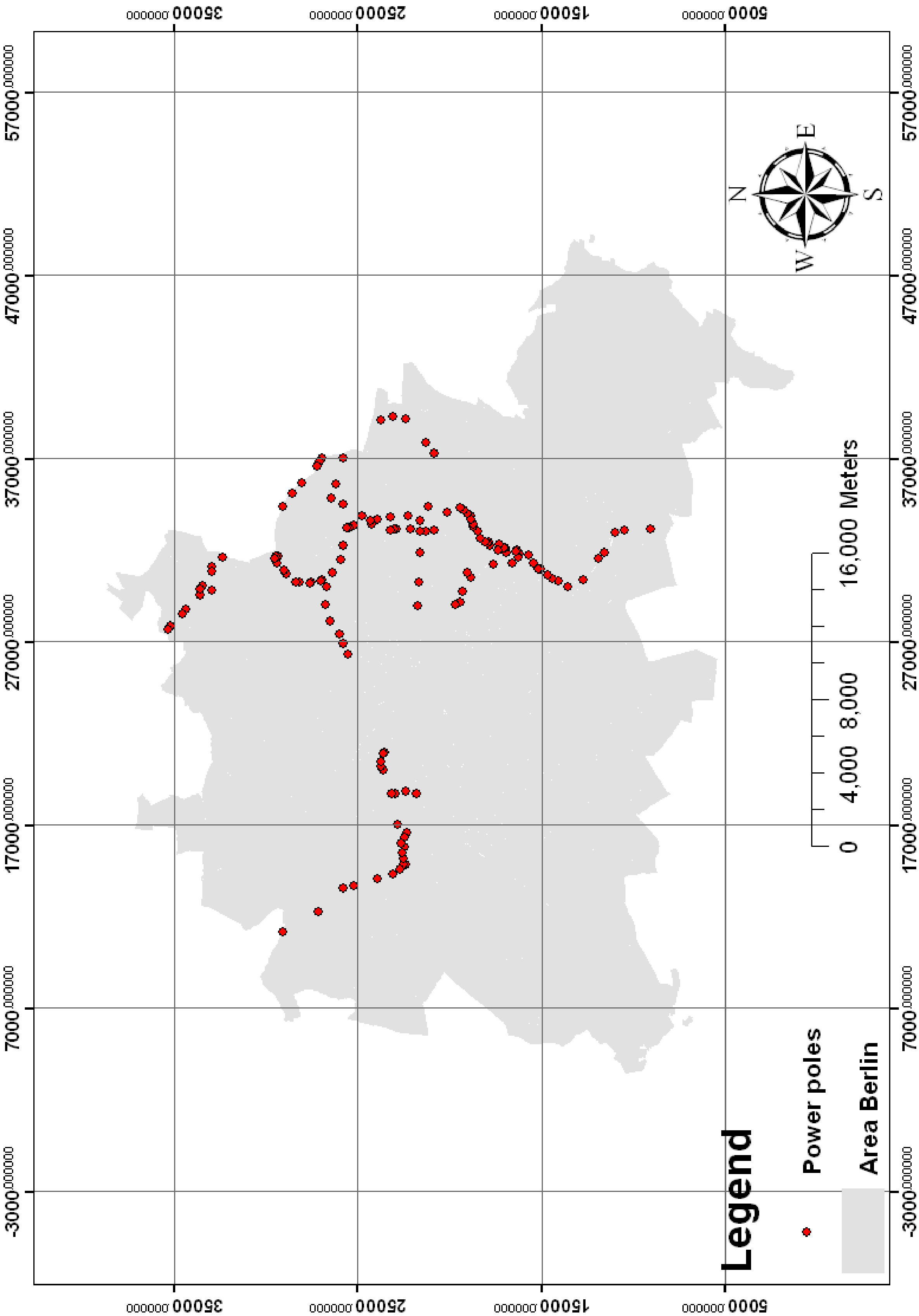

Figure 5.2: Power pole map.

5.3 Normalisation for weighting of datasets

To make the different datasets comparable in the overlay analysis step, it was necessary to perform a standardization procedure on the data. To do so, the datasets were normalised to the range from 0-1. The new values for the reclassification process were calculated using the following general formula in equation 10 for normalizing values to a 0-1 value range:

$$x_{norm} = \frac{(x_i - x_{\min})}{(x_{\max} - x_{\min})} \qquad \text{Eq. 10}$$

Where x_{norm} is the normalised value of x_i, which is the value to be standardized, x_{min} is the lowest value of a (set of) raster dataset(s), and x_{max} is the highest value of a (set of) raster dataset(s). Not all datasets, but only the ones used for the weighted overlay operation (all three wind speed raster datasets, the distance to power line network raster and the traditional land use raster) need to be normalised, whereas datasets used for the Boolean operations (all three distance to buildings buffer raster datasets, the combined Boolean raster, and, in case of part II, the above ground level power poles dataset) do not need to be normalised, as the Boolean raster datasets only include values equal to 0 and 1 or NoData.

5.3.1 Normalisation of land use raster

For the land use dataset, no numerical classification does exist yet. Therefore, the different land use classes need to be classified with numerical values according to their suitability for construction of small wind power plants on the respective land. Table 5.4 shows the numerical classifications together with arguments for the decisions.

Table 5.4: Numerical reclassification of the land use raster data set, including arguments for the decisions.

Land use	Effort of construction, social compatibility (good, medium, difficult, impossible) (1, 0.75, 0.5, 0.25, 0)	Comment
Residential use	0.5	High population density
Mixed use	0.5	High population density
Core area	0.5	High population density
Trade and industry, large-scale retail	0.75	
Public and special facilities	0.75	
Waste management and maintenance/supplying utilities	0.75	
Weekend cottages and allotment-like utilisation	0.5	High population density
Traffic area	0.75	
Forests and forestry	0.25	
Water bodies	0	Water
Grassland/green area	0.75	
Farmland	1	
Park/Green area	0.75	
City plaza/promenade	0.75	
Cemetery	0	Deference
Allotments	0.75	
Fallow land, without vegetation	1	

Continuation table 5.4.

Land use	Effort of construction, social compatibility (good, medium, difficult, impossible) (1, 0.75, 0.5, 0.25, 0)	Comment
Fallow land, grassland like vegetation	1	
Fallow land, mix of grassland, bushes and trees	0.75	
Sports use	0.75	
Tree nursery/horticulture	0.75	

5.3.2 Normalization of wind speed raster datasets

In order to construct the normalised wind speed raster data sets in such a way that they are comparable to each other, the data range for the normalisation process had to be defined from all wind speed raster datasets. Hereby, the smallest wind speed value of all three wind speed raster datasets is 2.5 m/s, and the highest wind speed value of all three wind speed raster datasets is 17.6 m/s. The normalised wind speed raster datasets for wind power plant heights of 10, 20 and 30 m, respectively, are then calculated using equation 10.

5.3.3 Normalization of distance to power line network raster

The smallest distance to power line network value is 0 m, and the highest distance to power line network value is 7784.86 m. No upper threshold of a distance to power line network has been defined, as this overlay factor is considered important, but not crucial, because power output of small wind power plants could also be stored in decentralized batteries or directly connected to households. It was therefore decided to classify the whole range of available distances to power line networks in Berlin. The calculation of normalised values is performed by using equation 10.

5.4 Overlay Analysis

The overlay analysis performance can be divided into two parts. In a first operation, factors were overlaid using different weights (weighted overlay of factors). In a second process, non-suitable areas were excluded with the means of Boolean constraint raster datasets (Boolean overlay of constraints).

5.4.1 Weighted overlay of factors

Three different overlay analyses in GIS were operated, in order to give an impression of how suitability of different sites for constructing small wind power plants changes with different weighting scenarios (operation 1-3) and in order to perform two different weighting methodologies (Table 5.5). For operation 1 and 2, factors were weighted applying rank sum methodology. For operation 3, ratio estimation methodology was applied for specifying weights. Thereby, the weights were calculated according to equation 5.

Table 5.5: Weights for overlay operations 1-3. Ranked weight estimation methodology was performed for overlay operation (OLO) 1 and OLO 2. Rated, ratio scale based weight estimation was conducted for OLO 3.

	Straight rank (r_j)		Weight ($n-r_j+1$)		Normalised weight		Original weight	Normalised weight
Criterion	**OLO1**	**OLO2**	**OLO1**	**OLO2**	**OLO1**	**OLO2**	**OLO3**	
Wind speed	1	1	3	2	0.5	0.5	10	0.625
Land use	2	2	2	1	0.34	0.25	5	0.3125
Distance to power line	3	2	1	1	0.16	0.25	1	0.0625

According to EWEA The European Wind Energy Association (2009) and Renewable UK (2012c), the wind speed datasets have always been ranked as most important. As the exact weights cannot be estimated from the data, two straight rankings to calculate weights were used. In the first ranking wind speed is most important and distance to power line is ranked as least important. The resulting weights are therefore 0.5 for the wind speed, 0.34 for the land use and 0.16 for the distance to power line. The latter can be well considered of being least important, as small wind power plants can also be used independently to a close power line network (Fleck and Huot 2009; Renewable UK 2011a, 2012a), for example by using battery-based decentralized systems to store the produced power. However, in a second ranking, land use and distance to power line have been given the same rank, resulting in 0.5 for wind speed, and 0.25 for both land use and distance to power line. This allows of a first assessment of the influence of the distance to power line network. As a third variant a ratio scale weight estimation has been employed. Thereby, an emphasis to the wind speed datasets was given and the distance to power line network was treated as ten times less important. These weights were chosen on a subjective decision basis and could be chosen differently, once a deeper knowledge is available on the interplay of the respective parameters. Nevertheless, the weights of the ratio scale methods were chosen in such a manner, that they can be used to compare the influence of the respective parameters in conjunction with the ranking weights in a reasonable way. For all weight combinations the overlay operation is conducted as in equation 4.

5.4.2 Boolean overlay of constraints

For the Boolean overlay of constraints, the three Boolean constraint datasets resulting from the combinations of the three different distance to buildings raster datasets (distance to buildings raster for wind speed at 10, 20 and 30 m height) and the combined Boolean raster dataset, incorporating the nature reserves-cemeteries-water bodies raster and the wind speed < 2.5 m/s raster, were utilized. To perform the Boolean overlay operation, each resulting raster of the weighted overlay operation was multiplied by the Boolean raster datsets.

5.4.3 Final reclassification and creation of suitability maps

For illustration, interpretation and statistical analysis purposes, the output raster datasets of the overlay were reclassified according to the following reclassification in Table 5.6.

Table 5.6: Scheme for final reclassification of the output raster data sets of the overlay.

Old value from overlay operations	New value for suitability maps
0 – 0.1	1
0.1 – 0.2	2
0.2 – 0.3	3
0.3 – 0.4	4
0.4 – 0.5	5
0.5 – 0.6	6
0.6 – 0.7	7
0.7 – 0.8	8
0.8 – 0.9	9
0.9 – 1.0	10

Suitability maps were created from the reclassified raster datasets using a green (unsuitable) to lilac (highly suitable) floating colour scheme, with yellowish and reddish values marking values in the transition zone between unsuitable and suitable cells.

5.4.4 Power pole Boolean factor overlay (Part II only)

For the investigation of suitability of existing power poles for small wind power implementation, reclassified results of Part II were used for further analysis. Therefore, no additional reclassification was necessary. In the overlay analysis of the second part, the resulting raster datasets of the overlay operations in the first part were overlaid with the overland power pole Boolean raster. The resulting raster datasets were converted to point feature datasets for reasons of better visual display.

6 Results

In order to investigate the influence of wind power plant height and all factored parameters (wind speed, land use and distance to power line network) a total suitability was calculated by summing the product of total area and suitability class for each wind power plant height and each overlay operation (Table 6.1). In addition, the areas of each suitability class, wind power plant height and overlay operation were normalised to the total area of Berlin for better comparability.

Table 6.1: Table showing the suitability classes and corresponding areas of Berlin for each overlay operation and wind power plant height. Also, a weighted area is calculated, were as the weights are the suitability classes.

Overlay operation 1									
Suitability class	Total area [km²]			Area of Berlin [%]			Suitability*Total area [km²]		
	Wind power plant height			Wind power plant height			Wind power plant height		
	10 m	20 m	30 m	10 m	20 m	30 m	10 m	20 m	30 m
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	43.50	35.11	0.00	4.88	3.94	0.00	87.00	70.22
3	0.24	18.19	26.00	0.03	2.04	2.91	0.72	54.58	77.99
4	2.53	20.06	11.50	0.28	2.25	1.29	10.14	80.24	46.00
5	32.90	38.77	30.47	3.69	4.35	3.42	164.49	193.85	152.37
6	0.62	22.18	48.34	0.07	2.49	5.42	3.74	133.06	290.02
7	0.00	0.62	0.57	0.00	0.07	0.06	0.00	4.36	3.96
8	0.00	0.17	2.44	0.00	0.02	0.27	0.00	1.39	19.49
9	0.00	0.00	0.39	0.00	0.00	0.04	0.00	0.00	3.51
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	36.30	143.50	154.81	4.07	16.09	17.36	179.09	554.48	663.55

Continuation of table 6.1

Overlay operation 2									
Suitability class	Total area [km²]			Area of Berlin [%]			Suitability*Total area [km²]		
	Wind power plant height			Wind power plant height			Wind power plant height		
	10 m	20 m	30 m	10 m	20 m	30 m	10 m	20 m	30 m
1	0.00	0.25	0.00	0.00	0.03	0.00	0.00	0.25	0.00
2	0.09	33.16	26.81	0.01	3.72	3.01	0.18	66.32	53.63
3	0.99	24.89	27.68	0.11	2.79	3.10	2.97	74.66	83.03
4	2.05	16.53	14.45	0.23	1.85	1.62	8.21	66.11	57.80
5	30.15	40.52	36.87	3.38	4.54	4.13	150.76	202.59	184.34
6	3.01	27.32	35.43	0.34	3.06	3.97	18.05	163.91	212.57
7	0.00	0.66	10.41	0.00	0.07	1.17	0.00	4.63	72.85
8	0.00	0.18	2.62	0.00	0.02	0.29	0.00	1.44	20.92
9	0.00	0.00	0.55	0.00	0.00	0.06	0.00	0.00	4.94
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	36.30	143.50	154.81	4.07	16.09	17.36	180.17	579.91	690.08

Overlay operation 3									
Suitability class	Total area [km²]			Area of Berlin [%]			Suitability*Total area [km²]		
	Wind power plant height			Wind power plant height			Wind power plant height		
	10 m	20 m	30 m	10 m	20 m	30 m	10 m	20 m	30 m
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.09	59.14	60.21	0.01	6.63	6.75	0.18	118.29	120.42
3	1.80	19.88	2.85	0.20	2.23	0.32	5.41	59.64	8.55
4	34.15	40.42	47.76	3.83	4.53	5.35	136.58	161.68	191.04
5	0.23	23.14	18.42	0.03	2.59	2.07	1.15	115.70	92.10
6	0.03	0.10	22.16	0.00	0.01	2.48	0.16	0.58	132.94
7	0.00	0.59	0.34	0.00	0.07	0.04	0.00	4.16	2.37
8	0.00	0.22	2.46	0.00	0.03	0.28	0.00	1.79	19.71
9	0.00	0.00	0.61	0.00	0.00	0.07	0.00	0.00	5.45
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	36.30	143.50	154.81	4.07	16.09	17.36	143.48	461.83	572.59

Wind power plant height significantly influences total suitability. The smallest wind power plant height yields a very narrow range of suitability classes around 4-5, whereas the higher wind power plant heights result in a broader range of suitability classes and a general increase of investigated area with increasing wind power plant height can be observed (Table 6.1, Figure 6.1-Figure 6.3). Only minor differences can be seen between the first two overlay operations, but major differences can be seen in relation to overlay operation 3. Overlay operation 3 yields significantly lower suitability classes than overlay operations 1 and 2 (Figure 6.1-Figure 6.3).

Total suitability increases with increasing wind power plant height, whereas the slope of increase from 10 m to 20 m of wind power plant height is steeper than from 20 m to 30 m of wind power plant height (Figure 6.4). This indicates an asymptotic behaviour towards a certain wind power plant height. However, differences between the different overlay operations are visible. Thereby, overlay operations 1 and 2 give the best and very similar results, while overlay operation 3 always yields the least total suitability.

When truncating the suitability classes at a suitability class value of 5, assuming that all locations with suitability class ≥ 5 are suitable locations, the difference between overlay operation 3 and the remaining two becomes more obvious (Figure 6.5). Hereby, overlay operation 3 yields between 50% and 100% less suitable area of Berlin for small wind power plant construction than overlay operations 1 and 2, whose results are almost equal. Around 4%, 7% and 9% of Berlin's area are designated to be suitable for wind power plant heights of 10, 20 and 30 m, respectively, if using overlay operations 1 and 2. This equals total areas of 33.5, 61.7 and 82.2 km^2 (overlay operation 1) and 33.2, 68.7 and 85.9 km^2 (overlay operation 1) for wind power plant heights of 10, 20 and 30 m, respectively. Overlay operation 3 yields suitable areas of < 1%/0.3 km^2, around 2.5%/24.1 km^2 and around 5%/44.0 km^2 for the respective wind power plant heights.

Figure 6.6-Figure 6.8 show the sum of the total suitability of each wind power plant height and overlay operation as a function of the respective weights of the factor constraints (land use, wind speed and distance to power line network). In overlay operation 1 and 2 the wind speed weight was kept constant and only the weights of the land use (increased weight from overlay operation 1 to 2) and distance to power line network (decreased from overlay operation 1 to 2) datasets were changed. This change results in a minor increase of the sum of the total suitability. When additionally changing the wind speed weight, the influence on total suitability appears to be much more prominent. In this case the wind speed weight has been increased, while the distance to power line weight has been significantly decreased in overlay operation 3, resulting in a lower total suitability. Thereby, the land use weight has been increased compared to overlay operation 1 and decreased compared to overlay operation 2.

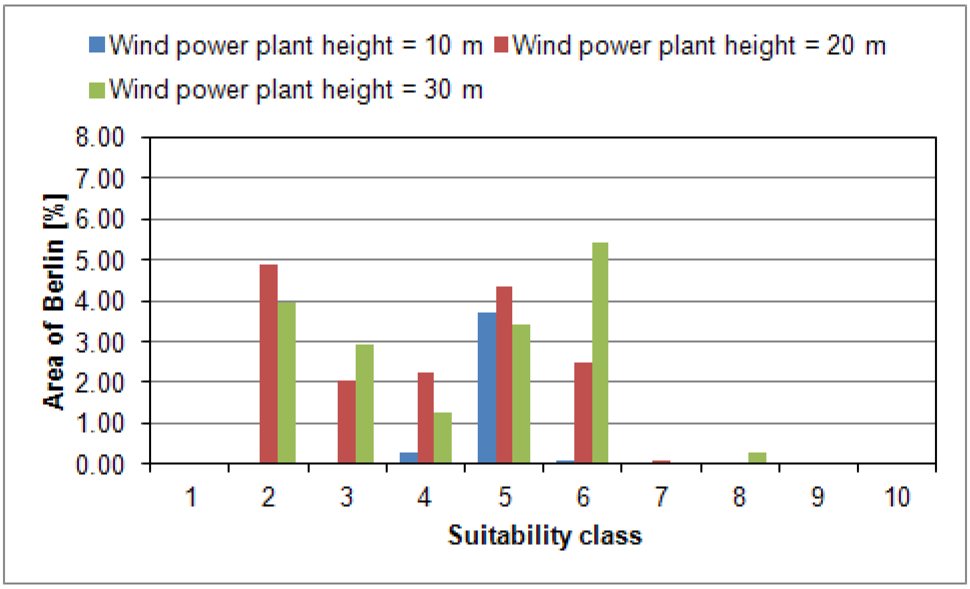

Figure 6.1: Area of Berlin assigned to each suitability class for overlay operation 1.

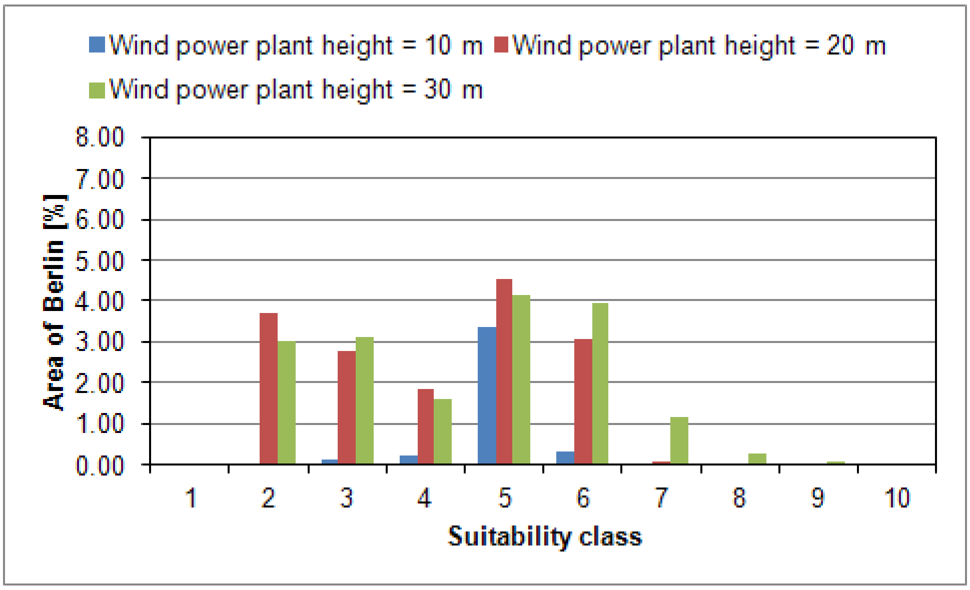

Figure 6.2: Area of Berlin assigned to each suitability class for overlay operation 2.

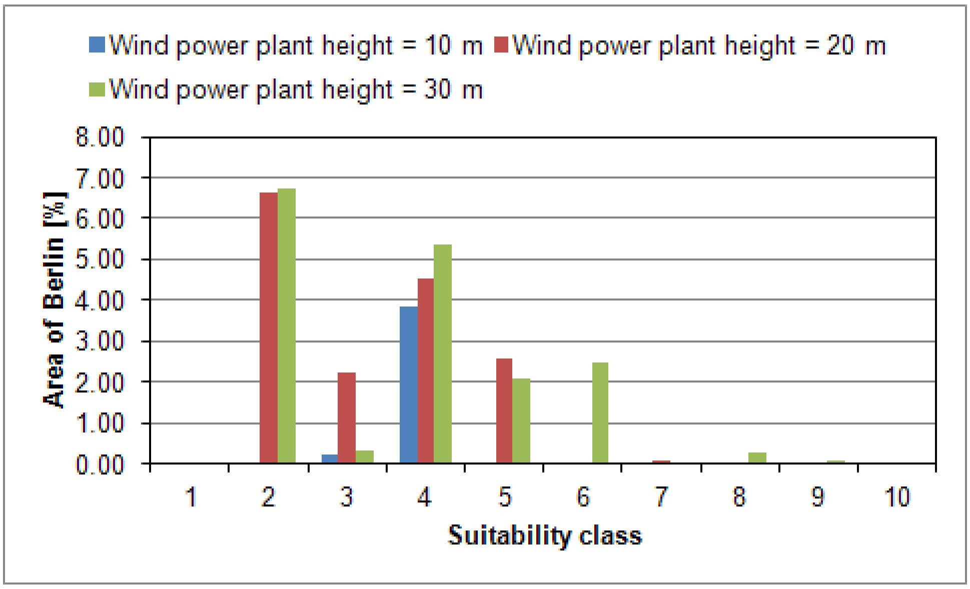

Figure 6.3: Area of Berlin assigned to each suitability class for overlay operation 3.

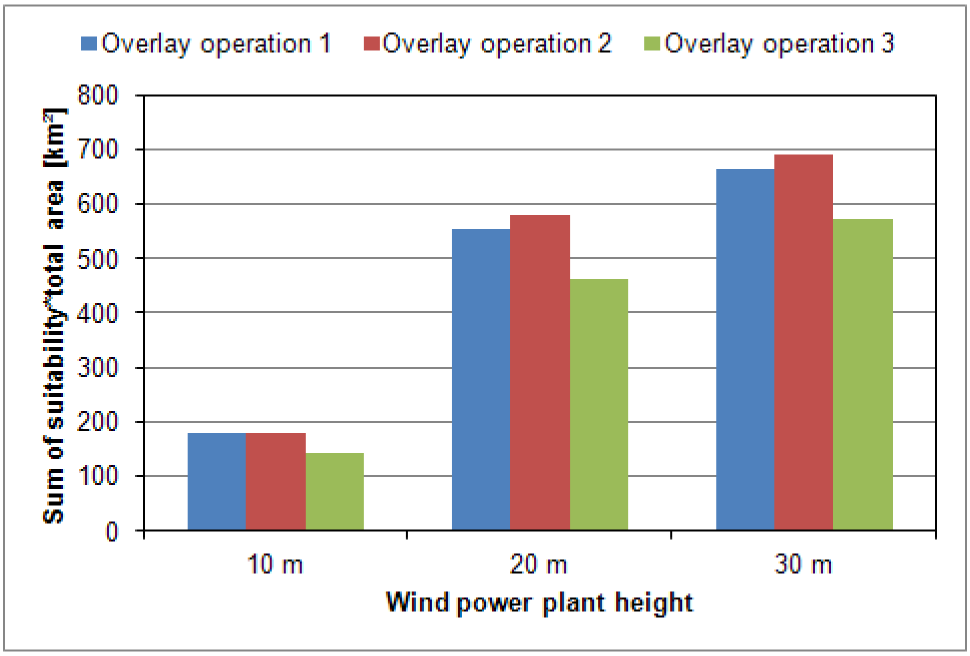

Figure 6.4: Wind power plant height vs. summed product of suitability and suitability class for each overlay operation.

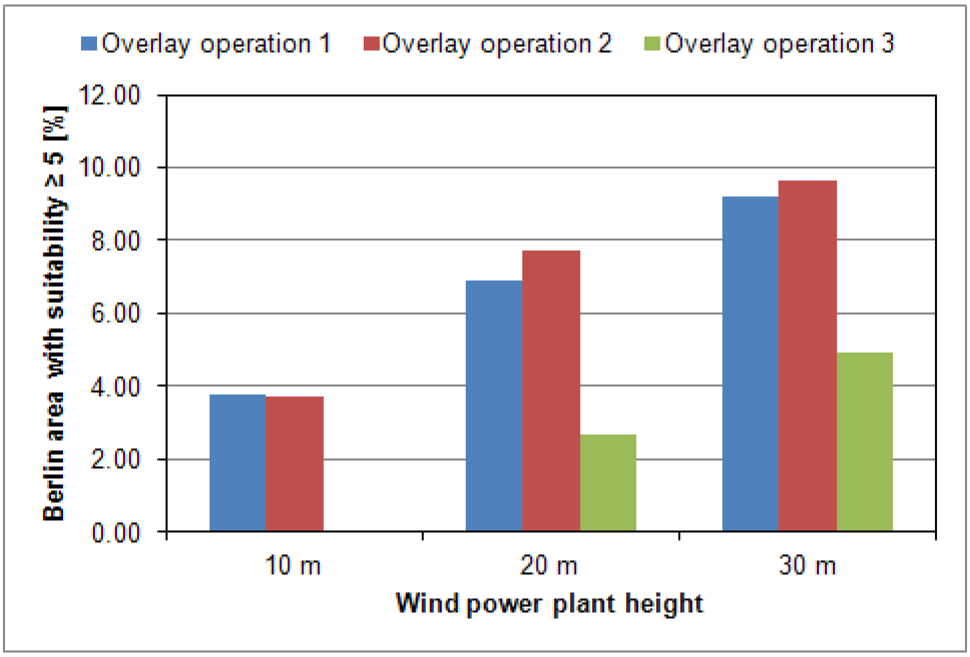

Figure 6.5: Fraction of Berlin area with suitability ≥ 5 for each overlay operation and wind power plant height.

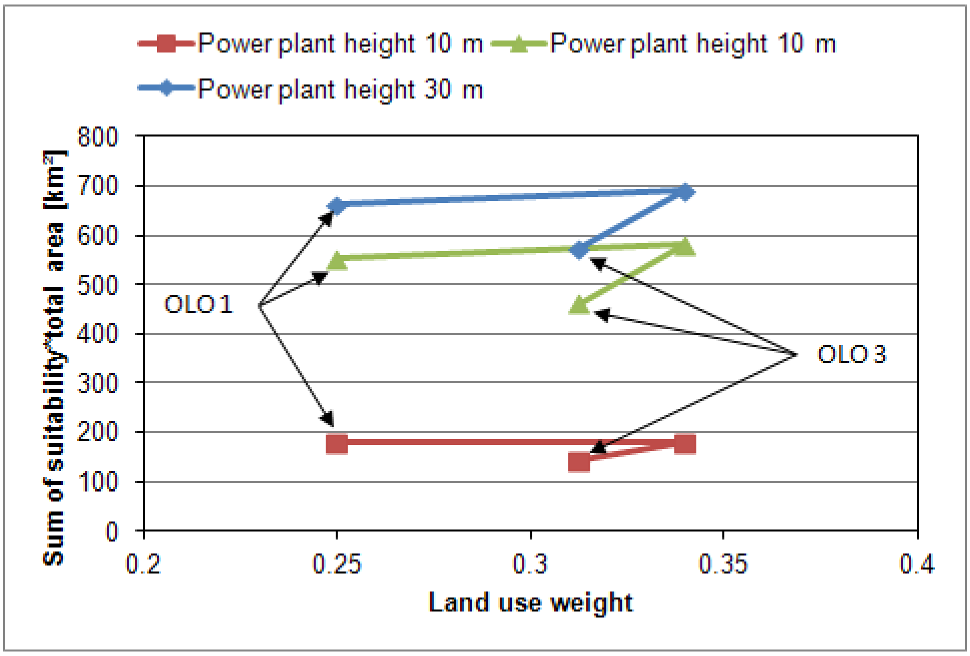

Figure 6.6: Total suitability as a function of land use weight for different wind power plant heights. The arrows indicate the respective overlay operations (OLO).

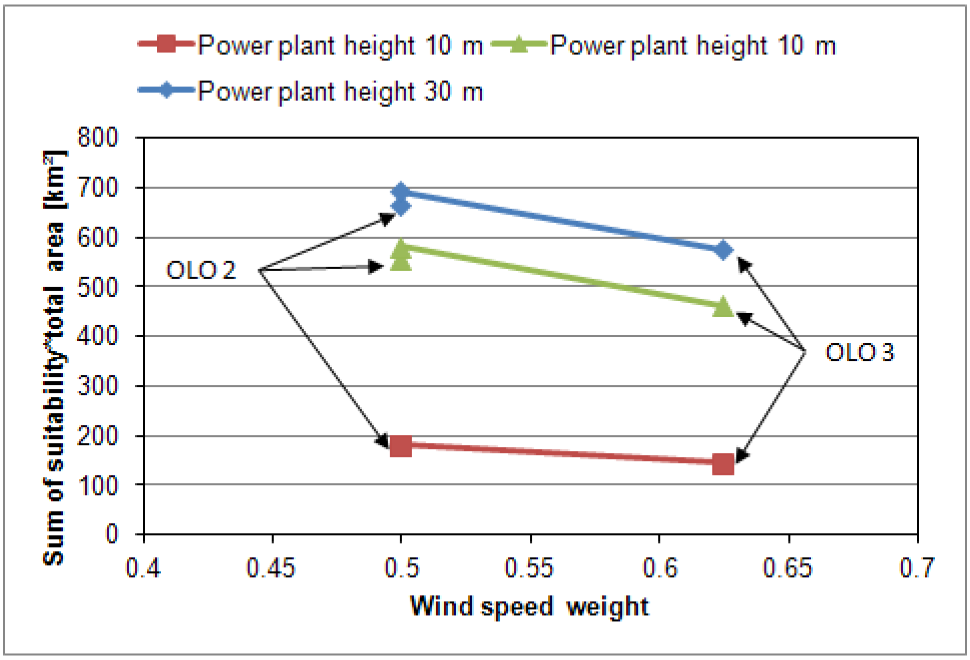

Figure 6.7: Total suitability as a function of wind speed weight for different wind power plant heights. The arrows indicate the respective overlay operations (OLO).

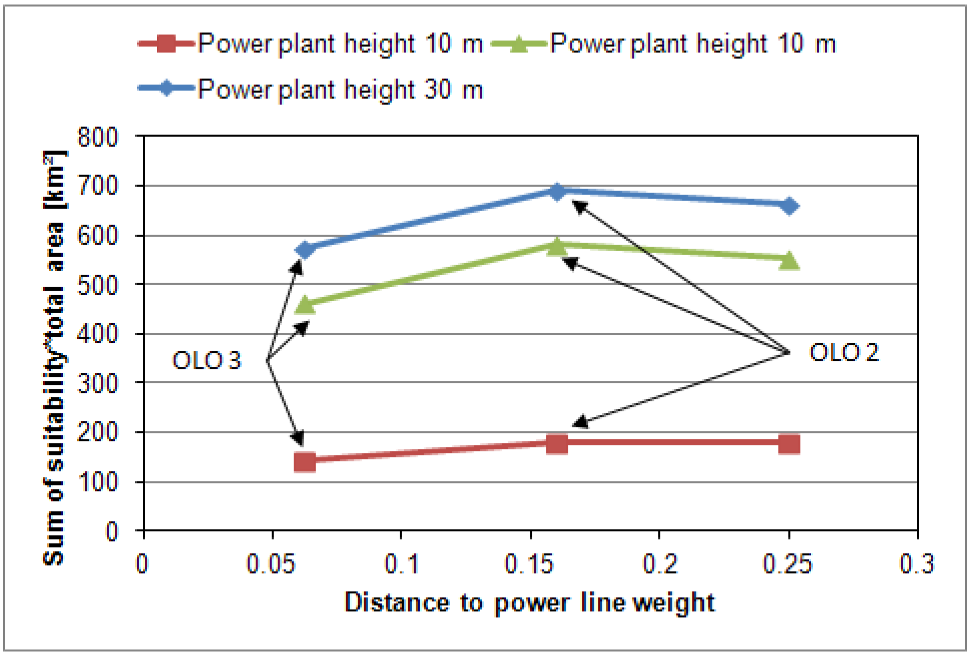

Figure 6.8: Total suitability as a function of distance to power line network weight for different wind power plant heights. The arrows indicate the respective overlay operations (OLO).

The final ranked output maps of the individual overlay operations confirm that with increasing wind power plant height, the area to be considered in the overlay operation (or the area which is not clipped by the Boolean constraints) increases. This is independent of the weight distribution of the overlay distribution and only depends on the wind power plant height associated Boolean constraints, as the total area considered for each overlay operation solely depends on the distance to buildings and starting wind speed Boolean datasets (Figure 6.9). The maps also demonstrate that the areas ranked for suitability are very scattered throughout the city (Figure 11.1-Figure 11.9).

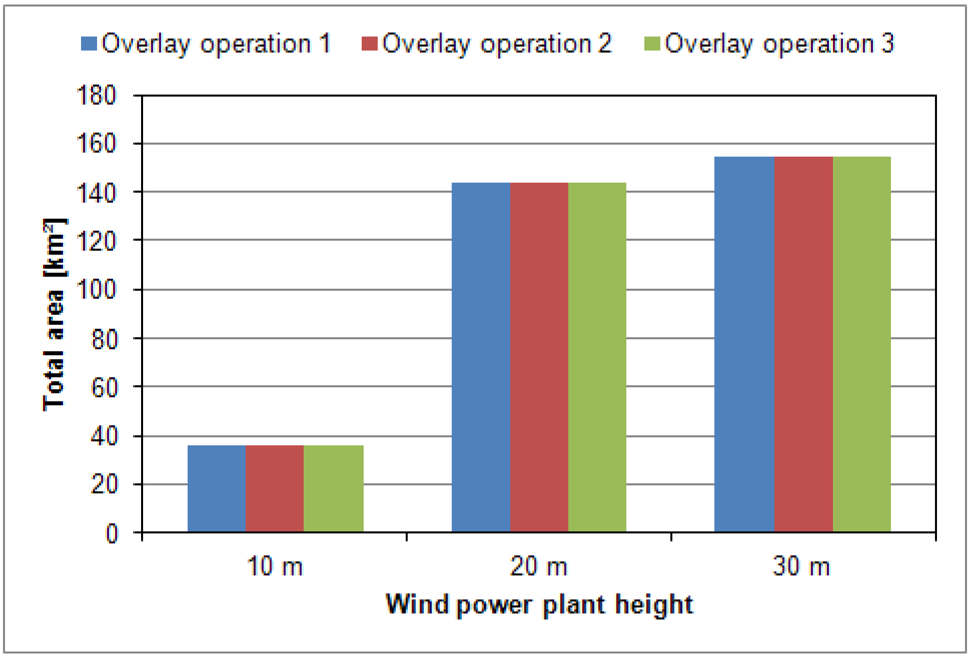

Figure 6.9: Influence of wind power plant height and overlay operation type on total included area of Berlin. Note that changes only occur as function of wind power plant height.

144 electric power poles have been investigated for their suitability to serve as tower for small wind power plant turbines and rotors. Seven power poles could not be included in the analysis as their location is in between blocs of the ISU 5 bloc map. Space between blocs of the ISU 5 bloc map has not been considered in this study, as no land use data is available at these locations. From the remaining 137 power poles 17 (for the wind power plant height of 10 m), 38 (for the wind power plant height of 20 m) and 43 (for the wind power plant height of 30 m) power poles were ranked for suitability with respect to the different overlay operations (Table 6.2).

Table 6.2: Results table for the Boolean overlay of electric power poles (Part II).

Suitability class	Overlay operation 1			Overlay operation 2			Overlay operation 3		
	Wind power plant height			Wind power plant height			Wind power plant height		
	10 m	20 m	30 m	10 m	20 m	30 m	10 m	20 m	30 m
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	5	5
3	0	5	5	0	0	0	0	0	0
4	0	0	0	0	5	5	12	15	16
5	8	3	2	3	2	1	5	18	6
6	9	30	36	14	31	21	0	0	16
7	0	0	0	0	0	16	0	0	0
8	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0
Sum	17	38	43	17	38	43	17	38	43

The number of ranked power poles and the rank value both increase with increasing wind power plant height for each overlay operation (Figure 6.10-Figure 6.12). Overlay operations 1 and 2 yield similar results significantly better results than overlay operation 3, which becomes in particular visible if a cut-off at a suitability class of 5 is conducted (Figure 6.13). Thereby, for overlay operations 1 and 2, 12.41, 24.09 and 27.74% of all considered power poles (137) have been rated with a suitability ≥ 5 for the respective wind power plant heights (10, 20 and 30 m), while for overlay operation 3, 3.65, 13.14 and 16.06% have suitabilities ≥ 5 for the respective wind power plant heights. The results are also shown in maps showing the colour coded power poles, which are mainly located on a north-to-south transect in the east of Berlin for each overlay operation and wind power plant height (Figure 11.10-Figure 11.18).

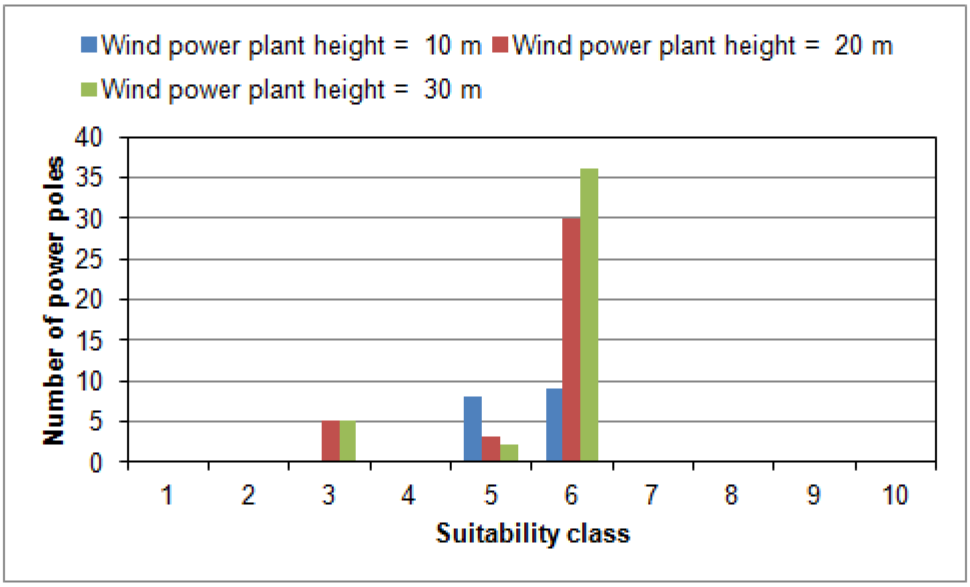

Figure 6.10: Number of power poles vs. suitability classes for overlay operation 1 and different wind power plant or power pole heights.

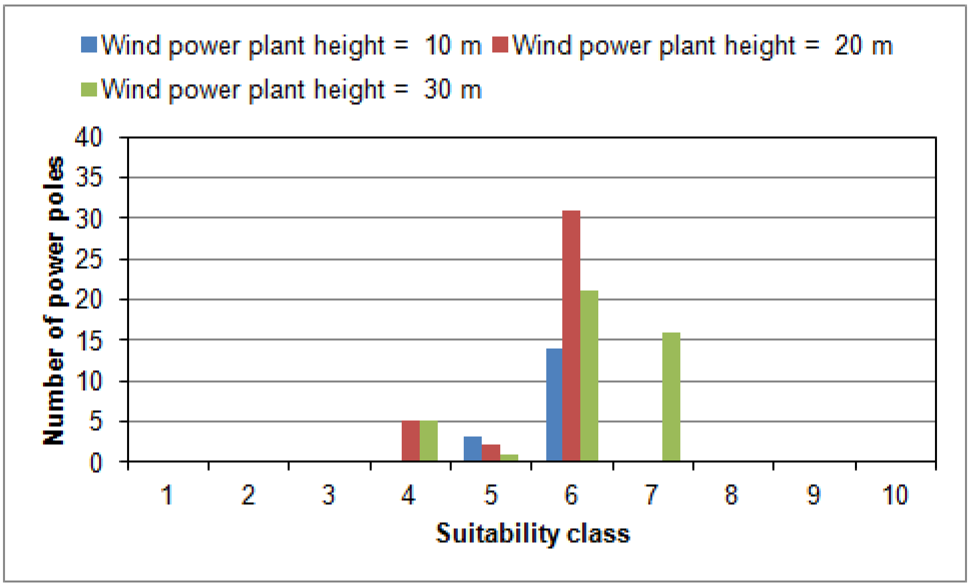

Figure 6.11: Number of power poles vs. suitability classes for overlay operation 2 and different wind power plant or power pole heights.

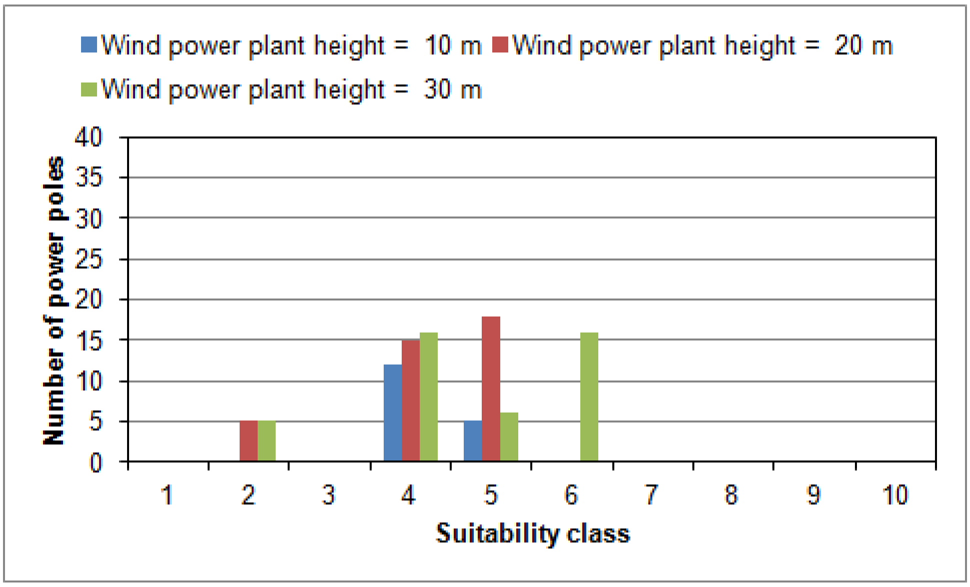

Figure 6.12: Number of power poles vs. suitability classes for overlay operation 3 and different wind power plant or power pole heights.

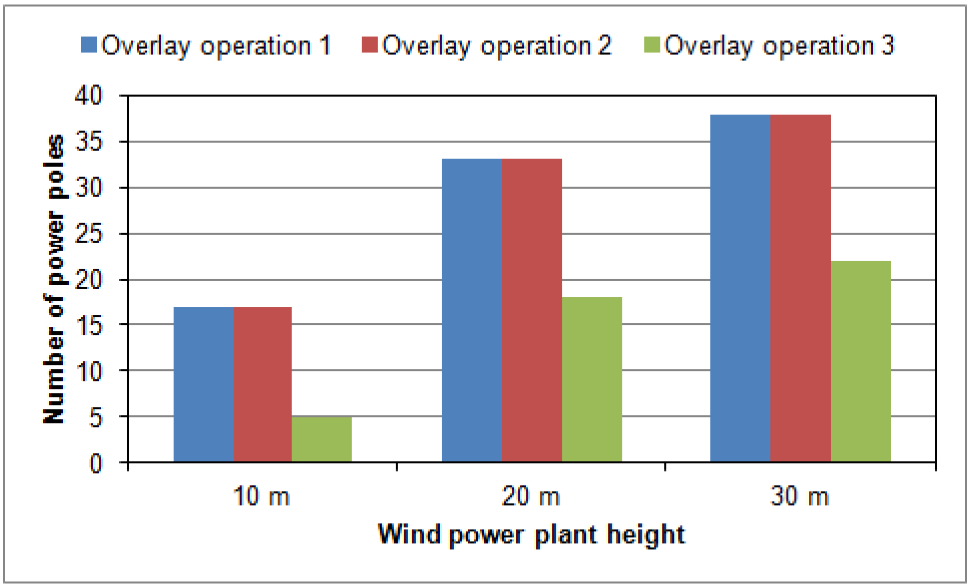

Figure 6.13: Number of power poles with a suitability ≥ 5. The total number of power poles included in this study have been 144, whereas 7 power poles could not be considered due to their location in between the blocs of the ISU 5 bloc map.

7 Discussion

Renewable energy generation is one of the main topics of the 21st century. In particular, wind energy has a large potential and is one of the most advanced technologies currently available (Gasch and Twele 2011). However, in many cases wind energy is restricted to large wind parks with wind power plants often reaching heights greater than 100 m (EWEA The European Wind Energy Association 2009). Where high population density and the presence of obstacles such as buildings prevent construction of large wind power plants, small wind power plants are an alternative (EWEA The European Wind Energy Association 2009). Nevertheless, small wind power plants are mainly used on roof tops of buildings in European cities, if at all. For example, in order to make use of wind energy in Berlin, an ongoing study concerns itself with the construction of small wind power plants on roof tops in Berlin (htw Hochschule für Technik und Wirtschaft Berlin 2012).Additionally, Berlin, as the capital of Germany, can serve as a typical example of this issue. Large wind power plants have been declared to being unsuitable for the Berlin area (BWE Bundesverband WindEnergie e.V. 2012), mainly due to the lack of spacious sites, high population density and therefore logistic challenges, which would cause high construction costs. The study presented in this thesis attempts to contribute to small wind power site assessment in Berlin by using a GIS based overlay analysis for small wind power plants on free space and in addition on electric power poles, whose ability to serve as tower for small wind power plants is recently discussed in Germany (Free energy 2012d; Frey architects 2011). To do so, a GIS based overlay analysis to investigate the small wind power potential of Berlin from a safety and performance point of view was conducted. Factors such as wind speed for three different power plant heights (10, 20 and 30 m), land use, distance to power line network, safety distance to buildings and wind shed/turbulences distance to buildings were included. The latter two vary as a function of the regarded wind power plant height. Safety and performance factors are the most important factors in wind power plant site assessment (Renewable UK 2012c). However, for a complete assessment, further aspects, which could not been covered in this study due to inaccessibility of the respective data, should be included. These factors are e.g. wind direction (e.g. van Haaren and Fthenakis 2011; Gasch and Twele 2011), distance to roads (Ouammi et al. 2012; Phuangpornpitak and Tia 2011), slope (e.g. Ouammi et al. 2012; Voivontas et al. 1998), visual impact (e.g. Bishop and Miller 2007; Jerpåsen and Larsen 2011; Molina-Ruiz et al. 2011; Möller 2006; Voivontas et al. 1998), noise effects (e.g. Cavallaro and Ciraolo 2005; Kaldellis et al. 2012; Saidur et al 2011; Son et al.2010), birds or other wild life habitats (e.g. Dahl et al. 2011; EWEA The European Wind Energy Association 2009; Farfán et al. 2009;

Saidur et al. 2011) and a more detailed investigation on social acceptance (e.g. Graham et al. 2009; Jobert et al. 2007; Jones and Eiser 2009, 2012; Meyerhoff et al. 2010; Musall and Kuik 2011; Pasqualetti 2011; Warren and Birnie 2009; Wolsink 2000). In addition, the used datasets have limitations to some extent. For example, the ISU 5 bloc map was used as base map for most calculations of this study. This map with its bloc and sub-bloc structure was used for the generation of the land use raster, as well as for the generation of the three wind speed raster datasets. Therefore, the land use raster classes and the wind speed values were also assigned bloc and sub bloc-wise. This form of assignment resulted in land use and wind speed raster datasets that were more generalized than necessary and pose a source of uncertainty. If it had been available, a classic base map without bloc and sub bloc structure, but with single features and “natural” areas would have been used in order to avoid these inaccuracies. Also, the assignment of wind speed values to the bloc map was very complex, as due to the wind speed measurements dating back to 1995, no direct match of structural classes was possible. Thus, a new assignment of values had to be performed on the basis of three different up-to-date structural classes, which goes in hand with a certain degree of subjectivity. However, it was tried to perform the reassignment on the basis of an outlined scheme with strict rules to reduce the human decision bias.

In most cases GIS based multi-criteria analysis techniques are employed in recent wind power site assessment studies (e.g. Janke 2010; Mondal and Denich 2010; Tiba et al. 2010). GIS have the ability of endorsing complex planning and management problems by supporting problem-solving in complex environments, where many spatially referenced data types have to be integrated (Carrion et al. 2008; Tegou et al. 2010; Tiba et al. 2010). Thereby, GIS can facilitate the acquisition, management, manipulation, analysis, modelling and visualization of spatially referenced data. These properties make a GIS the ideal tool for multi-criteria analysis of spatially referenced data. Hereby, different multi-criteria analysis approaches have been applied in the past (compare Malczewski 1999). Usually an overlay operation of the different datasets is the central part of a multi-criteria analysis. By doing so, two steps always have to be performed and can vary with respect to the different approaches. These steps are criterion weighting and definition of decision rules (compare Malczewski 1999). As data acquisition and integration has not been straight-forward in this study, it has been decided to choose a simple and transparent overlay analysis approach. Thus, a ranking and ratio scale method as criterion weighting method and simple additive weighting as decision rule were employed. The ranks were based on the fact that wind speed is the most important factor in wind power plant planning (EWEA The European Wind Energy Association 2009; Renewable UK 2012c) and distance to power line network can be considered as least important (Fleck and Huot 2009; Renewable UK 2011a, 2012a). However, the ratio scale only followed the ranks, but was chosen subjectively to set a focus on wind speed data, as this has been the dataset, which influenced most of the remaining produced datasets, such as distance to houses and land use data sets. It should be mentioned that other weight estimation techniques, such as pair-wise comparison and trade-off analysis methods might have yielded different results (Malczewski 1999). However, as two different weight estimation methods, leading to three different weight distributions, were used, it was possible to assess the influence of the overlay factors. Therefore, it could be argued, that the chosen weighting criteria supply enough sensitivity for a reliable wind power plant site assessment in Berlin. In addition, other decision rules than the simple additive weighting method, which was used in this study, could have yielded different results. In particular, a fuzzy additive weighting method could have been useful to address the uncertainties in this study in a more detailed manner by defining a fuzzy weight membership function, but this was beyond the scope of this thesis.

In general, suitable area increases with increasing wind power plant height, as wind speed is a function of height and more area becomes available with increasing wind power plant height due to more wind power plants towering above buildings. The results are promising. Up to 9% of Berlin's area has been assessed as suitable for construction of small wind power plants ≥ 20 m in this study, although nature and land reserves have been entirely excluded in this study and in contrast to some other studies (BWE Bundesverband WindEnergie e. V. 2012). This suggests an enormous potential for energy generation from small wind power plants in Berlin - in particular, when compared to previous studies, which investigated Berlin's potential for large wind power plants (BWE Bundesverband WindEnergie e.V. 2012).

The effect of changing the weights on total suitability is complex and has to be seen as an inter-play of the respective weights, as changing one weight necessarily leads to the change of at least one other weight. To fully assess the influence of each parameter the weights must be varied in a more comprehensive way than in this study. However, the weights have been applied with realistic ranks, with wind speed being the most important criterion (EWEA The European Wind Energy Association 2009; Renewable UK 2012c) and distance to power line network being the least important criterion (Fleck and Huot 2009; Renewable UK 2011a, 2012a). Consequently, the three different overlay operations allow drawing some general conclusions on weight influence. Hereby, it can be seen that an increase of the wind speed weight together with a significant decrease of the distance to power line network weight and a small change of the land use weight has a negative effect on total suitability. This might be explained by having the majority of low-medium wind speed areas close to power line networks, as such a combination would promote a decrease in total suitability, if increasing the wind speed weight and decreasing the distance to power line network weight. However, this explanation does not consider the small change of the land use weight. Anyways, even for a wind speed focused weighting criterion (overlay operation 3) around 5% of Berlin's area is rated as suitable for wind power plant heights ≥ 30 m. In overlay operations 1 and 2 the wind speed weight is kept constant. Thus, the results on these operations allow for an interpretation of the influence of land use and distance to power line network on total suitability. Thereby, an increase of the land use weight together with a decrease of the distance to power line network weight results in a slight increase of total suitability. A possible explanation might be that a majority of suitable land use areas are more likely in areas, where power line networks are not too common. However, the increase in total suitability is very weak and the correlation should be treated with care.

Economically, the results are very important for Berlin, as an area up to 80 km^2 could be used for wind power generation in addition to small wind power plants installed on roof tops of buildings, based on safety and performance factors. Assuming a wind power plant density of 1 power plant per hectare (10000 m^2) and an average maximum output of 5 kW this can be set equally to 8000 small wind power plants or a maximum total power output of 40 MW.

Similar results can be seen for the wind power plant site assessment for installation of wind power plants on existing electric energy poles. For power pole heights ≥ 20 m up to 38 power poles have been sited as suitable (suitability ≥ 5). This seems to be fairly low in number, but given the fact, that only 137 out of 144 power poles could be included in this study, adds up to 28% of suitable power poles. In cities, where more power poles are available this strategy might have a greater impact. Also, telephone poles or other existing constructions which could be suitable to carry small wind power plant rotors were not included.

8 Conclusions

For the area of Berlin, Germany, a GIS based multi-criteria analysis with simple additive weighting decision rule and a ranking and rating weight estimation for the assessment of small wind power plants has been conducted. In addition, the suitability of existing power poles in Berlin to serve as constructional base for small wind power plant rotors has been investigated. The study involves mainly safety and performance factors, which are wind speed for three different wind power plant heights (10, 20 and 30 m), land use, distance to power line network and performance and safety distances to houses. From the results the following conclusions can be drawn:

- Small wind power plants with a height ≥ 20 m have been rated as suitable for up to 9% of the total area of Berlin. Based on a density of 1 power plant per hectare this would equal 8000 wind power plants and a power output of 40 MW (assuming an average output of 5 kW per wind power plant). Thereby, the locations of suitable areas are very scattered throughout Berlin.
- Depending on the weight distribution of the overlay analysis, up to 28% of Berlin's power poles have been rated as suitable as constructional bases for small wind power plant rotors. Although this equals only a total number of 38 power poles, the result is promising for cities, where a larger absolute number of power poles is available. Also, the result is encouraging with respect to further studies investigating not only the potential of power poles for small wind power plant bases, but other pole type structures, such as telephone poles, antenna towers, etc.
- Even though the overlay analysis technique and associated weight criteria and decision rules used in this study are simple techniques, they have been proven to be useful to honour the included assessment factors in this study.
- Energy generation from wind power is possible in Berlin and has a medium to high potential. However this potential is hidden in decentralized installation of small wind power plants.

Finally, in comparison to large wind power plant installation potential of Berlin, the results of this study demonstrate the possible impact of unconventional, decentralized power generation. This form of power generation has the advantage of being highly flexible and to have cheap individual units, which, as a further plus, allows for stake holding of communities and citizens. Ultimately, the promising results of this study suggest conducting more future studies related to small wind power site assessment in cities such as Berlin, combining more or different types of data sets.

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10 Appendix A: Wind speed assignment table

Table 10.1: Table showing the assignment scheme to link structural types of the wind speed table from 1995 to new land use types. The Wind ID column can be used to link this table to the wind speed and roughness length tables in chapter 4 and chapter 5, respectively.

Decision Comment	Wind speed ID	Old Structural types wind map	General land use entry	Constructional land use	City structure land use
Water bodies can be treated similar to Tempelhof because these are "open areas" with almost no or only few obstacles	1	Reference station Airport Tempelhof (now open area)	Water bodies	Water bodies	None
"Core area" is defined as structural type of Berlin	2	Core area	Core area	Core area	Building with predominant use for trade and service
Garden courtyard	3	Garden courtyard	Residential use	Closed and semi-open block developments, tidy and garden courtyards, 4-storied	Wilhelminian style perimeter block developments with side and rear buildings
	3	Garden courtyard	Mixed use	Mixed building, semi-open and open shingle courtyard , 2-4 storied	Wilhelminian style perimeter block developments with side and rear buildings
Garden courtyard	3	Garden courtyard	Mixed use	Closed and semi-open block developments, tidy and garden courtyards, 4-storied	Wilhelminian style perimeter block developments with side and rear buildings
	3	Garden courtyard	Residential use	Mixed building, semi-open and open shingle courtyard , 2-4 storied	Wilhelminian style perimeter block developments with side and rear buildings
	4	Closed courtyard	Mixed use	Closed block developments, backyard, 5-storied	Wilhelminian style block developments with side wings and rear buildings
	4	Closed courtyard	Residential use	Closed block developments, backyard, 5-storied	Wilhelminian style block developments with side wings and rear buildings
Closed courtyards	4	Closed courtyard	Residential use	Narrow block developments, closed courtyards, 5-6 storied	Wilhelminian style block developments with side wings and rear buildings
Closed courtyards	4	Closed courtyard	Mixed use	Narrow block developments, closed courtyards, 5-6 storied	Wilhelminian style block developments with side wings and rear buildings
Public and special facilities, sealing above 50%	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Public and special facilities	New building school (built after 1945)	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
Public and special facilities, sealing above 50%	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Public and special facilities	Culture	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
Public and special facilities, sealing above 50%	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Public and special facilities	Daycare facility for children	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites

Continuation of table 10.1.

Decision Comment	Wind speed ID	Old Structural types wind map	General land use entry	Constructional land use	City structure land use
Public and special facilities, sealing above 50%	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Public and special facilities	University and research	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
Trade and industry	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Trade and industry, large-scale retail	Trade and industrial area, large-scale retail with little building	Light building with predominant use for trade and industry
Public and special facilities, sealing above 50%	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Public and special facilities	Hospital	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
Public and special facilities, sealing above 50%	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Public and special facilities	Other youth facilities	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
Traffic area	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Traffic area	Other traffic areas	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
Trade	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Mixed use	Mixed area, predominantly handcraft and small trade, with little building	Light building with predominant use for trade and industry
Public and special facilities, sealing above 50%	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Public and special facilities	Administration	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
Public and special facilities, sealing above 50%	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Public and special facilities	Old building school (built before 1945)	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
City plaza without high amount of vegetation	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	City plaza/promenade	Other traffic areas	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
Parking area with building=> in area with high sealing	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Traffic area	Parking site	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites

Continuation of table 10.1.

Decision Comment	Wind speed ID	Old Structural types wind map	General land use entry	Constructional land use	City structure land use
Public and special facilities, sealing above 50%	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Traffic area	Rail station and facilities without railway tracks	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
Public and special facilities, sealing above 50%	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Public and special facilities	Safety and order	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
Covered=>sealing above 50%	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Sports use	Covered sports grounds	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
Trade and industry	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Waste management and maintenance/supplying utilities	Areas of waste management and maintenance/supplying utilities	Light building with predominant use for trade and industry
Public and special facilities, sealing above 50%	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Public and special facilities	Church	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
Public and special facilities, sealing above 50%	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Public and special facilities	Other heterogeneous public facilities and special facilities areas	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
Trade and industry	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Trade and industry, large-scale retail	Trade and industrial area, large-scale retail with dense building	Dense building with predominant use for trade and industry

Continuation of table 10.1.

Decision Comment	Wind speed ID	Old Structural types wind map	General land use entry	Constructional land use	City structure land use
Traffic area	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Traffic area	Rail track	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
City plaza without high amount of vegetation	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	City plaza/promenade	Church	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
City plaza without high amount of vegetation	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	City plaza/promenade	Rail track	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
Trade and industry	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Mixed use	Mixed area, predominantly handcraft and small trade, with dense building	Dense building with predominant use for trade and industry
Like Airport Tempelhof	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	Traffic area	Airport	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
City plaza without high amount of vegetation	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	City plaza/promenade	Rail station and facilities without railway tracks	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
City plaza without high amount of vegetation	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	City plaza/promenade	Parking site	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
City plaza without high amount of vegetation	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	City plaza/promenade	Culture	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
City plaza without high amount of vegetation	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	City plaza/promenade	University and research	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites

Continuation of table 10.1.

Decision Comment	Wind speed ID	Old Structural types wind map	General land use entry	Constructional land use	City structure land use
City plaza without high amount of vegetation	5	Mixed area with mainly manufacturing trade, industrial-/trading area, city plaza, parking area public facilities, waste management and maintenance/supplying utilities, special utilities, sealing above 50%	City plaza/promenade	Other heterogeneous public facilities and special facilities areas	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
Perimeter block developments after 1945=postwar	6	Unsorted rebuilding , postwar perimeter block developments	Mixed use	Closed and semi-open, cored perimeter block developments, gaps closed after 1945	Wilhelminian style perimeter block developments with extensive changes
Perimeter block developments after 1945=postwar	6	Unsorted rebuilding , postwar perimeter block developments	Residential use	Closed and semi-open, cored perimeter block developments, gaps closed after 1945	Wilhelminian style perimeter block developments with extensive changes
Gaps closed after 1945	6	Unsorted rebuilding , postwar perimeter block developments	Residential use	Heterogeneous , inner-city mixed building, gaps closed after 1945	High postwar building
Gaps closed after 1945	6	Unsorted rebuilding , postwar perimeter block developments	Mixed use	Heterogeneous , inner-city mixed building, gaps closed after 1945	High postwar building
Large housing estate and high building	7	Large housing estates/large residential areas	Mixed use	Large housing estates with point (square ground area) tower blocks , 4-11 storied	High postwar building
Residential area/housing estate probably large	7	Large housing estates/large residential areas	Residential use	Settlements of the 1990ies and younger	Residential areas of the 90ies
"Large housing estate" is the more detailed description	7	Large housing estates/large residential areas	Residential use	Large housing estates with point (square ground area) tower blocks , 4-11 storied	High postwar building
Residential area/housing estate probably large	7	Large housing estates/large residential areas	Mixed use	Settlements of the 1990ies and younger	Residential areas of the 90ies
"Large housing estate" is more detailed than "core area"	7	Large housing estates/large residential areas	Core area	Large housing estates with point (square ground area) tower blocks , 4-11 storied	High postwar building
"Large housing estate" is the more detailed description	7	Large housing estates/large residential areas	Trade and industry, large-scale retail	Large housing estates with point (square ground area) tower blocks , 4-11 storied	High postwar building
Buildings/houses in rows	8	Houses in rows	Residential use	Buildings in rows with landscape-like settlement greenery, 3-6 storied	Building in rows, from the 50ies onwards
Buildings/houses in rows	8	Houses in rows	Residential use	Perimeter block development with large courtyards, 3-5 storied	Perimeter block developments and buildings in rows of the 20ies and 30ies
Buildings/houses in rows	8	Houses in rows	Residential use	Buildings in rows with architectural row greenery, 3-5 storied	Perimeter block developments and buildings in rows of the 20ies and 30ies
Buildings/houses in rows	8	Houses in rows	Mixed use	Buildings in rows with architectural row greenery, 3-5 storied	Perimeter block developments and buildings in rows of the 20ies and 30ies
Buildings/houses in rows	8	Houses in rows	Mixed use	Buildings in rows with landscape-like settlement greenery, 3-6 storied	Building in rows, from the 50ies onwards

Continuation of table 10.1.

Decision Comment	Wind speed ID	Old Structural types wind map	General land use entry	Constructional land use	City structure land use
Buildings/houses in rows	8	Houses in rows	Mixed use	Perimeter block development with large courtyards, 3-5 storied	Perimeter block developments and buildings in rows of the 20ies and 30ies
Village	9	Village type	Residential use	Village-like mixed building	Village-like building
Village	9	Village type	Mixed use	Village-like mixed building	Village-like building
"Uncovered"=> sealing below 50%	10	Public facilities, waste management and maintenance/supplying utilities, special utilities, sealing below 50%	Sports use	Uncovered sports grounds	Not or slightly built-up areas of public and special use, as well as green and open areas
Garden use	11	Garden ranks type, garden type, park-like garden type, gardens and semi-private surrounding greens	Residential use	Free-standing family homes with garden	Low building with gardens
garden semi-detached house	11	Garden ranks type, garden type, park-like garden type, gardens and semi-private surrounding greens	Residential use	Terraced and semi-detached houses with garden	Low building with gardens
Gardens and semi-private surrounding greens	11	Garden ranks type, garden type, park-like garden type, gardens and semi-private surrounding greens	Residential use	Density in single-unit detached house areas, mixed building with gardens and semi-private green surroundings	Building with gardens and semi-private surrounding greens
Park-like garden type	11	Garden ranks type, garden type, park-like garden type, gardens and semi-private surrounding greens	Residential use	Villas and rental villas with park-like gardens	Villas with park-like gardens
Family homes with gardens	11	Garden ranks type, garden type, park-like garden type, gardens and semi-private surrounding greens	Mixed use	Free-standing family homes with garden	Low building with gardens
Park-like garden type	11	Garden ranks type, garden type, park-like garden type, gardens and semi-private surrounding greens	Mixed use	Villas and rental villas with park-like gardens	Villas with park-like gardens
Gardens and semi-private surrounding greens	11	Garden ranks type, garden type, park-like garden type, gardens and semi-private surrounding greens	Mixed use	Density in single-unit detached house areas, mixed building with gardens and semi-private green surroundings	Building with gardens and semi-private surrounding greens
garden semi-detached house	11	Garden ranks type, garden type, park-like garden type, gardens and semi-private surrounding greens	Mixed use	Terraced and semi-detached houses with garden	Low building with gardens
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, grassland like vegetation	Parking site	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, grassland like vegetation	Fallow land	Not or slightly built-up areas of public and special use, as well as green and open areas
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Farmland	Farmland	Not or slightly built-up areas of public and special use, as well as green and open areas
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, grassland like vegetation	Other youth facilities	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, grassland like vegetation	Rail track	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Farmland	University and research	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites

Continuation of table 10.1.

Decision Comment	Wind speed ID	Old Structural types wind map	General land use entry	Constructional land use	City structure land use
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, grassland like vegetation	Trade and industrial area, large-scale retail with little building	Light building with predominant use for trade and industry
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, without vegetation	Fallow land	Not or slightly built-up areas of public and special use, as well as green and open areas
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, grassland like vegetation	Airport	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, without vegetation	Mixed area, predominantly handcraft and small trade, with little building	Light building with predominant use for trade and industry
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Farmland	Culture	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, without vegetation	Trade and industrial area, large-scale retail with little building	Light building with predominant use for trade and industry
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, grassland like vegetation	Safety and order	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, grassland like vegetation	Other traffic areas	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, grassland like vegetation	Other heterogeneous public facilities and special facilities areas	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, grassland like vegetation	Administration	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, without vegetation	Areas of waste management and maintenance/supplying utilities	Light building with predominant use for trade and industry
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, grassland like vegetation	New building school (built after 1945)	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, grassland like vegetation	Hospital	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, grassland like vegetation	Culture	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, without vegetation	Other traffic areas	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites

Continuation of table 10.1.

Decision Comment	Wind speed ID	Old Structural types wind map	General land use entry	Constructional land use	City structure land use
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, grassland like vegetation	Areas of waste management and maintenance/supplying utilities	Light building with predominant use for trade and industry
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, grassland like vegetation	Mixed area, predominantly handcraft and small trade, with little building	Light building with predominant use for trade and industry
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, grassland like vegetation	Daycare facility for children	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, without vegetation	Daycare facility for children	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, grassland like vegetation	Rail station and facilities without railway tracks	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, without vegetation	Rail station and facilities without railway tracks	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	12	Farmland, ruderal /fallow land with or without grassland like vegetation	Fallow land, without vegetation	Parking site	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	13	Allotments, weekend home area, cemetery, tree nursery,camping, parking area, city plaza with high amount of vegetation	Allotments	Allotments	Not or slightly built-up areas of public and special use, as well as green and open areas
"NUTZUNG"/Use is best defined	13	Allotments, weekend home area, cemetery, tree nursery,camping, parking area, city plaza with high amount of vegetation	Weekend cottages and allotment-like utilisation	Weekend cottages and allotment-like areas	Low building with gardens
Green area and camping site --> 13	13	Allotments, weekend home area, cemetery, tree nursery,camping, parking area, city plaza with high amount of vegetation	Public and special facilities	Camping site	Not or slightly built-up areas of public and special use, as well as green and open areas
Green city plaza/city plaza with high amount of vegetation	13	Allotments, weekend home area, cemetery, tree nursery,camping, parking area, city plaza with high amount of vegetation	City plaza/promenade	City plaza/promenade	Not or slightly built-up areas of public and special use, as well as green and open areas
"NUTZUNG"/Use is best defined	13	Allotments, weekend home area, cemetery, tree nursery,camping, parking area, city plaza with high amount of vegetation	Cemetery	Cemetery	Not or slightly built-up areas of public and special use, as well as green and open areas
"NUTZUNG"/Use is best defined	13	Allotments, weekend home area, cemetery, tree nursery,camping, parking area, city plaza with high amount of vegetation	Tree nursery/horticulture	Tree nursery/horticulture	Not or slightly built-up areas of public and special use, as well as green and open areas
"NUTZUNG"/Use is best defined	13	Allotments, weekend home area, cemetery, tree nursery,camping, parking area, city plaza with high amount of vegetation	Tree nursery/horticulture	University and research	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites

Continuation of table 10.1.

Decision Comment	Wind speed ID	Old Structural types wind map	General land use entry	Constructional land use	City structure land use
"NUTZUNG"/Use is best defined	13	Allotments, weekend home area, cemetery, tree nursery,camping, parking area, city plaza with high amount of vegetation	Allotments	Rail track	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	13	Allotments, weekend home area, cemetery, tree nursery,camping, parking area, city plaza with high amount of vegetation	Tree nursery/horticulture	Other heterogeneous public facilities and special facilities areas	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	13	Allotments, weekend home area, cemetery, tree nursery,camping, parking area, city plaza with high amount of vegetation	Allotments	Rail station and facilities without railway tracks	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	13	Allotments, weekend home area, cemetery, tree nursery,camping, parking area, city plaza with high amount of vegetation	Cemetery	Church	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	Forest	Not or slightly built-up areas of public and special use, as well as green and open areas
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	Other heterogeneous public facilities and special facilities areas	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	Hospital	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	Rail track	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	Other traffic areas	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	Safety and order	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	Other youth facilities	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	Trade and industrial area, large-scale retail with little building	Light building with predominant use for trade and industry
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	New building school (built after 1945)	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites

Continuation of table 10.1.

Decision Comment	Wind speed ID	Old Structural types wind map	General land use entry	Constructional land use	City structure land use
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	Rail station and facilities without railway tracks	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	Village-like mixed building	Village-like building
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	Camping site	Not or slightly built-up areas of public and special use, as well as green and open areas
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	Administration	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	Areas of waste management and maintenance/supplying utilities	Light building with predominant use for trade and industry
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	Mixed area, predominantly handcraft and small trade, with little building	Light building with predominant use for trade and industry
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	Parking site	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	Airport	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	Culture	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	Daycare facility for children	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	14	Forest, ruderal/fallow land with forest like vegetation	Forests and forestry	University and research	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Park/Green area	Park/Green area	Not or slightly built-up areas of public and special use, as well as green and open areas
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Park/Green area	Forest	Not or slightly built-up areas of public and special use, as well as green and open areas
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Fallow land, mix of grassland, bushes and trees	Fallow land	Not or slightly built-up areas of public and special use, as well as green and open areas
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Grassland/green area	Farmland	Not or slightly built-up areas of public and special use, as well as green and open areas
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Grassland/green area	University and research	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Park/Green area	Culture	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites

Continuation of table 10.1.

Decision Comment	Wind speed ID	Old Structural types wind map	General land use entry	Constructional land use	City structure land use
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Park/Green area	Other traffic areas	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Fallow land, mix of grassland, bushes and trees	Other traffic areas	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Fallow land, mix of grassland, bushes and trees	Rail track	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Park/Green area	University and research	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Park/Green area	Hospital	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Park/Green area	Church	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Fallow land, mix of grassland, bushes and trees	Trade and industrial area, large-scale retail with little building	Light building with predominant use for trade and industry
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Park/Green area	Rail track	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Fallow land, mix of grassland, bushes and trees	Rail station and facilities without railway tracks	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Park/Green area	Other heterogeneous public facilities and special facilities areas	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Fallow land, mix of grassland, bushes and trees	Airport	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Fallow land, mix of grassland, bushes and trees	Parking site	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Fallow land, mix of grassland, bushes and trees	Areas of waste management and maintenance/supplying utilities	Light building with predominant use for trade and industry
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Fallow land, mix of grassland, bushes and trees	Village-like mixed building	Village-like building

Continuation of table 10.1.

Decision Comment	Wind speed ID	Old Structural types wind map	General land use entry	Constructional land use	City structure land use
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Fallow land, mix of grassland, bushes and trees	Culture	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Park/Green area	Parking site	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Park/Green area	Fallow land	Not or slightly built-up areas of public and special use, as well as green and open areas
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Park/Green area	Daycare facility for children	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Park/Green area	New building school (built after 1945)	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Fallow land, mix of grassland, bushes and trees	Other heterogeneous public facilities and special facilities areas	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Grassland/green area	Safety and order	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Fallow land, mix of grassland, bushes and trees	Safety and order	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Fallow land, mix of grassland, bushes and trees	Mixed area, predominantly handcraft and small trade, with little building	Light building with predominant use for trade and industry
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Park/Green area	Administration	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Park/Green area	Safety and order	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Fallow land, mix of grassland, bushes and trees	Administration	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Park/Green area	Other youth facilities	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Fallow land, mix of grassland, bushes and trees	Old building school (built before 1945)	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Fallow land, mix of grassland, bushes and trees	New building school (built after 1945)	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites
"NUTZUNG"/Use is best defined	15	Green area, park, ruderal/fallow land with bushes/tree vegetation	Park/Green area	Old building school (built before 1945)	Building with predominant use for public utilities and special utilities, traffic areas without street areas or building sites

11 Appendix B: Result maps

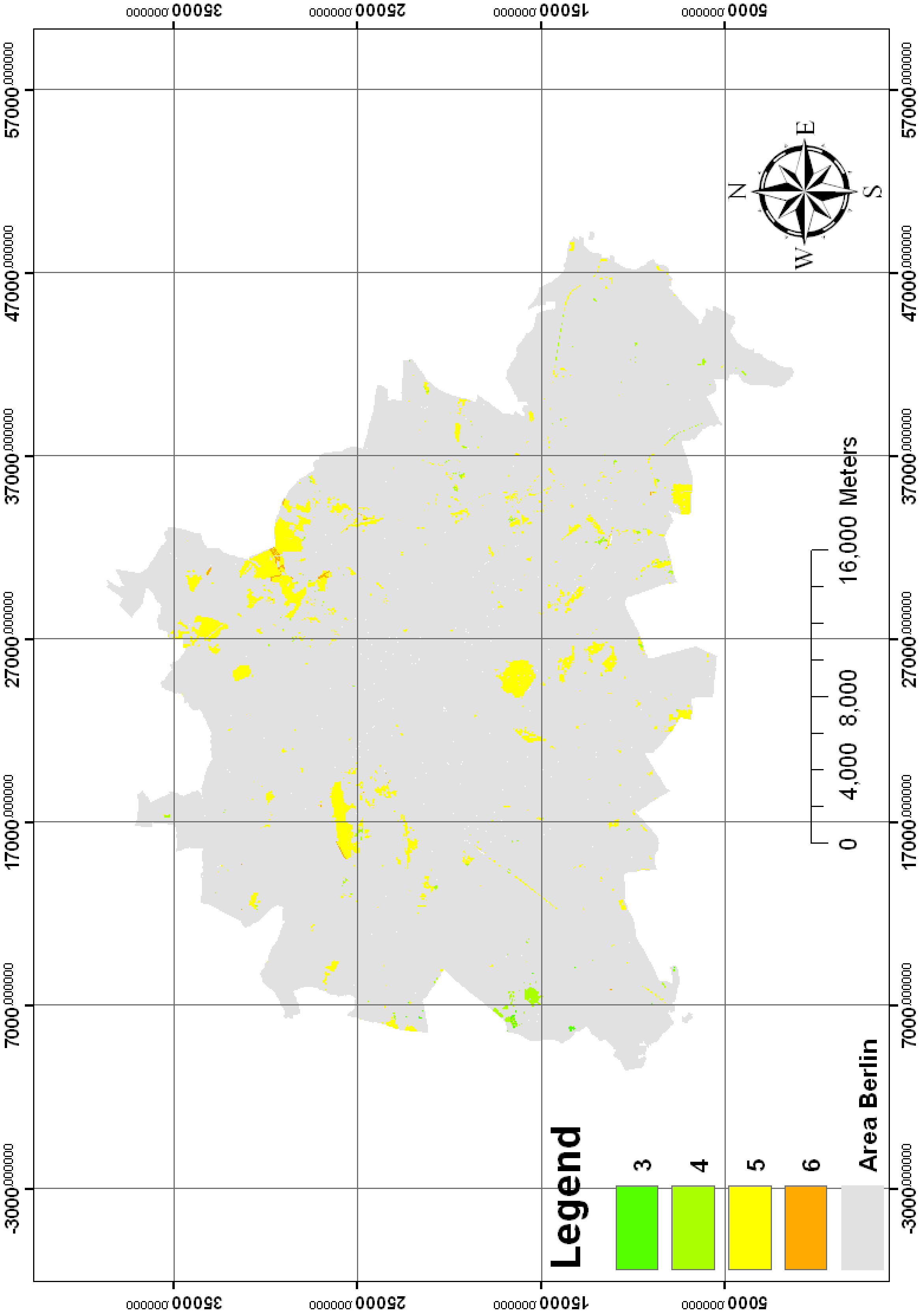

Figure 11.1: Map showing areas ranked for suitability for small wind power plants resulting from overlay operation 1 and a wind power plant height of 10 m.

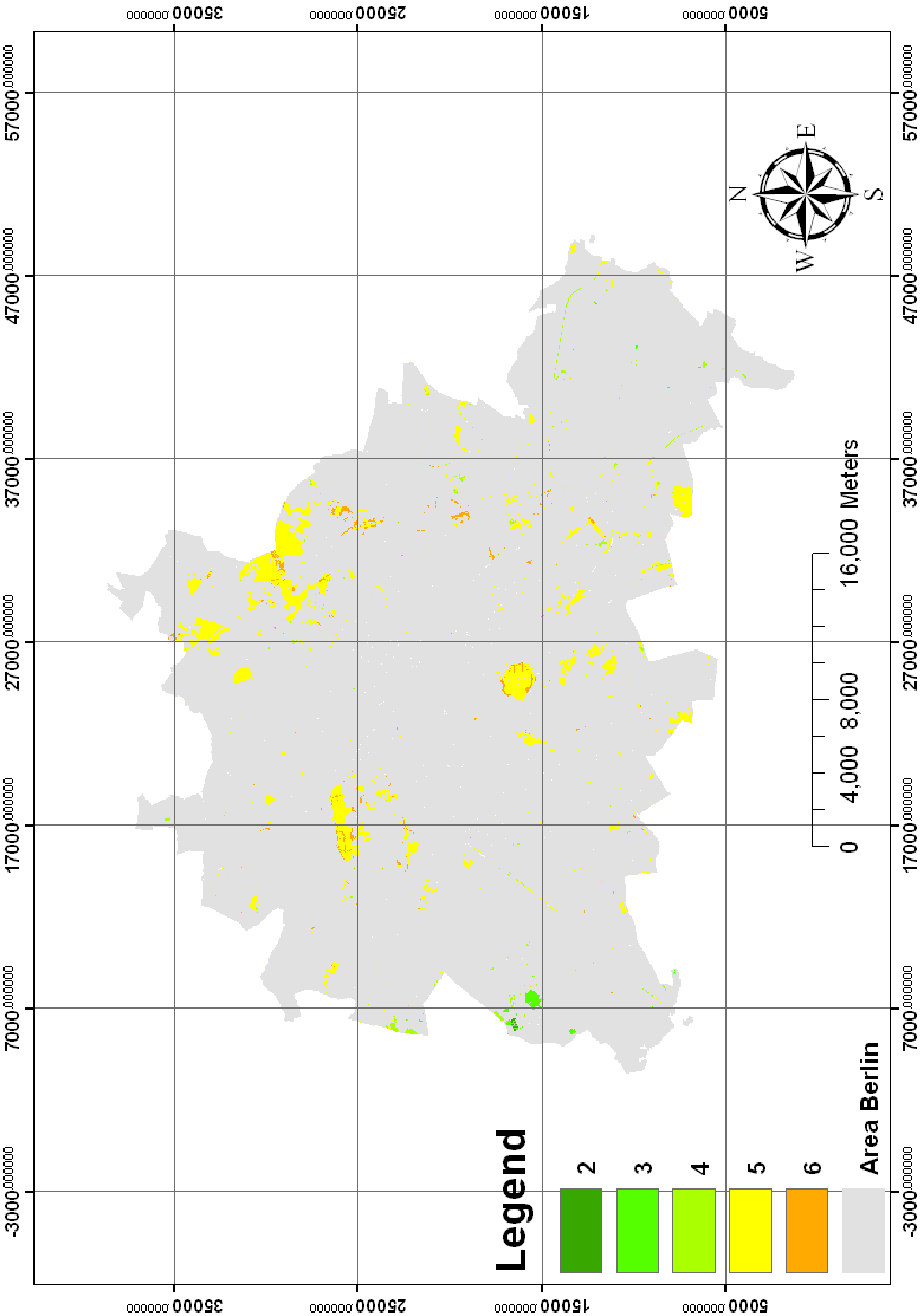

Figure 11.2: Map showing areas ranked for suitability for small wind power plants resulting from overlay operation 2 and a wind power plant height of 10 m.

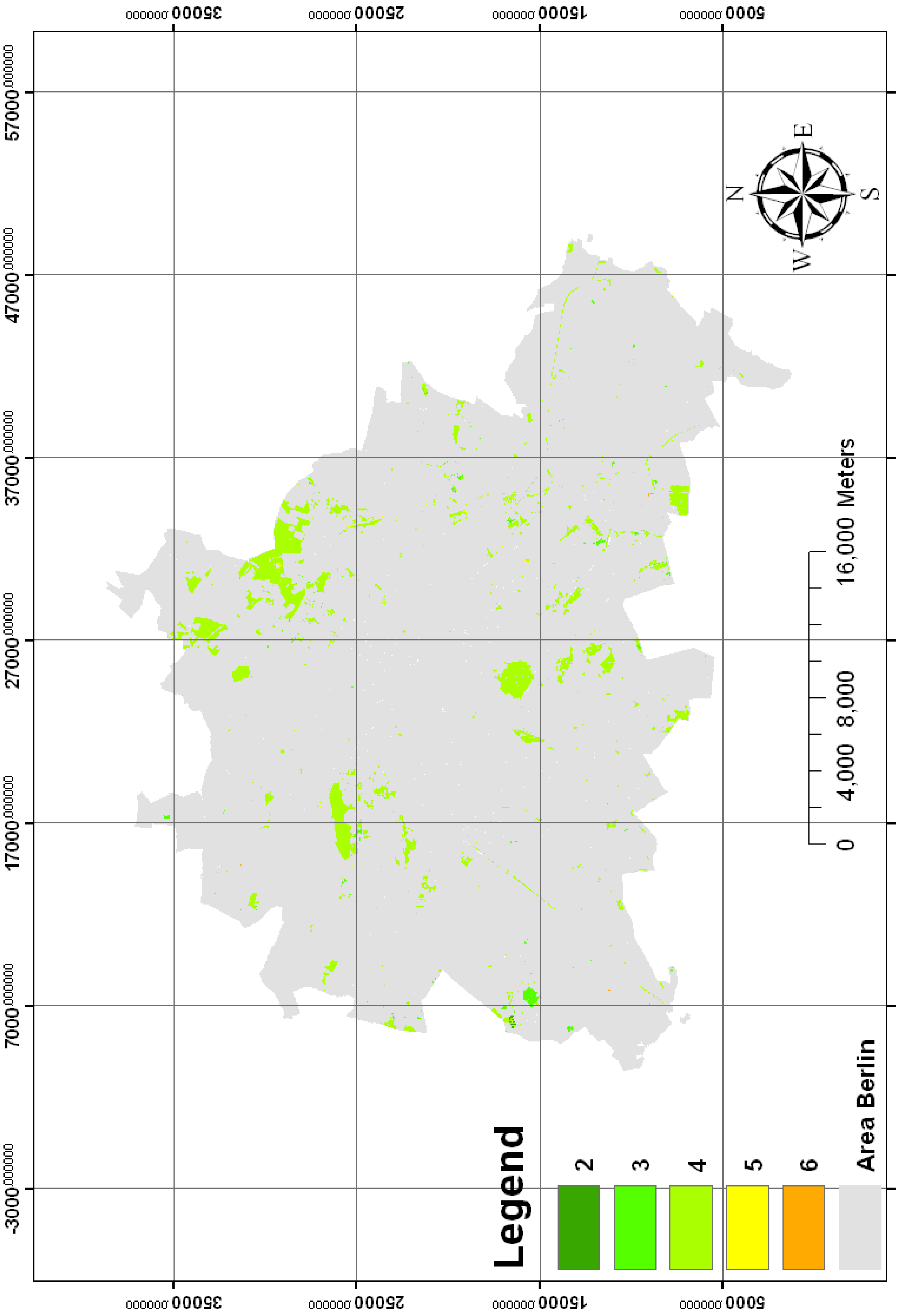

Figure 11.3: Map showing areas ranked for suitability for small wind power plants resulting from overlay operation 3 and a wind power plant height of 10 m.

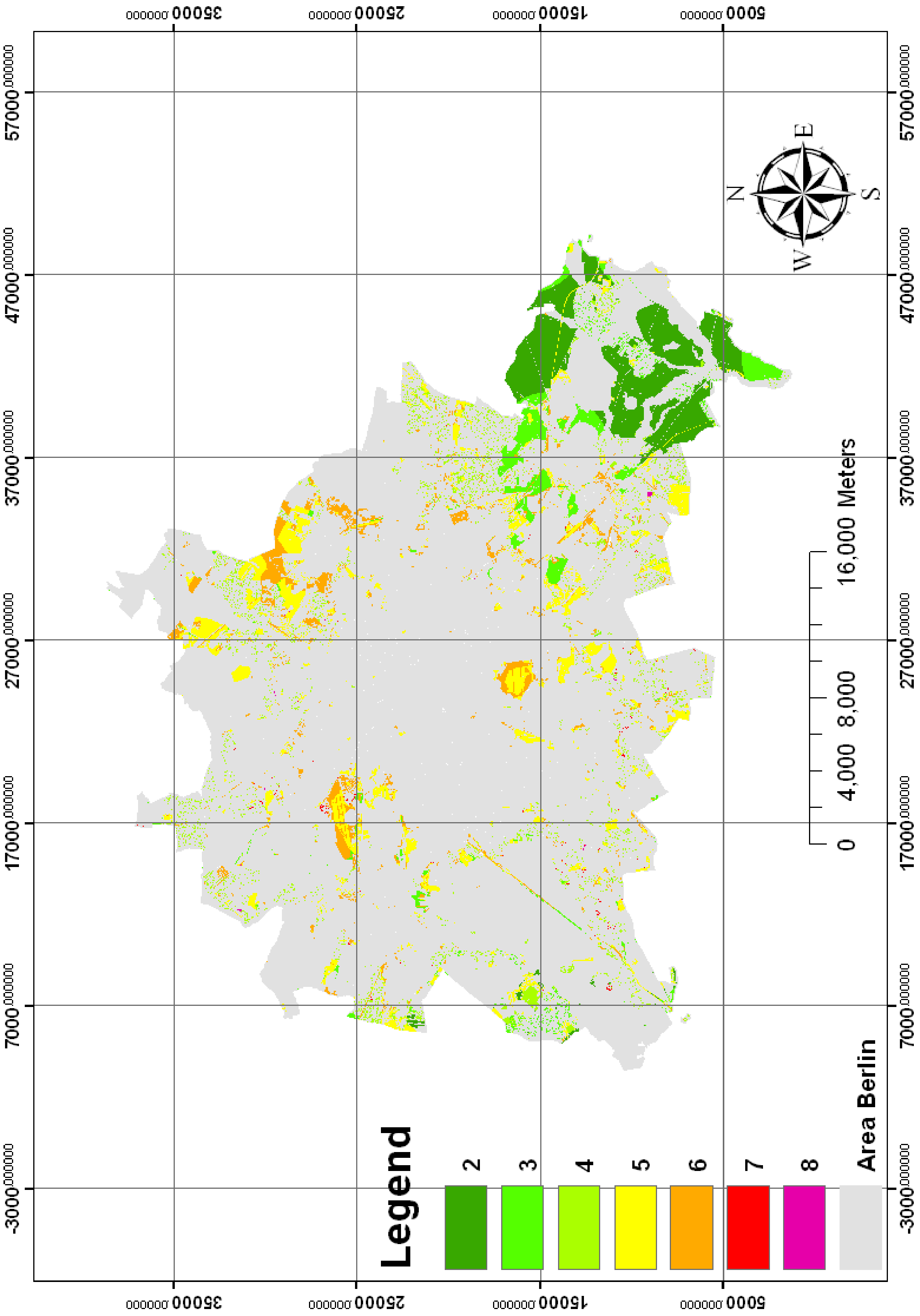

Figure 11.4: Map showing areas ranked for suitability for small wind power plants resulting from overlay operation 1 and a wind power plant height of 20 m.

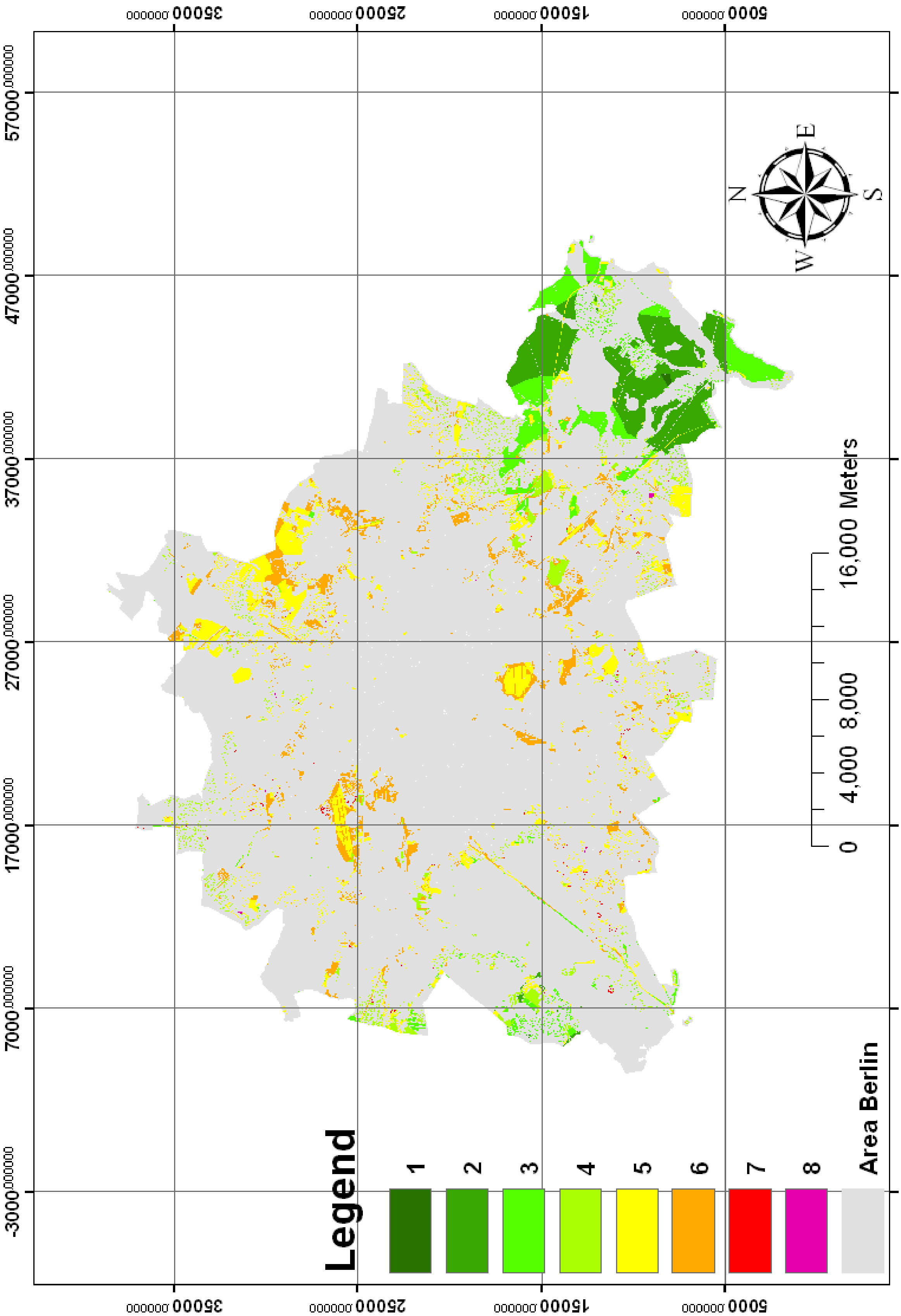

Figure 11.5: Map showing areas ranked for suitability for small wind power plants resulting from overlay operation 2 and a wind power plant height of 20 m.

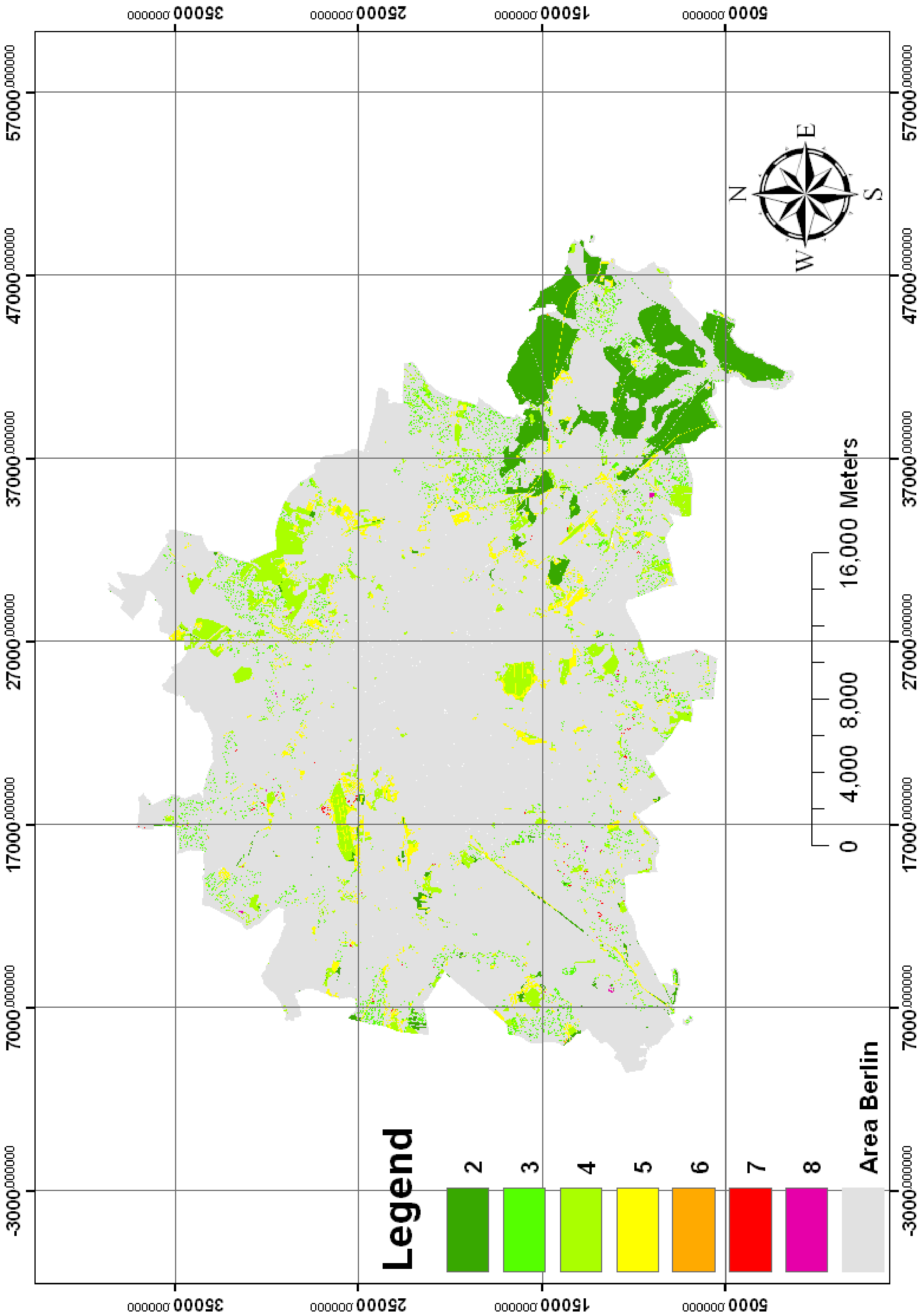

Figure 11.6: Map showing areas ranked for suitability for small wind power plants resulting from overlay operation 3 and a wind power plant height of 20 m.

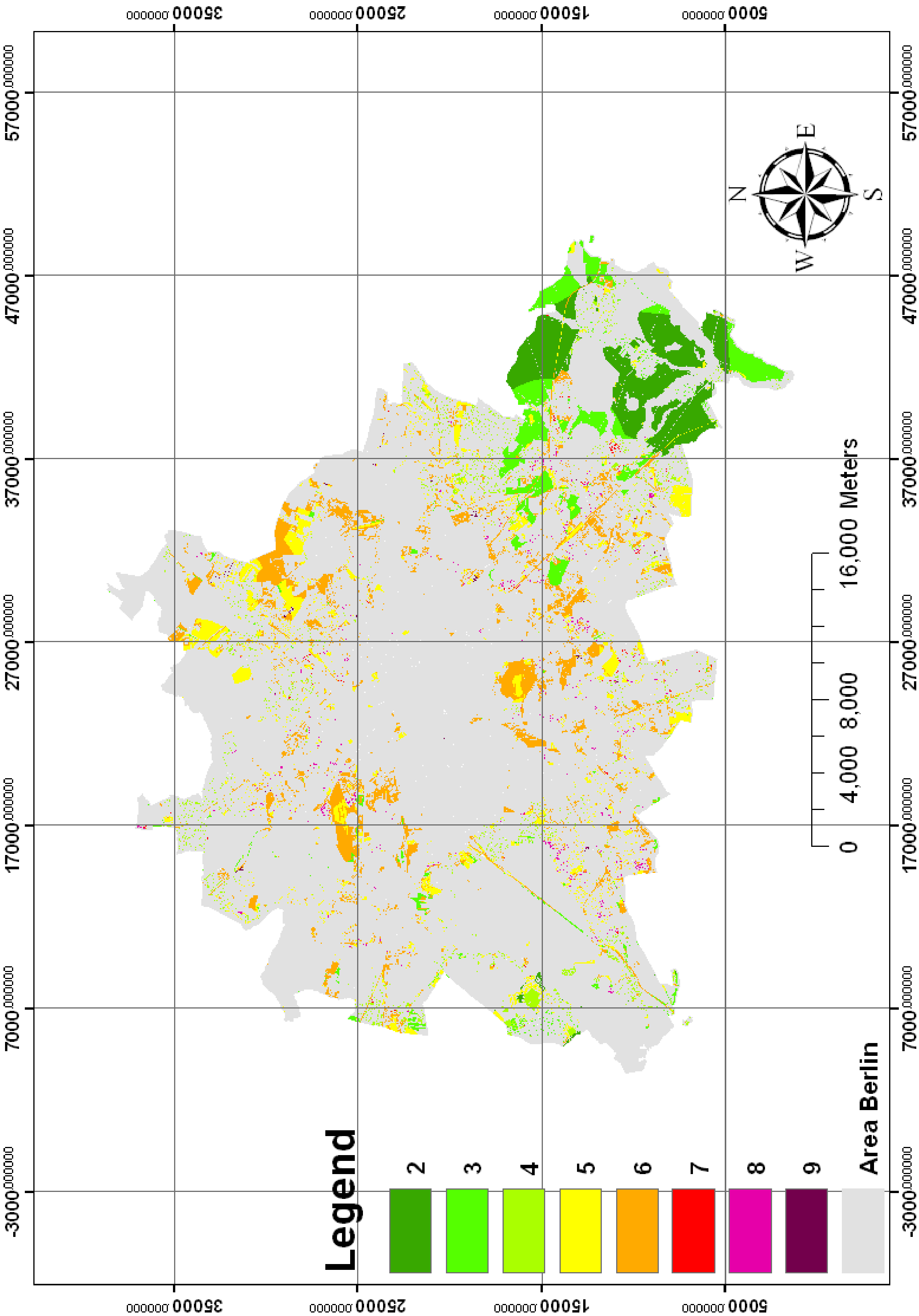

Figure 11.7: Map showing areas ranked for suitability for small wind power plants resulting from overlay operation 1 and a wind power plant height of 30 m.

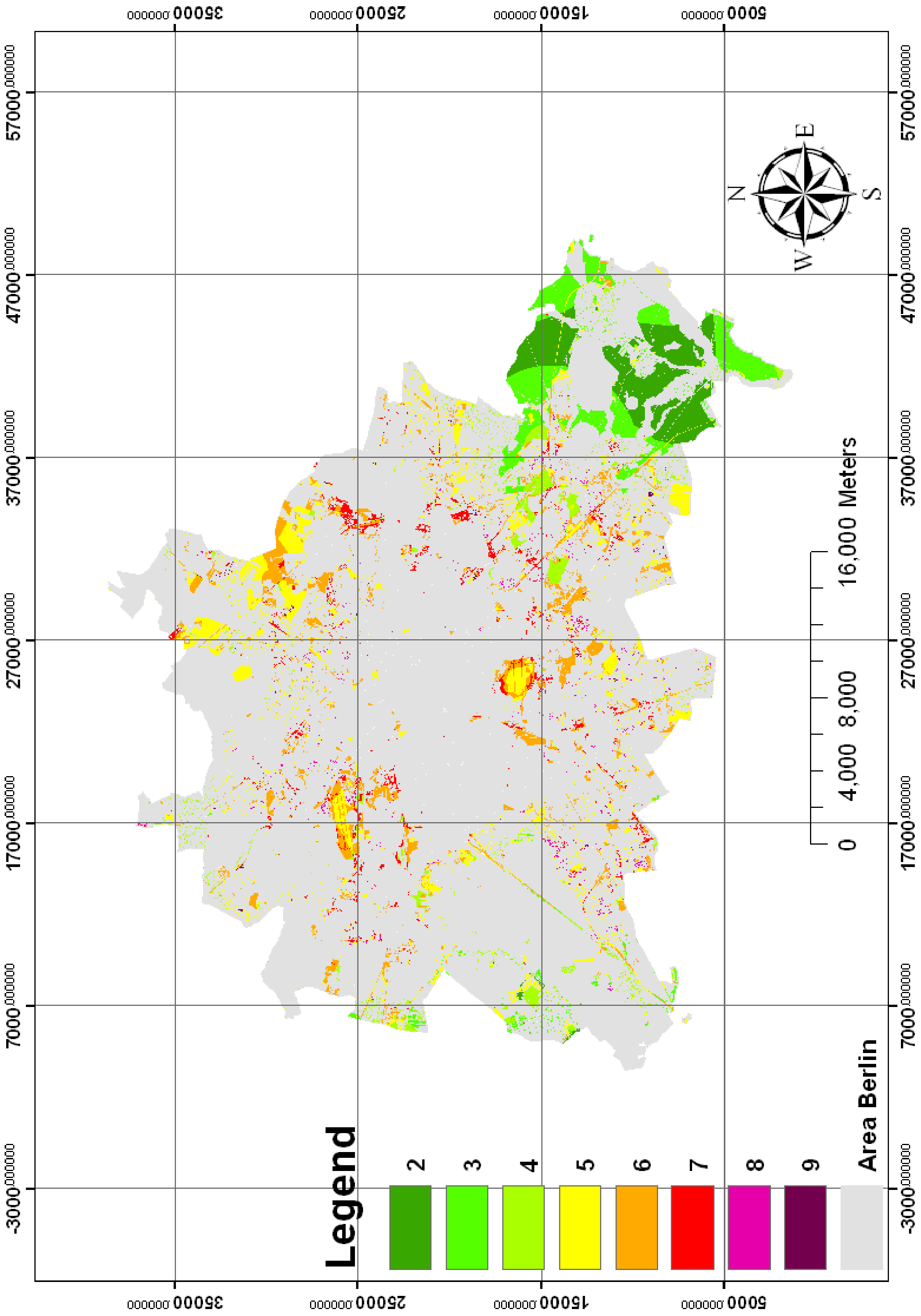

Figure 11.8: Map showing areas ranked for suitability for small wind power plants resulting from overlay operation 2 and a wind power plant height of 30 m.

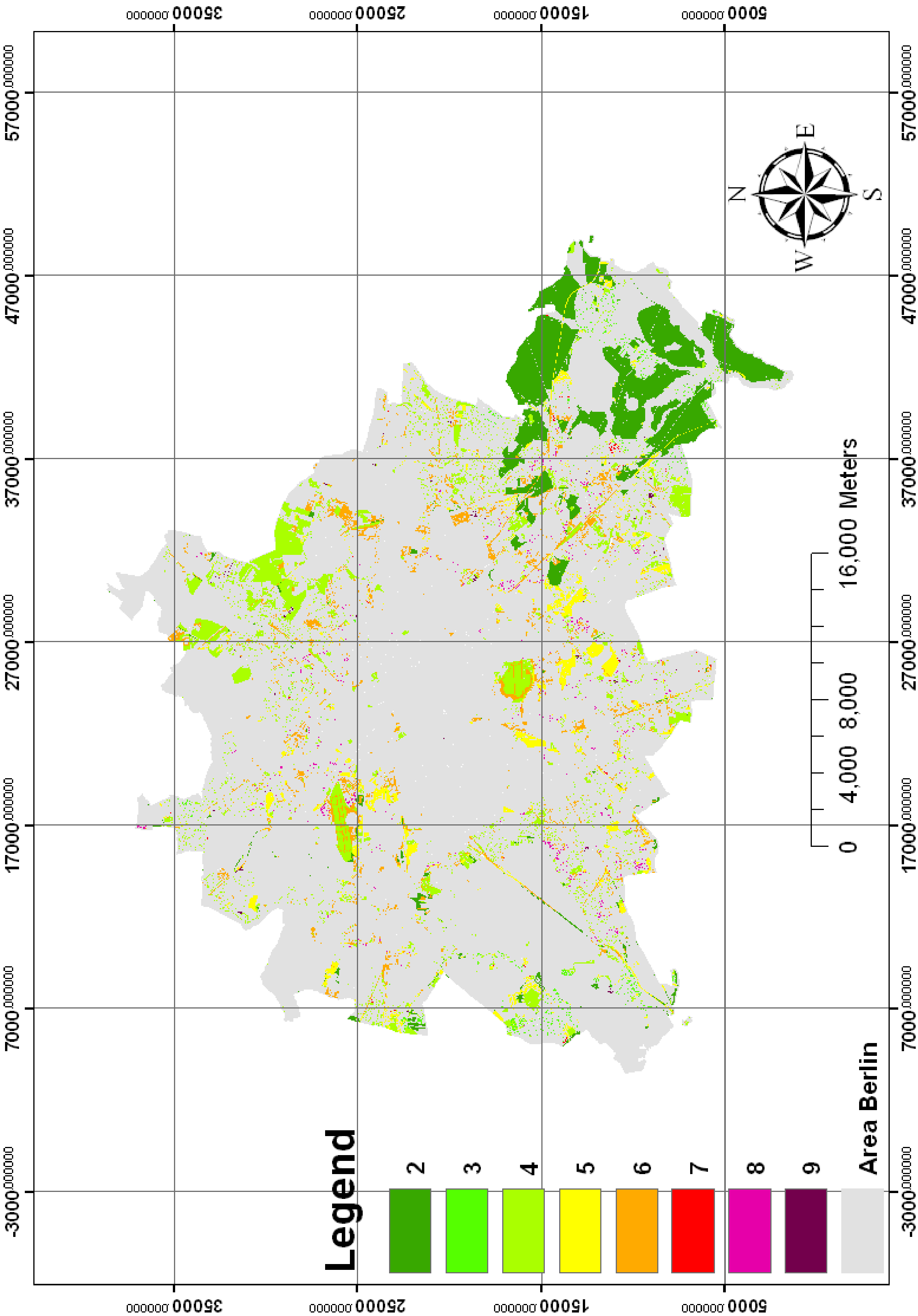

Figure 11.9: Map showing areas ranked for suitability for small wind power plants resulting from overlay operation 3 and a wind power plant height of 30 m.

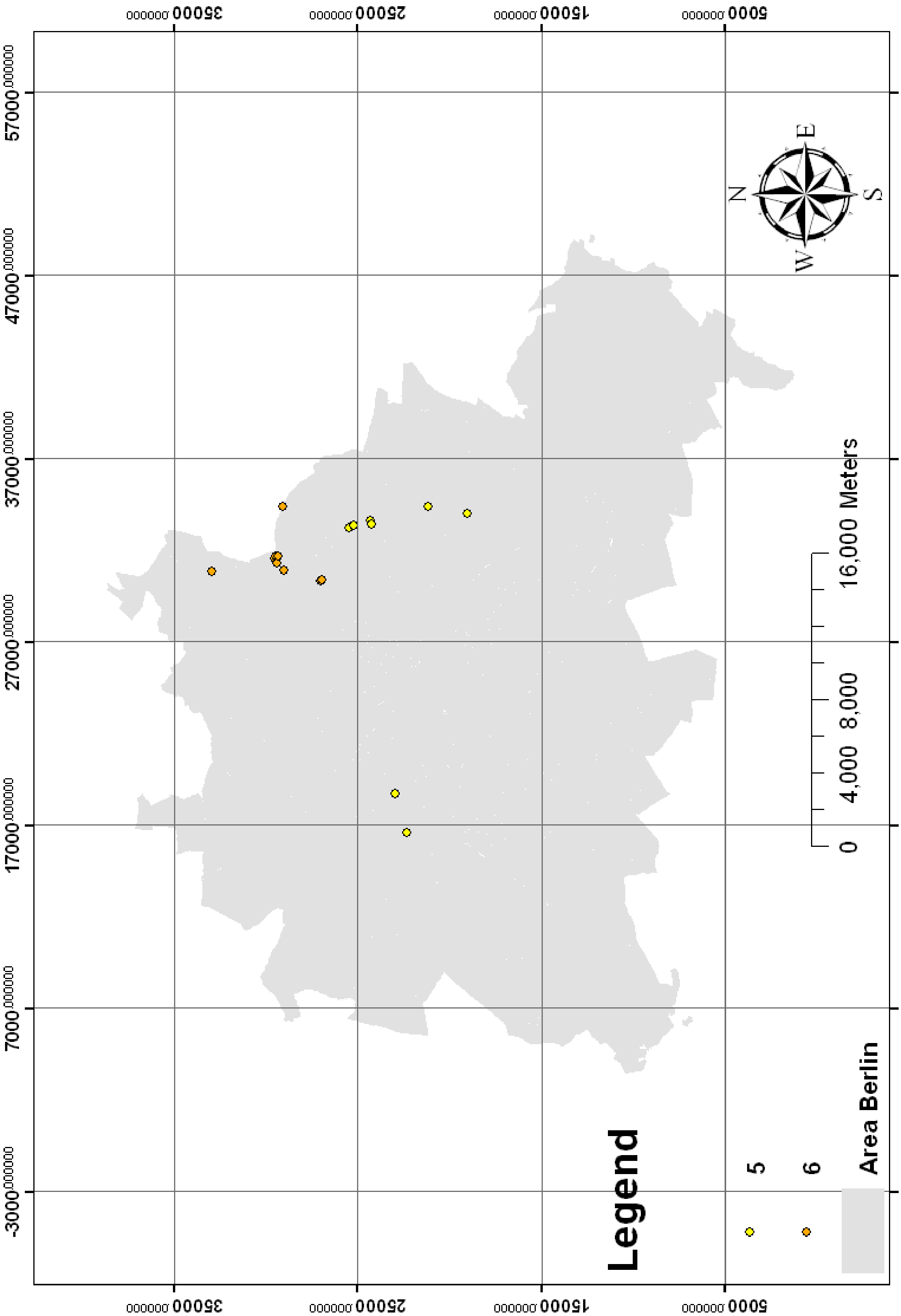

Figure 11.10: Suitability map for power poles, overlay operation 1 and wind power plant height of 10 m.

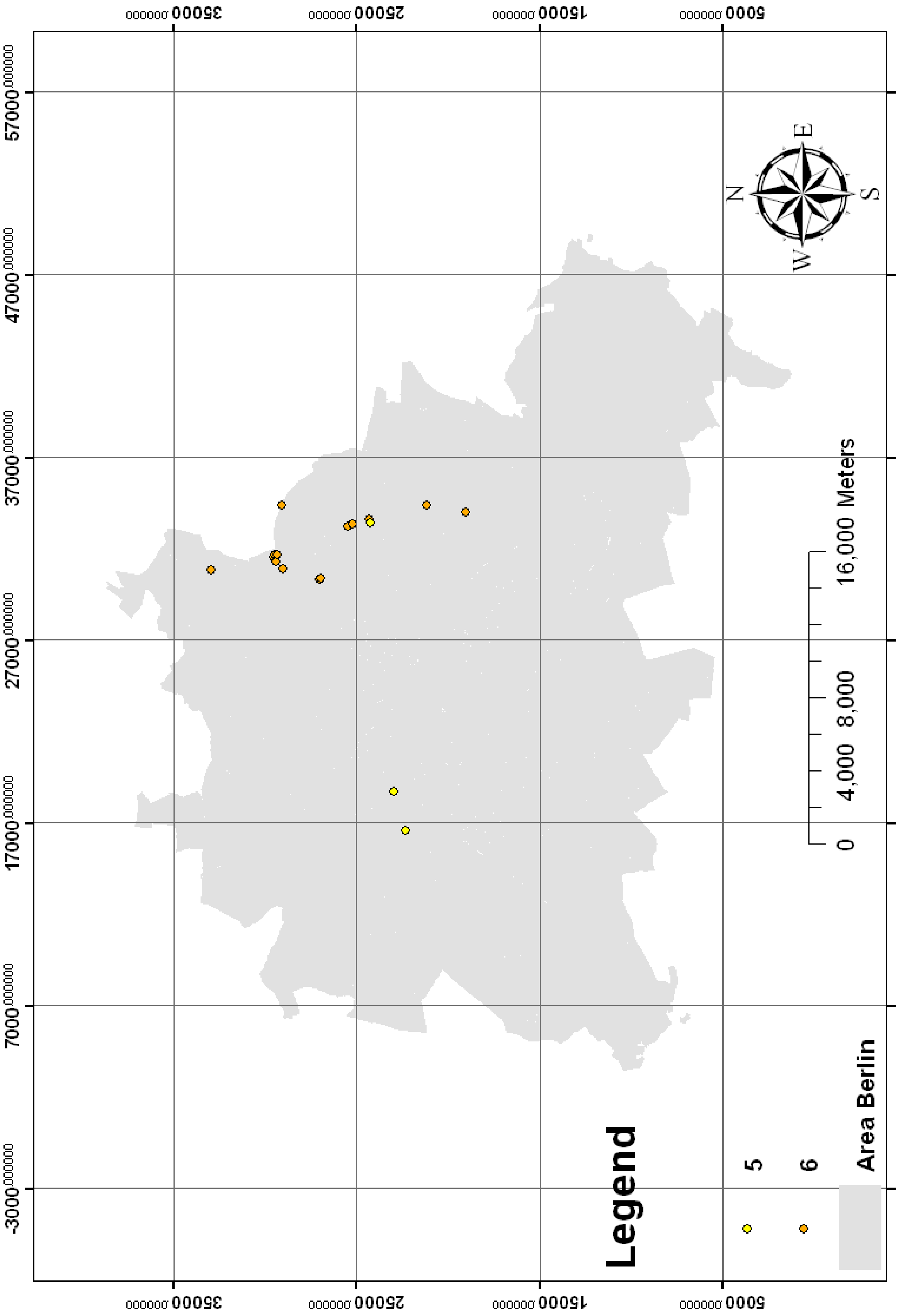

Figure 11.11: Suitability map for power poles, overlay operation 2 and wind power plant height of 10 m.

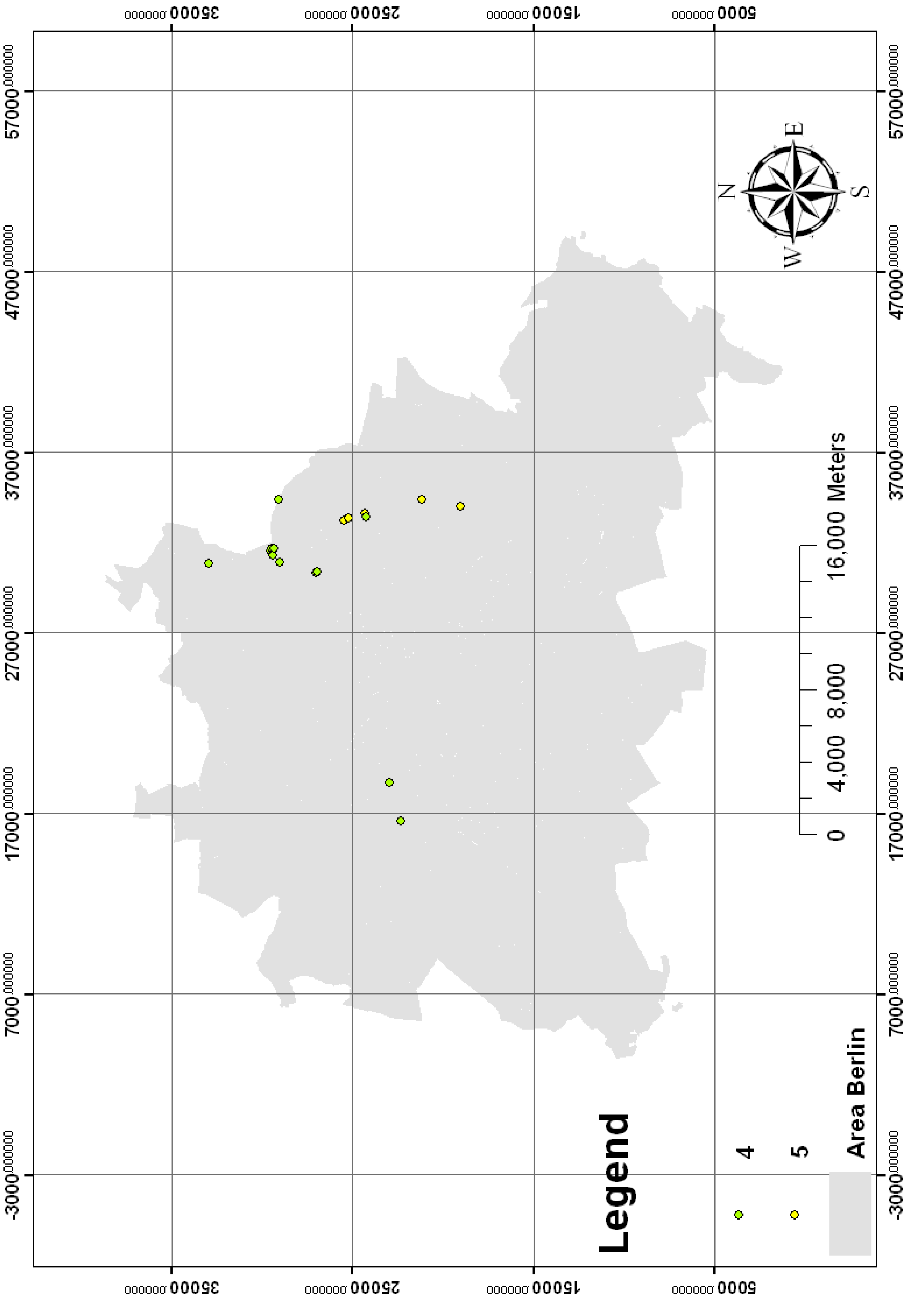

Figure 11.12: Suitability map for power poles, overlay operation 3 and wind power plant height of 10 m.

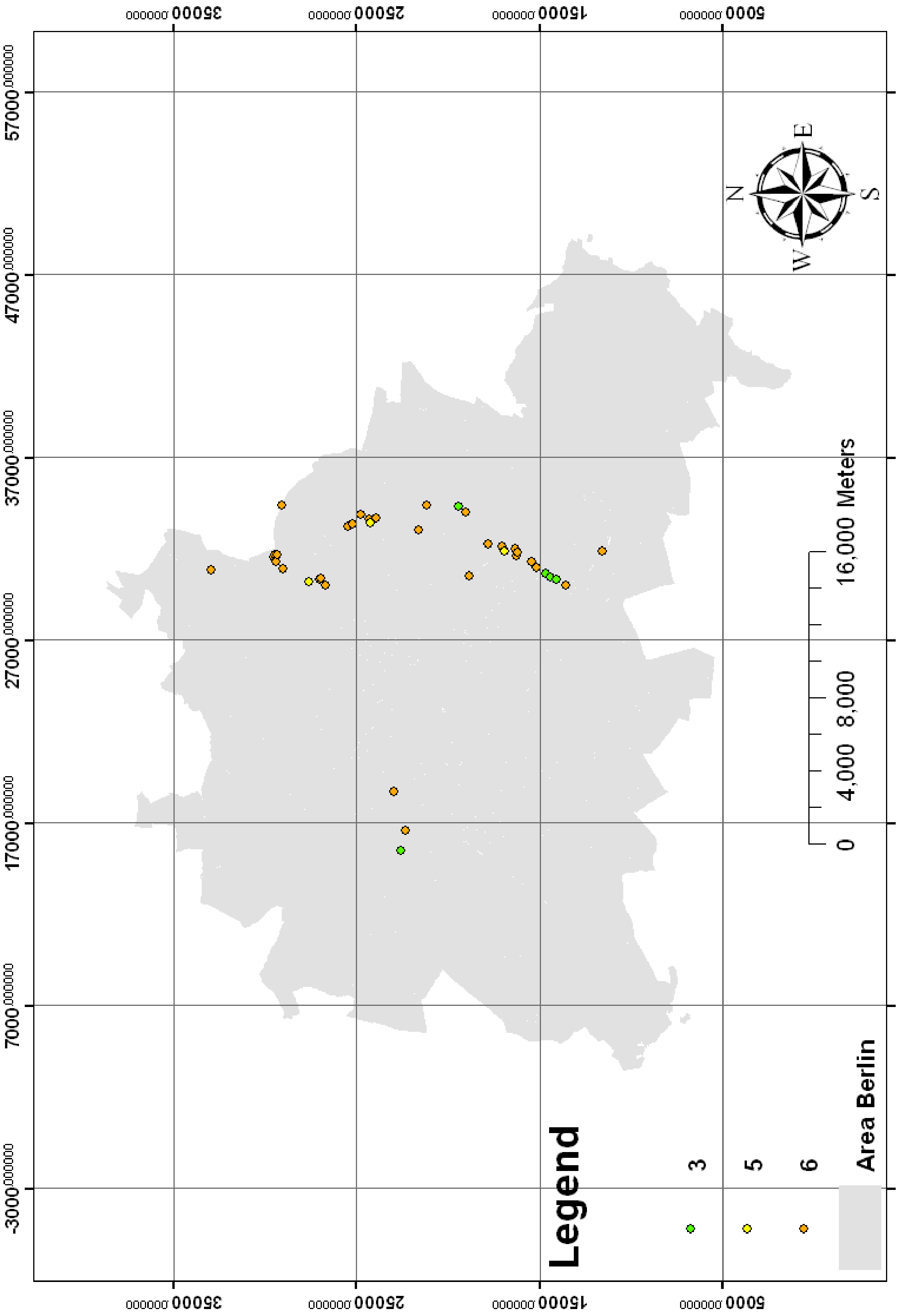

Figure 11.13: Suitability map for power poles, overlay operation 1 and wind power plant height of 20 m.

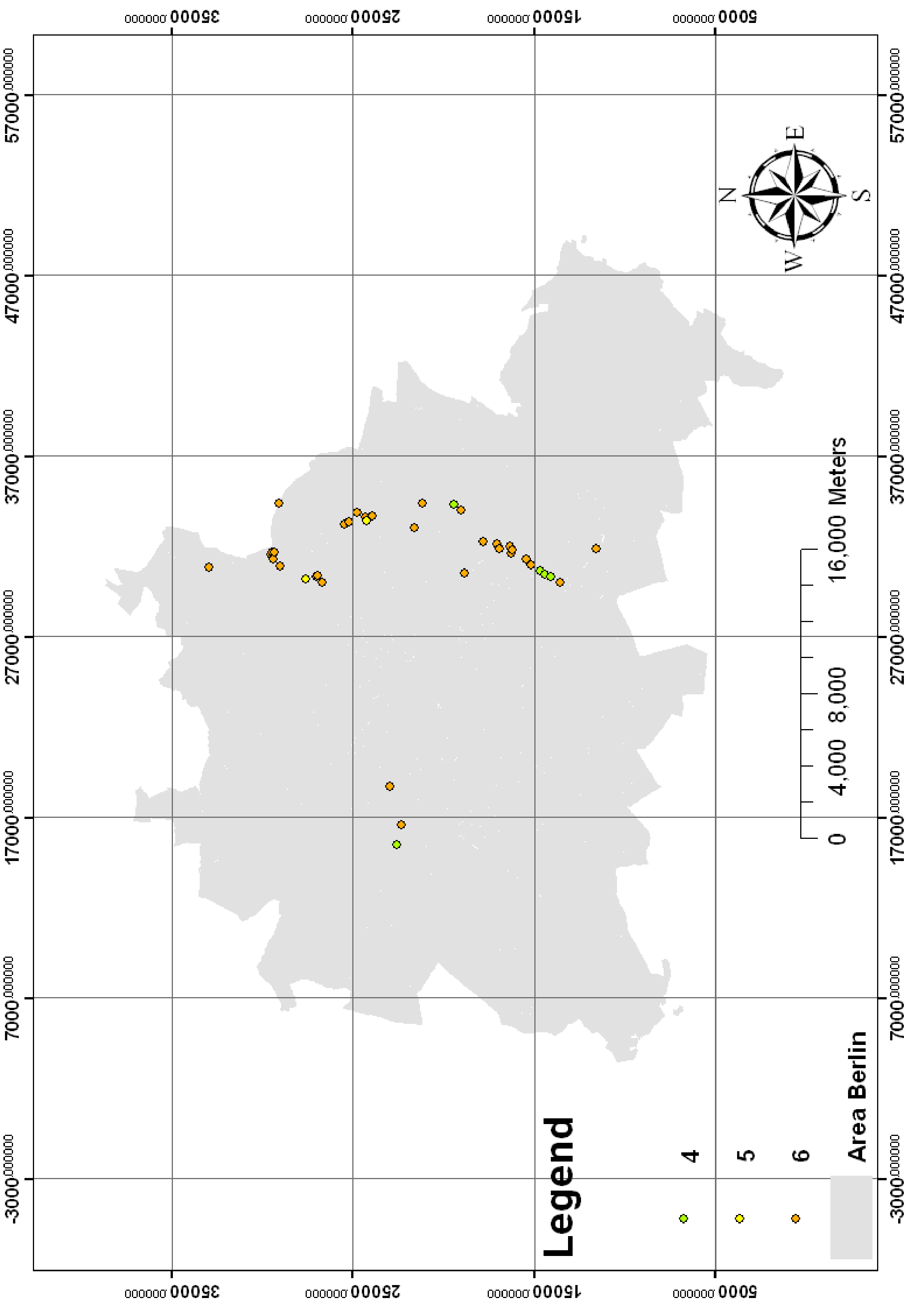

Figure 11.14: Suitability map for power poles, overlay operation 2 and wind power plant height of 20 m.

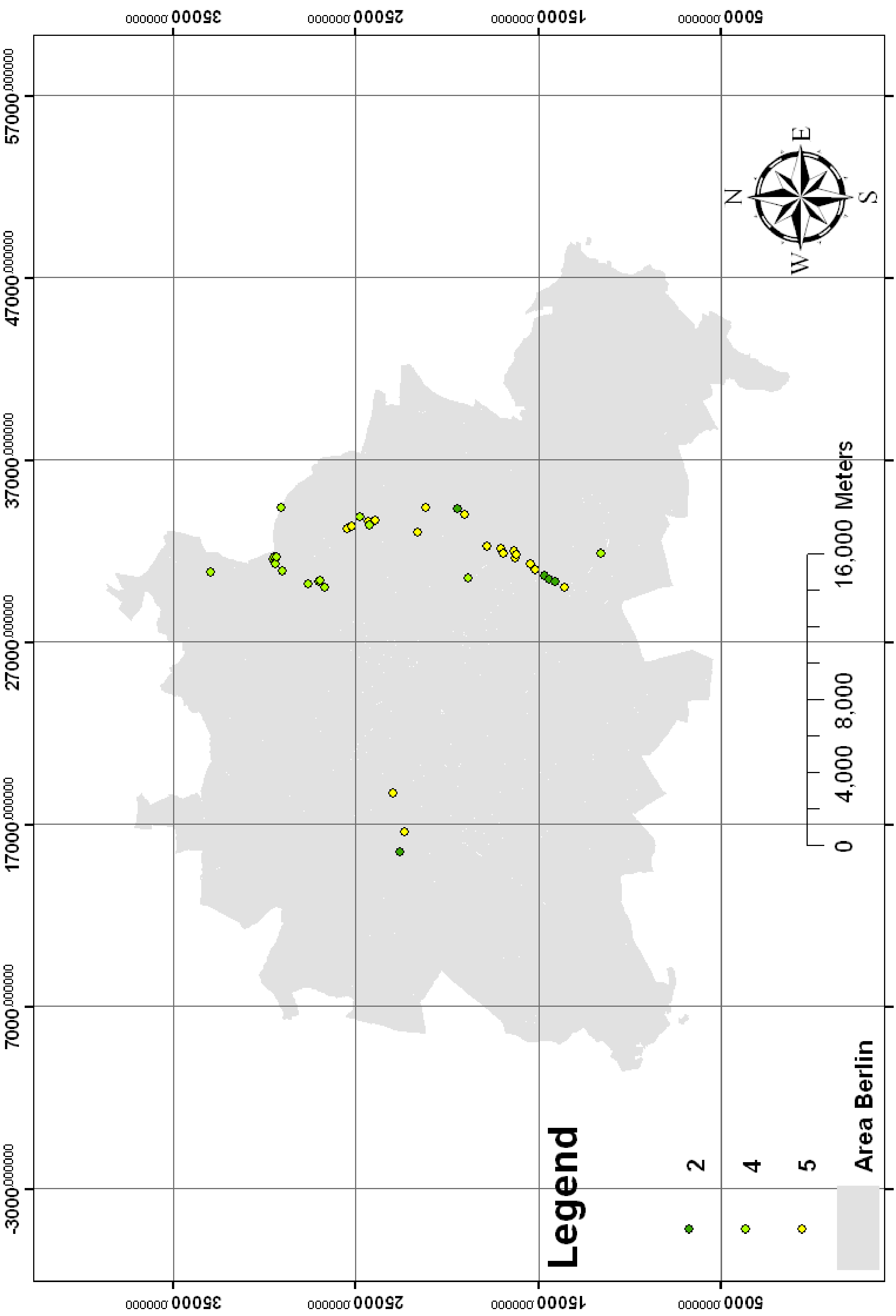

Figure 11.15: Suitability map for power poles, overlay operation 3 and wind power plant height of 20 m.

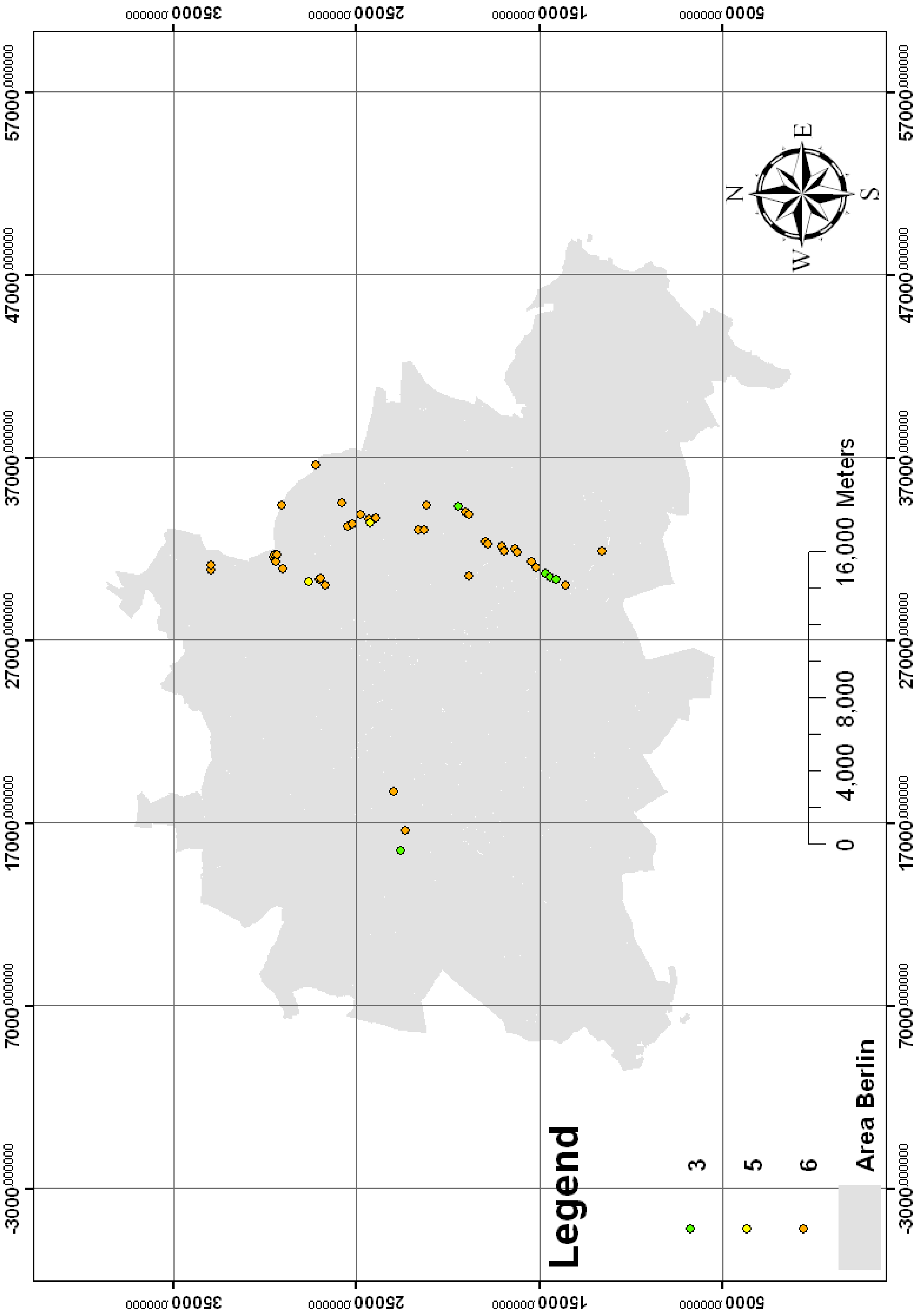

Figure 11.16: Suitability map for power poles, overlay operation 1 and wind power plant height of 30 m.

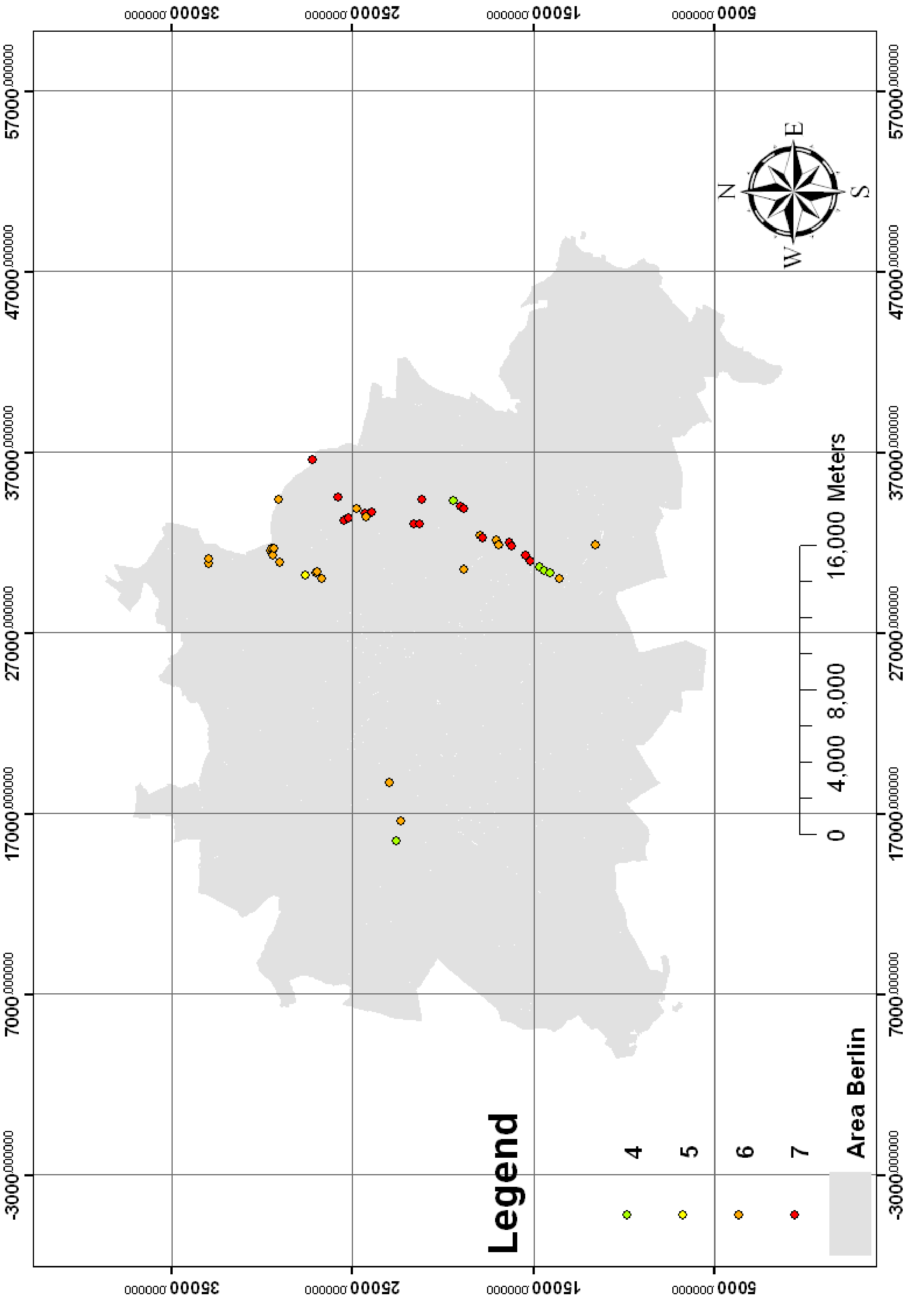

Figure 11.17: Suitability map for power poles, overlay operation 2 and wind power plant height of 30 m.

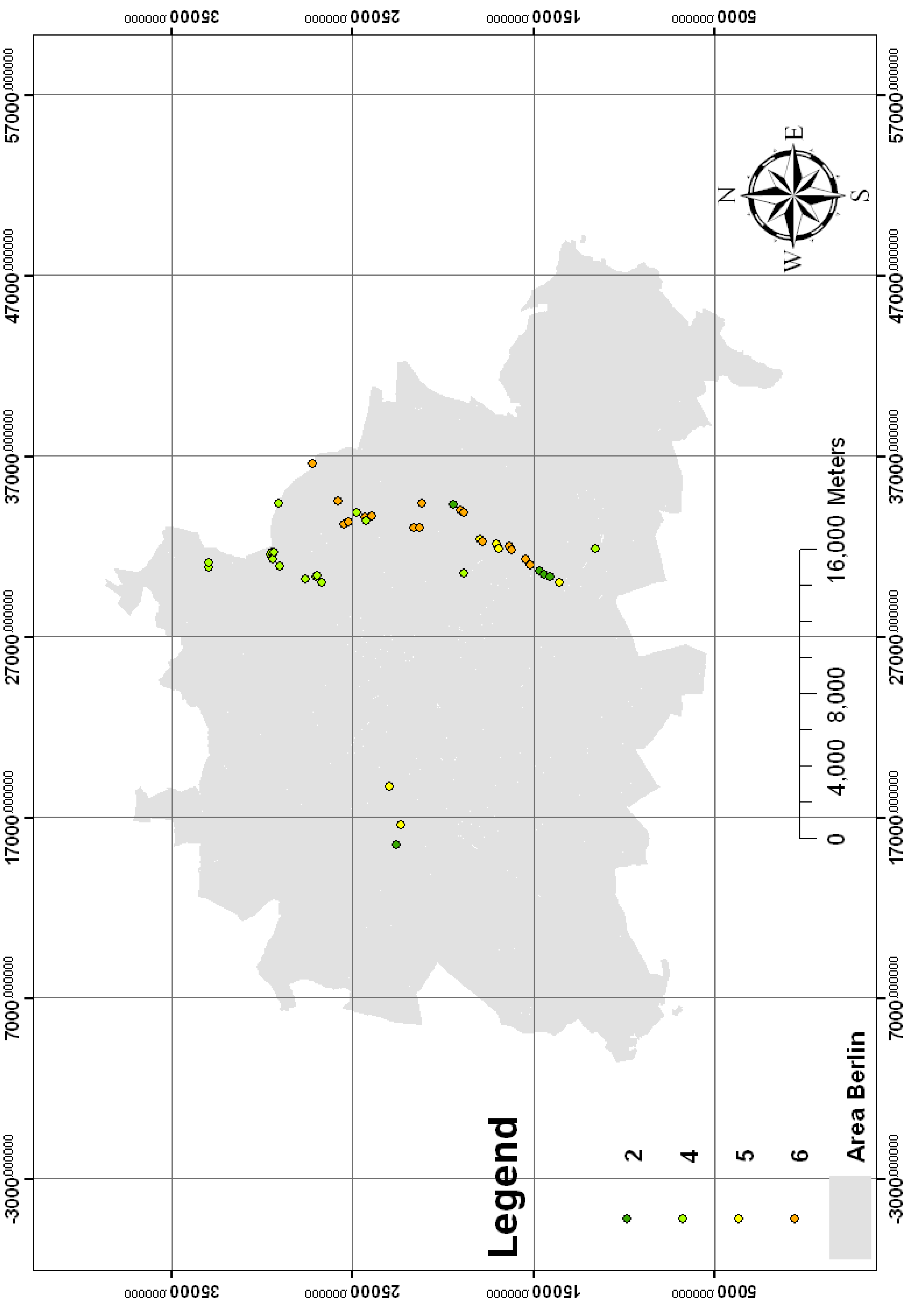

Figure 11.18: Suitability map for power poles, overlay operation 3 and wind power plant height of 30 m.

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