Julius-Maximilians-Universität Würzburg - Institut für Geographie

Impacts of Extreme Hydro-Meteorological Events on Electricity Generation and Possible Adaptation Measures
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A GIS-based Approach for Corporate Risk Management and Enhanced Climate Mitigation Concepts in Germany

Dissertation zur Erlangung des akademischen Grades eines Doktors der Naturwissenschaften (Dr. rer. nat.)
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von

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“Hochwasser ist, wenn der Fluß tiefer wird.”

Dipl.-Ing. Heinrich Sieber 2008

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List of Abbreviations and Acronyms

Abbreviation	Term
€/kW	Euro per kilowatt
A	Ampere
ADAM	Adaptation and Mitigation Strategies: Supporting European Climate Policy
AG	Aktiengesellschaft/*Joint stock company*
asl	above sea level
A. u.	Author unknown
BASF	Badische Anilin- & Soda-Fabrik/*Baden Aniline and Soda Factory*
BfG	Bundesanstalt für Gewässerkunde/*Federal Institute for Hydrology*
BImSchV	Bundes-Immissionsschutzverordnung/*Federal Immission Control Ordinance*
BMI	Bundesministerium des Innern/*Federal Ministry of the Interior*
BMU	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit/*Federal Ministry for Environment, Nature Conservation and Nuclear Safety*
BSW	Bundesverband Solarwirtschaft/ *German Solar Industry Association*
BUWAL	Bundesamt für Umwelt, Wald und Landschaft der Schweiz/*Swiss Federal Office for the Environment, Forest and Landscape*
CC	combined cycle
CCS	Carbon Capture and Storage
CEDIM	Center for Disaster Management and Risk Reduction Technologies
cm	Centimeter
CO_2	carbon dioxide
COSO	Committee of Sponsoring Organizations of the Treadway Commission
CWIF	Caithness Windfarm Information Forum
DAX	Deutscher Aktienindex/*German Stock Market index*
DEM	Digital Elevation Model
DIN	*German Institute for Standards*/Deutsches Institut für Normung
DIN EN	Deutsche Industrie Norm Europäische Norm/*German Industrial Norm European Norm*
DOE/NETL	United States Department of Energy/National Energy Technology Laboratory
DPSIR	Driving forces, pressures, state, impact and response
e.g.	exempli gratia/for example
e.V.	eingetragener Verein/*Voluntary Association*
EEA	European Environment Agency
EIFER	European Institute for Energy Research
EIS	Environmental Information System
EMAS	Eco-Management and Audit Scheme
EnBW	Energie Baden-Württemberg AG
EPRI	Electric Power Research Institute
ESRI Inc.	Environmental Systems Research Institute
ESWD	European Severe Weather Database
et al.	et alii/and others
EU	European Union
Fx	Fujita-scale, x marks the index number for events
GDV	Gesamtverband der Deutschen Versicherungswirtschaft/*German Insurance Association*

GIL	gas insulated lines
GIS	Geographical Information Systems
GK	Gauß-Krüger coordinates
GmbH	Gesellschaft mit beschränkter Haftung/*company with limited liability*
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit/*Association for facility and reactor safety*
GWS	*German Weather Service*/Deutscher Wetterdienst DWD
h	Hour
HP	heating plant
$HQ_{10,000}$	runoff coefficient for a 10.000-year flood
HQ_{100}	runoff coefficient for a 100-year flood
i.e.	id est/that is
IAEA	International Atomic Energy Agency
ICLEI	International Council for Local Environmental Initiatives
IDW	Inverse Distance Weighting
IEC	International Electrotechnical Commission
IPCC	Intergovernmental Panel on Climate Change
ISA	International Federation of the National Standardizing Associations/*Organisation zur Internationalen Normung*
ISO	International Organization for Standardization/*Internationale Organisation für Normung*
IT	Information Technology
K	Kelvin
kg/m³	kilograms per cubicmeter
KLIWA	Klimaveränderung und Konsequenzen für die Wasserwirtschaft/*Climate change and consequences for water management Research group*
km	Kilometer
KonTraG	Gesetz zur Kontrolle und Transparenz im Unternehmensbereich/*Corporate Sector Supervision and Transparency Act*
KSI	Nationale Klimaschutzinitiative/*National Climate Protection Initiative*
KTA	Kerntechnischer Ausschuss/*German Nuclear Safety Standards Commission*
kV	Kilovolts
kW	Kilowatt
LfU	Bayerisches Landesamt für Umwelt/*Bavarian State Office for the Environment*
Ltd.	Limited Company
m/s	meter per second
M€	Million Euro
max.	Maximum
min	Minute
min.	Minimum
mm	Millimeter
MW	Megawatt
MW_{el}	Megawatt electrical
n.d.	no date
n.s.	not specified
n/a	not available

N/m	Newton per meter
NASA	National Aeronautics and Space Administration
NGO	Non-governmental Organisation
NPP	Nuclear Power plant
OcCC	Organe consultatif sur les Changements Climatiques
p.	Page
PMP	probable maximum precipitation
PP	power plant
PV	Photovoltaics
QC1	report confirmed by reliable sources/Quality condition
QC2	event fully verified/Quality condition
RWE	Rheinisch-Westfälisches Elektrizitätswerk AG
T	Temperature
TPP	thermal power plant
TÜV	Technischer Überwachungsverein/*Technical Inspection Association*
UBA	Umweltbundesamt/*Federal Environmental Agency*
UNFCCC	United Nations Framework Convention on Climate Change
URBAS	Vorhersage und Management von Sturzfluten in urbanen Gebieten/*Prediction and management of flash floods in urban areas*
VDI	Verein Deutscher Ingenieure/*Association of German Engineers*
x (-years)	Placeholder
x^{10}	placeholder to the power of 10
ZCA	Zip code area
µm	Micrometer

List of Mathematical Symbols

Symbol	Term
-	minus
%	percent
&	and
*	multiplied by
+	plus
<	less than
=	equals
>	greater than
±	plus-minus
≤	less than or equal to
≥	greater than or equal to
°C	degrees Celcius
∅	diameter

Abstract

This thesis on the “Impacts of extreme hydro-meteorological events on electricity generation and possible adaptation measures – a GIS-based approach for corporate risk management and enhanced climate mitigation concepts in Germany” presents an identification of hydro-meteorological extreme events in Germany and their effects on electricity generating units, i.e. on conventional thermal and nuclear power plants as well as on installations of the renewable energies of hydropower, wind energy and photovoltaic installations. In addition, adaptation measures and strategies are named that help power plant operators to prepare for a changing climate. Due to the different requirements of large facility operators and local planners and owners of renewable energies, the work contains the two approaches of corporate risk management and climate mitigation concepts. A changing climate not only consists of a shift in mean values of weather parameters such as global and regional air temperature and precipitation, but may also result in more frequent and more severe single events such as extreme precipitation, tornadoes and thunderstorms.

In two case studies, these findings are implemented into an adjusted general risk management structure. This is enhanced by the use of Geographical Information Systems (GIS) to accomplish a localisation of events and infrastructure. The first example gives insight into the consequences of ice throw from wind turbines and how climate mitigation concepts can act as a framework for an adapted, sustainable energy planning. The second example on the other hand highlights a GIS-based flood risk management for thermal power plants and the benefits of an adjusted corporate risk management cycle.

The described approach leads to an integrated management of extreme hydro-meteorological events at power plant site respectively district level by combining two cycles of site-related and local planning in addition to GIS-based analyses. This is demonstrated as an example by the comparison of two districts in Germany. The practical outcome is a comprehensive support for decision-making processes.

Zusammenfassung

Die vorliegende Arbeit zum Thema “Einflüsse extremer hydro-meteorologischer Ereignisse auf Elektrizitätserzeugung und mögliche Anpassungsmaßnahmen – ein GIS-basierter Ansatz für ein betriebliches Umweltrisikomanagement und erweiterte Klimaschutzkonzepte in Deutschland” identifiziert zunächst die relevanten hydro-meteorologischen Ereignisse und ihre Auswirkungen auf elektrizitätserzeugende Einheiten in Deutschland. Dies sind hier konventionelle thermische Kraftwerke und Kernkraftwerke sowie die Installationen der Erneuerbaren Energien Wasserkraft, Windenergie und Photovoltaik. Im Anschluss werden Anpassungsmaßnahmen und -strategien aufgezeigt, die es den Betreibern von Kraftwerken ermöglichen, sich auf ein sich veränderndes Klima vorzubereiten. Durch die verschiedenen Voraussetzungen für Betreiber großer Anlagen und die Regionalplanung und Besitzer von Anlagen Erneuerbarer Energien werden zwei Ansätze verfolgt. Der eine Ansatz beinhaltet betriebliches Umweltrisikomanagement, der andere beleuchtet den Aspekt Anpassung als Erweiterung von Klimaschutzkonzepten. Der Klimawandel in diesem Sinne beinhaltet nicht nur die Veränderungen in Mittelwerten, wie zum Beispiel der regionalen und globalen Lufttemperaturen oder des Niederschlages, sondern auch ein verändertes Verhalten von extremen Einzelereignissen, wie häufigere und schwerere Extremniederschläge, Tornados und Gewitter.

In zwei Fallbeispielen werden diese Ergebnisse in eine Risikomanagementstruktur eingebunden und durch die Verwendung von Geographischen Informationssystemen (GIS) lokalisiert und erweitert. Das erste Beispiel zeigt die Konsequenzen von Eiswurf von Windenergieanlagen und wie Klimaschutzkonzepte als Rahmen für eine angepasste, nachhaltige Energieplanung dienen können. Das zweite Beispiel hebt die Notwendigkeit von GIS-gestützten Hochwasserrisikoanalysen für thermische Kraftwerke und die Vorteile eines angepassten betrieblichen Umweltrisikomanagements hervor.

Die beschriebene Vorgehensweise kombiniert zwei Managementzyklen. Dabei werden die standortspezifische Planung und Regionalplanung sowie GIS-basierte Analysen verknüpft. Dies wird am Beispiel zweier Landkreise verdeutlicht. Das Resultat ist ein umfassender Ansatz zur Unterstützung von Entscheidungsprozessen.

1. Introduction

1.1 Background

The integration of extreme hydro-meteorological events as a model parameter which is responsible for increased vulnerability is an emerging topic in energy system planning. The adjustment of corporate risk management and climate mitigation concepts in this thesis on the “Impacts of Extreme Hydro-Meteorological Events on Electricity Generation and Possible Adaptation Measures – A GIS-based Approach for Corporate Risk Management and Enhanced Climate Mitigation Concepts in Germany” creates a basis for a reliable and sustainable energy supply under a changing environment in the future. The necessity to adapt small and large electricity generating units to a changing climate on the one hand and the options to mitigate negative impacts of electricity generation on the environment on the other hand appear as main targets for research. To meet these requirements the assessments in the present work deals with corporate risk management as well as with climate mitigation concepts[1].

Environmental Risk Management should be an integral part in power plant operation and may be enhanced by using Geographical Information Systems (GIS) in data handling and analyses. Though several guidelines address risk handling, none of these contain a specific approach to managing hydro-meteorological risks through Geographical Information Systems. ZIMMERMAN & FARIS (2011) highlight that adaptation should be integrated into climate action and sustainability plans in order to prepare districts and infrastructures for environmental changes. Furthermore, NEUMANN (2009) states that “*the location of major critical infrastructure should be mapped against those areas of the country considered most vulnerable to climate stress […]*”. These conclusions are the foundation for the following work.

Critical infrastructures as mentioned here, used in this study and defined by the Federal Ministry of the Interior (*Federal Ministry of the Interior*/Bundesministerium des Innern BMI 2003 in FEDERAL MINISTRY OF THE INTERIOR 2005) are important infrastructure for supply and disposal and public security, e.g. energy supply (electricity and heat), IT, communication, health care but also cultural goods and research and administrative centres. Critical infrastructure failure usually causes extensive consequences.

There is no commonly agreed definition of the term *extreme weather events*. In general, extreme events are rare, severe and, depending on the system, rapidly occurring (STEWART & BOSTROM 2002).

[1] Climate Mitigation Concepts are also known as Climate Action Plans

Data from SWISS RE (2005, p. 23) and other sources cited therein show that the numbers of weather-related worldwide disasters have increased over the past decades. These data include storms, floods, extreme temperatures and droughts as well as wild fires[2] and landslides[3]. Other disasters that directly affect man are listed in addition. In the following figure, the development of these events is plotted against the date of their occurrence to illustrate the increase in extreme events per decade (Figure 1).

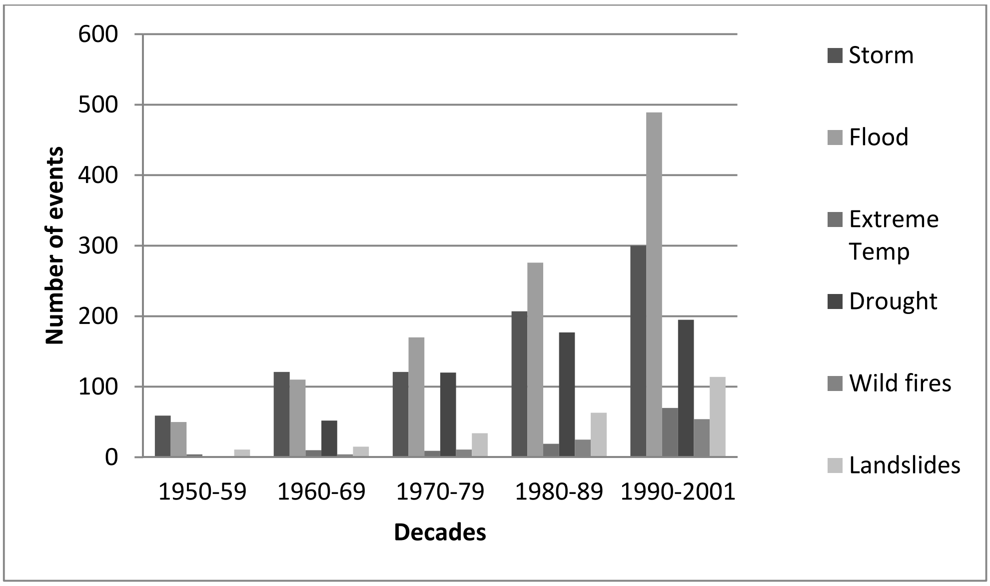


Figure 1: Frequency of weather-related disasters worldwide (according to SWISS RE 2005)

This increase depicts that the number of extreme hydro-meteorological events has increased in the past years. Therefore, for planners and operators the necessity emerges to take these changes into account while developing new infrastructures and energy supply concepts. The time frame of this study is set by some general assumptions about the dimensioning of energy infrastructure and the increase in frequency of extreme weather events. The lifetime of power plants covers a period of 15 - 40 years and that of transmission lines a period of 40 - 75 years (THE WORLD BANK n.d.). Similarly, the Intergovernmental Panel on Climate Change IPCC (2012) points out that the long life times of infrastructure require tools, guidance and consistent adaptation measures to withstand the constant environmental changes. Since approximately 91 % of natural catastrophes between 1980 and 2005 are attributed to extreme weather events (MCEVOY ET AL. 2010) this analysis covers possible impacts from 1980 - 2009.

The impact of extreme weather events on electricity generating structures is also linked to the term “vulnerability”. GREEN (2004) outlines different definitions and concepts of

[2] Possible causes for wild fires are either man-made or lightning in combination with dry periods
[3] Landslides might be the consequence of both extreme precipitation and man-made land mismanagement

vulnerability. The first approach was given by the IPCC in 1992 (in GREEN 2004) stating that vulnerability is the "*incapability to cope with the consequences of climate change and accelerated sea-level rise*". Following this, most definitions include society or individuals and their ability to handle critical situations; not only in relation to climate change, but also to irregular weather conditions. In 1998, Clark et al. initiated an approach to include property and system sensitivity to coping with external influences (in GREEN 2004). Also, Nicholls & Klein (2000 in GREEN 2004) extended this definition to include stress and shock as possible triggers. In 2001, the IPCC renewed their statement on vulnerability to "*the extent to which a natural or social system is susceptible to sustaining damage from climate change*." (IPCC 2001, p. 89) The definition, on which the analyses of this work fit most closely, is provided by ALCANTARA-AYALA (2002, p. 119):

> "*the propensity of an endangered element due to any kind of natural hazard to suffer different degrees of loss or amount of damage depending on its particular social, economic, cultural and political weaknesses."* [sic!]

In this last definition the influences of natural hazards, in this case extreme weather events, on any kind of structure are included and reference is made to the social, cultural, political and economic consequences of this damage.

These definitions are followed by a description of the term "adaptation". Adaptation was defined by the IPCC in 2001, at the same time as it characterised vulnerability, in the context of how to cope with extreme situations. They said adaptation is the

> *"adjustment in natural or human systems in response to actual or expected climate stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation."(IPCC 2001, p. 982)*

The IPCC kept to that definition also in the Fourth Assessment Report in 2007 (IPCC 2007). Here again, human systems as well as natural ones are mentioned, while using climate change or climate parameters as driving forces. Adaptation may be planned or not, in either public or private interest, and adaptation can, above all, be forward-looking or responding to existing changes and damages.

Therefore, following three kinds of adaptation options are identified with electricity generation:

- adaptation of thermal power plants, especially cooling options;
- adaptation of renewable energies, especially to their source of energy; and

- adaptation of connected on-site infrastructures, e.g. distribution and storage.

Only a few approaches to adaptation are considered in the literature as such. These approaches were either established for the protection of existing power plants or to improve newly built ones. Although these approaches were not originated in the direct context of climate change, they are often adequate for adaptation in the face of climate change and related extreme weather events.

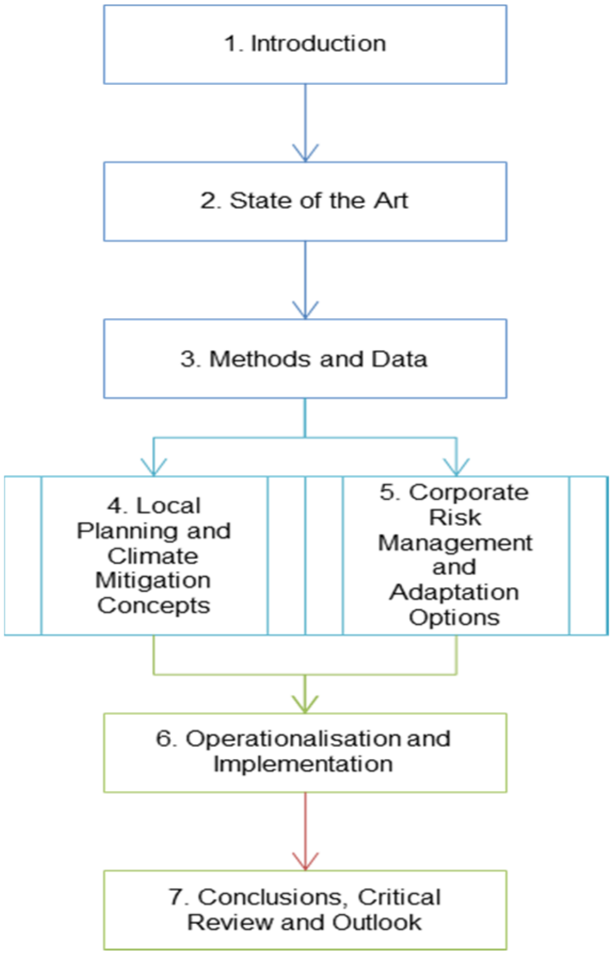
According to BAILEY & LEVITAN (2008), supplemented by the author's own experience, power plant sites usually contain the following components: process structures, process towers, tanks, compressors, drums, exchangers, furnaces, pumps, reactors/boilers, pipes, cooling towers, storage warehouses, control rooms, maintenance buildings, administration buildings, recreational areas, walls and protective facilities as well as interim storage facilities (alternative storage sites, temporary storage of [nuclear] waste).

1.2 Knowledge Gaps and Research Questions

This knowledge leads to three main research questions which will be addressed during the thesis. The first question deals with vulnerability: Which regions or districts in Germany and which electricity generating units are especially affected by extreme weather events? The second question on adaptation and risk management is: How can electricity generating units and/or regions be protected? The third main question includes the decision making process: How do local planning or corporate risk management deal with this vulnerability?

Literature reviews, statistics on extreme hydro-meteorological events, GIS-based spatial and temporal analyses and the implementation of the results into decision support and decision making in climate mitigation concepts regarding the installation of renewable energies are used to find answers to these questions.

Therefore the thesis is structured as follows:



Section 2 shows the state of identification of the influences of extreme weather events and the options for their subsequent adaptation by using recent and, to some extent, older but still important and meaningful literature. This is followed by an introduction into risk management chains and cycles which allow for the implementation of all relevant information into concepts and plans in local planning as well as in engineering projects.

Section 3 is a brief introduction to methods used for the analyses and refers to the main sources of data. Herein, classical risk management concepts are adjusted and modified to fit to adaptation and mitigation strategies in local planning and corporate risk management. Moreover, data on extreme weather events is taken from European databases as well as national weather services. These databases contain substantial data on extreme single weather events like tornadoes which are often not measured at monitoring stations. Moreover, power plant data was derived from several commercial databases, as well as from network operators in case of renewable energies. A statistical analysis of the extreme hydro-meteorological events leads to statements on temporal distribution, changes over the time frame 1980 to 2009 and the trends in said 30 year period.

The results of the analyses of local planning and climate mitigation concepts are shown in Section 4. The GIS-based analyses display the spatial and temporal distribution of events in combination with renewable electricity generation. Even though climate mitigation concepts should also include adaptation as a topic, the usual process concentrates on greenhouse gas emissions and their reduction. Moreover, climate mitigation concepts are conducted on a district or city level without taking into account bigger spatial context. The spatial and temporal analyses of extreme hydro-meteorological events leads to a first compilation of where and when extreme events happened in the past and which regions are most vulnerable to these events due to their power plant park. Therefore, not only extreme events are integrated in the assessment but also number and distribution of electricity generating units. The goal is to establish the first comprehensive assessment in Germany on a district level. This is achieved by using spatial joining and clipping functions in combination with buffering and further data comparison tools provided in Geographical Information Systems. A case study on wind turbines illustrates the exposure of wind turbines to cold conditions and ice accretion and possible threats to their surroundings. As wind turbines are one of the most recommended renewable energies in the German Energy Turnaround[4] and therefore also in climate mitigation concepts, focus is put on the particular risk of ice throw during cold conditions and simultaneous precipitation. Moreover, emphasis is given to installation distances and the move towards national standards due to the risks that non-adapted wind turbines pose on other infrastructures. The results of this section are the foundation for further assessments on risk indices on a district level to combine the established and adjusted approaches. This will be discussed in Section 6.

In Section 5, emphasis is put on corporate risk management and climate adaptation of major electricity generating units such as thermal power plants. Until now, Corporate Risk Management focuses either on financial risks or on the effects that mis-management might have on the environment. Recent publications, e.g. on the stress tests of nuclear power plants by the EU outline the effects of natural factors on these utilities (EUROPEAN NUCLEAR SAFETY REGULATORS GROUP ENSREG 2012). Still, a critical remark and a need for further research is the fact that plant safety and security in Germany is adjusted via regulations and standards in retrospective not taking into account recent changes especially in the field of extreme hydro-meteorological events. A case study on thermal power plants shows a practical approach to how floods impact thermal power plants and how flood risk management at a site needs to be organised. At this point, the corporate risk management as described is applied. The illustrated risk management cycle of “plan”, “do”, “check” and “act” is used as the basic concept of how to integrate GIS-based spatial and temporal analysis into the site-specific management system and emergency planning. The analyses are carried out as described in Section 4 which represents a transferable approach. The

[4] Also called German Energy Transition or Energiewende

findings are subsequently integrated into the risk management cycle as described in Section 2 and adjusted in Section 3.

Section 6 takes into account the conclusions of Sections 4 and 5 and leads to a discussion on the implementation of the new findings into corporate risk management as in the example of the flooding of a thermal power plant and furthermore into local planning and climate mitigation concepts as stressed in the example of the wind turbines. In order to achieve an integrated concept, emphasis is not only put on wind turbines and thermal power plants but also on the renewable energies of photovoltaic (PV) installations and hydropower plants. These two estimations relate to improved corporate risk management on the one hand and enhanced climate mitigation concepts on the other hand. Sections 2 to 5 show the gaps concerning the implementation of extreme hydro-meteorological events into climate mitigation concepts and corporate risk management. Thus, Section 6 highlights these gaps in research and application by introducing risk indices per district which encompasses the number of current and possible future installations as well as the number of extreme events. As a conclusion, a risk map in combination with the most affected districts and consequently the best adaptation options leads to the envisaged integrated approach. It becomes clear that environmental changes need to be taken into account in future planning for sustainable energy systems.

Finally, Section 7 includes a discussion and critical review on the thesis and its results as well as an outlook on further research in the field of the implementation of extreme hydro-meteorological events into common practice of local planning, climate mitigation concepts, corporate risk management and adaptation options.

This work on the "Impacts of Extreme Hydro-Meteorological Events on Electricity Generation and Possible Adaptation Measures – a GIS-based Approach for Corporate Risk Management and Climate Mitigation Concepts in Germany" establishes a comprehensive data collection of extreme hydro-meteorological events in the following categories "temperature", "wind", "precipitation" and "combined events". The work also includes a mapping of the identified impacts within a GIS, a display of risks and a subsequent risk assessment. Finally, a GIS-based approach for the management of extreme events will be developed. The advantage of a GIS-based approach is its ability for storage, handling and visualisation of all available data for each specific power plant site, as well as for legislation and regulation. The first aim is to establish a consequent integration of adaptation as well as mitigation into climate mitigation concepts for sustainable renewable energy planning in local planning approaches. The second goal is the integration of extreme weather events and adaptation into corporate risk management for large power plants in order to reduce the vulnerability for centralised electricity generation.

2. State of the Art

The literature review consists of four sub-sections which address in detail: extreme hydro-meteorological events and possible shifts in parameters in a changing climate, the impacts of said extreme hydro-meteorological events on electricity generating infrastructure as well as an overview of adaptation measures to be prepared for future extreme events. Furthermore, the state of the art introduces risk management concepts and decision making processes to frame this work. This section will give detailed insight on each research question especially which extreme events need to be considered most and how power plant operators can adapt the infrastructures in the future.

2.1 Extreme Events and Shifts in a Changing Climate

Extreme weather events[5] can be compared to a rapid change, or shift, in climate and usually have a direct and negative impact on people and the built environment (McBean 2004). Unlike a changing climate, extreme weather events are specifically located, both in place and time. Most of the literature reviewed uses a definition that implies either exceedance of the 90%-percentile or the fall short of the 10%-percentile occurrence probability in a probability density function (Steininger et al. 2003). Other definitions rely on a low probability of occurrence (Organe Consultatif sur les Changements Climatiques [OcCC] 2003), e.g., 100-year or 10,000-year flood events. Climate change is expected to cause changes in the occurrence of extreme weather events (Linnenluecke, Griffiths & Winn 2012, Botzen, Bouwer & van den Bergh 2010, Energy Networks Association 2009). It might alter the probability of occurrence, the intensity of parameters of extreme events, or even both factors at the same time. This would mean that either the mean temperature or the variance increases or that the mean temperature and the variance shift (Figure 2).

[5] Also called severe weather, hazardous weather, high consequence weather or extreme hydro-meteorological events

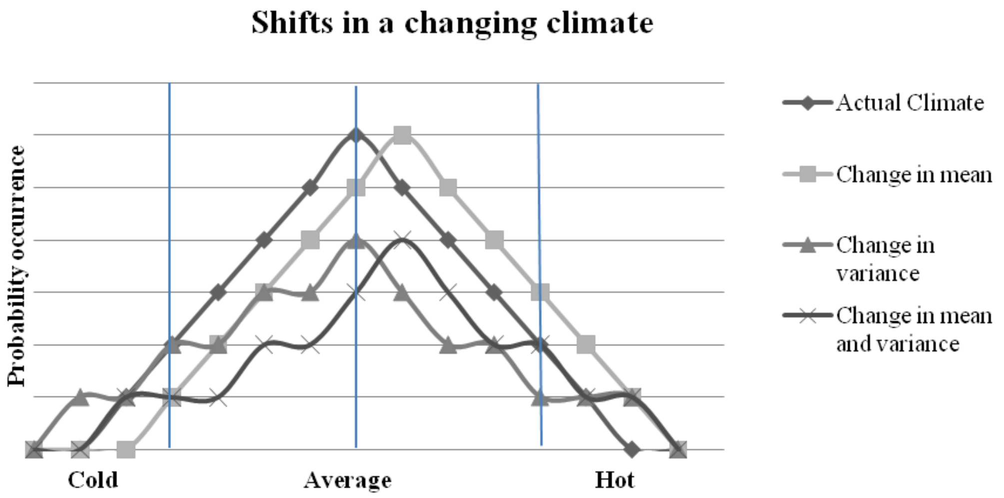


Figure 2: Effect on extreme temperatures, when the mean temperature increases (line with box), the variance increases (line with triangle) or mean temperature and variance increase (line with cross) (according to FOLLAND ET AL. 2001, p. 155)

The factors of extreme events should be approached with care since as every region has identifiable parameters of their own characteristic extreme events, which may not be considered extreme elsewhere (FOELSCHE 2003). All of these characteristics are also implemented in the report “Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation” by the IPCC (2012). A review of different national and independent meteorological services in Europe showed that extreme events can be classified in four categories “temperature-related”, “precipitation-related”, “wind-related” and “combined events”.

Temperature-related extreme events can best be defined by using minimum or maximum daily air temperature. Precipitation-related extreme weather events on the other hand can be defined by using a measure of rain, hail or snow per minute as well as a visibility range in the case of fog and ice fog. Wind-related events can be categorised as storms, blizzards and tornadoes. Storms are defined by the Beaufort scale where “9” or more than 20 m/s indicates a storm, “10” or more than 25 m/s, a heavy storm and “11” or more than 28 m/s, a so-called gale-force storm. Blizzards are defined by air temperature, wind speed and the visibility range at the same time. Tornadoes are defined by the Fujita scale with a total of six types or ranges of severity. Combined events categorise thunderstorms, floods or low water and water temperatures. Thunderstorms include simultaneous meteorological parameters, namely lightning, heavy or extreme precipitation (rain, hail or snow) and strong winds or storms. An aggregated overview of these events and their criteria is shown in Table 1.

Table 1: Wind-related and combined extreme weather events and the criteria for definition (SIEBER NÉE SCHULZ [accepted] according to GERMAN WEATHER SERVICE 2011; METOFFICE 2009; THE WEATHER CHANNEL 2009)

Event	Criteria/Threshold
Temperature-related	
Frost Days	Min. air T < 0 °C
Icing Days	Max. air T < 0 °C
Tropical Days	Min. air T > 20 °C
Summer Days	Max. air T > 25 °C
Heat Days	Max. air T > 30 °C
Precipitation-related	
Hail	Precipitation in form of ice
	Usually diameters of 5 - 50 mm, rarely to 10 cm
Fog and ice fog	Visibility range < 1 km
Heavy precipitation (liquid)	> 5 mm / 5 min; > 7.1 mm / 10 min
	> 10 mm / 20 min; > 17.1 mm / 60 min
Heavy snow	2 cm/h for at least 2 h
Wind-related	
Storm	Beaufort-scale: 9 - 11
	9 = storm (20.8 - 24.4 m/s)
	10 = heavy storm (24.5 - 28.4 m/s)
	11 = gale-force storm (28.5 - 32.6 m/s)
Blizzard	Air T < 7 °C
	Wind speed > 16 m/s
	Visibility range < 200 m due to snow fall
Tornado	According to Fujita-scale
	6 types/ranges of severity
Combined Events	
Thunderstorm	Lightning
	Heavy precipitation
	Extreme precipitation (rain, hail, snow)
	Strong winds
Floods/low water	e.g. 100-year event
Water temperatures	Thresholds for cyprinid and salmonid water bodies

Unfortunately, most extreme events are recorded in highly populated areas, where a dense net of gauging stations collects reliable data on the effects on people, sites and facilities. Data collection is sometimes enhanced by remote sensing, so that the maps may be more reliable. Further studies here will therefore focus on moderate climates with highly equipped environments, such as Northern America, Europe and, to some extent, Australia. There is a special focus on facilities for energy conversion and electricity supply and particularly on the flooding on thermal power plants as well as wind speed and wind turbines icing.

2.2 Impacts of Extreme Events on Electricity Infrastructure

Providing electricity, generally speaking, consists of the steps exploration of resources, transport and distribution, conversion, transmission and demand or consumption. In this context, only the aspects conversion in power plants and transport and on-site distribution will be analysed in detail. Moreover, it has to be kept in mind that the precondition of risk and vulnerability is not only the occurrence of extreme events but also the exposure, i.e. the location of an electricity generating unit in the area affected (IPCC 2012).

Usually, coal-, oil- and gas-fired power plants are considered as conventional thermal power plants. For a better understanding nuclear power plant strategies and regulations are a further reference. The impacts of extreme weather events on thermal power plant structures are mostly the same as on other types of buildings or power plants. The events detailed in Section 2.1 offer a broad spectrum of potential damages. In the following section, direct as well as indirect impacts will be identified and described. Direct impacts of extreme weather events on thermal power plants can affect the technology or installation as well as the resource (storage, handling and on-site transportation). This work will analyse the direct impacts on both the thermal power plants and on coal, gas and oil resources. Table 2 shows the direct impacts of extreme weather events on the installation and resource of coal-fired, gas and oil power plants.

With renewable energies, the power source is an important factor which can become hazardous to the infrastructure itself. Hydropower plants are subject to high or low water damage. Flooding can damage both plant infrastructure and reduce electricity generation. Damage can be caused by debris and resistance to water flow, damage to electrical units can be cause by water inundation as well as the deposit of bed rock (PIRKER & WIESINGER 2005). Low runoff usually only leads to a shortfall in electricity production but does not damage the infrastructure. Wind turbines suffer from material stresses due to varying temperatures, impacts from hail and icing, high wind speeds and lightning impact. Photovoltaic performance can be influenced by temperatures, impacts from precipitation (blinding due to coverage, impacts of hailstones), wind can cause failures in the mounting and thunderstorms can lead to lightning damage.

Table 2: Identification of the direct impacts of extreme weather events on coal-fired, gas and oil power plants (SIEBER NÉE SCHULZ [accepted]), a check mark (✓) indicates an impact whereas a cross (X) indicates no impact of the extreme events defined in the first column on the power plant installation or resources defined in the following columns

Event	Coal Installation	Coal Resource	Gas Installation	Gas Resource	Oil Installation	Oil Resource
Temperature-related						
Hot temperatures	✓	✓	✓	✓	✓	✓
Cold temperatures	✓	✓	✓	✓	✓	✓
Precipitation-related						
Hail	✓	X	✓	X	✓	X
Fog and ice fog	X	X	X	X	X	X
Heavy precipitation	✓	✓	✓	X	✓	✓
Heavy snow	✓	✓	✓	X	✓	X
Wind-related						
Storm	✓	✓	✓	X	✓	✓
Blizzard	✓	✓	✓	X	✓	✓
Tornado	✓	✓	✓	X	✓	✓
Combined events						
Thunderstorm	✓	✓	✓	✓	✓	✓
Floods/low water	✓	✓	✓	X	✓	X
Water temperatures	✓	X	✓	X	✓	X

Table 3 gives a general overview of the impacts of extreme weather events on renewable energy installations.

Table 3: Identification of the direct impacts of extreme weather events on the renewable energies plants of hydropower, wind energy and photovoltaic installations (SIEBER 2011), a check mark (✓) indicates an impact whereas a cross (X) indicates no impact of the extreme events defined in the first column on the power plant installation

Event	Hydropower plants	Wind energy plants	Photovoltaic installations (PV)
Temperature-related			
Hot temperatures	X	✓	✓
Cold temperatures	X	✓	✓
Precipitation-related			
Hail	X	✓	✓
Fog and ice fog	X	X	✓
Heavy precipitation	✓	X	✓
Heavy snow	✓	✓	✓
Wind-related			
Storm	X	✓	✓
Blizzard	X	✓	✓
Tornado	✓	✓	✓
Combined events			
Thunderstorm	X	✓	✓
Floods/low water	✓	X	X
Water temperatures	X	X	X

2.2.1 Temperature-related Impacts

Electricity generation by **thermal power plants** is directly impacted by high and low ambient air temperatures. The efficiency of steam and gas cycles depends on the difference between hot working medium and a colder ambient temperature; this is known as Carnot efficiency. Carnot efficiency describes the maximum, theoretically possible energy conversion efficiency from heat to mechanical or electrical energy. Moreover, cooling towers need relatively low ambient air temperatures for the condensing process (PARKPOOM, HARRISON & BIALEK 2004). A case study in the USA showed that the `*effect of global warming on thermal power production is likely to be small […] estimating efficiency reductions of between 0.1 and 0.2 %*´ (PARKPOOM, HARRISON & BIALEK 2004, p. 5). Transferred to a thermal power plant unit with an electric capacity of 1,000 MW_{el}, this efficiency reduction accounts for about 10 - 20 MW_{el}. According to the ADAM-PROJECT (Adaptation and Mitigation Strategies: Supporting European Climate Policy), an increase in ambient air temperatures by about 1 °C would reduce thermal efficiency by 0.1 - 0.5 %. However, this would result in a capacity loss of 1.0 - 2.0 % per 1 °C increase in air temperatures and would decrease the efficiency of cooling processes and conclude in shutdowns (ADAM-PROJECT 2009).

A review of current literature on the topic reveals that air temperatures are not considered to have a direct impact on **hydropower plants**. Exceptions might be (pumped) storage power plants, but no references were found. Usually, air temperature changes are regarded as a driving force of precipitation pattern changes (e.g. HARRISON & WHITTINGTON 2002a and 2002b).

Wind turbines are constructed to operate in a temperature range of -20 to +40 °C. Some so-called "low temperature turbines" work in the range of -30 to +40 °C (e.g. VESTAS V80-2.0 MW, VESTAS 2010). High or low ambient temperatures can increase material stresses (RADEMAEKERS ET AL. 2011). These material stresses include brittleness especially of glass fibres and steel components and therefore fracturing as well as an increase in viscosity of lubrication and therefore increased friction (ACKERMANN & SÖDER 2000; LACROIX & MANWELL 2000). Low air temperatures, in combination with precipitation, can result in ice accumulation along blades and masts during frost situations (PRYOR & BARTHELMIE 2010). This parameter will be described in the section on precipitation impacts.

In general, **photovoltaic installations (PV)** are vulnerable to most extreme events because of their exposed location, either on roofs or in solar parks. Every increase in temperature of 1 K results in a reduction in efficiency of about 0.4 - 0.5 % in crystalline silicon cells (RADEMAEKERS ET AL. 2011). This means that the efficiency of a typical German installation, with an average of ~ 18 kW, would be reduced by 0.074 - 0.09 kW per 1 K increase in temperature.

Heat waves and high temperatures can indirectly impact infrastructure connected to power plants. **Coal stockpiles** may be subject to spontaneous combustion and self-ignition (BRADSHAW, GLASSER & BROOKS 1991). Additionally, cooling ponds could become increasingly inefficient, as they depend on weather conditions (FURLONG 1974). Melting permafrost can lead to damage on pipelines and to infrastructure (HEYMANN 2007; MILLS 2007) due to an increased rate of deterioration of concrete structures, increased corrosion, weathering and inundation (AULD, KLAASSEN & COMER 2006).

Moreover, heat and frost stress **materials** of all kinds and during hot or cold seasons installations age faster and corrode more easily than during normal conditions. Other problems might occur due to instrument decalibration and resulting incorrect measurements (BEARD ET AL. 2010).

Temperatures have a major influence on the **electricity network**. During hot days, transmission line problems can occur due to an expansion of material and resulting cable sag (ELECTRIC POWER RESEARCH INSTITUTE [EPRI] 2009). The usual aluminium cables sag by about 4.5 cm per 1 K rise in air temperature (RADEMAEKERS ET AL. 2011), which could lead to a complete blackout of transmission lines at a total temperature of about 50 °C. Moreover, cable resistance increases in copper and aluminium lines by 0.4 % per 1 K rising air temperatures between 0 °C and 100 °C (FEENSTRA ET AL. 1998). So in total, RADEMAEKERS ET AL. (2011) state that per 3 K rise in air temperatures, the influences of capacity losses in transformers and resistance increases in cables can lead to 1 % network losses, compared to total initial losses of 8 %.

2.2.2 Precipitation-related Impacts

Precipitation-related events, e.g. heavy rain, hail, heavy snow and fog have a direct impact on **thermal power plants**, but mostly have no direct effect. This means that precipitation may fall on a thermal power plant site and not disrupt electricity production because power plant sites are usually equipped with drainage. However, the installation and infrastructure of thermal power plants are affected by extreme precipitation events. Therefore, the qualitative identification of the impact on the power plant itself is not as relevant as for the corresponding structures. The 2000 flooding event of the nuclear power plant Chernobyl caused by extreme precipitation resulted in a reactor shutdown because several emergency power supply systems did not work properly (INTERNATIONAL ATOMIC ENERGY AGENCY [IAEA] 2003). In this case, it was poor drainage systems rather than flooding from rivers or rising sea levels that resulted in flooding.

Concerning **wind turbines**, the blades are most vulnerable to the impacts of extreme precipitation. Blades are usually made of two parts which are connected by a filler. As soon as small air inclusions appear in the filler, hail stones that hit the material lead to a cracking and erosion (JONAS 2000).

Icing is another very important issue for wind turbine operators. In general, there are two types of icing accretion on wind turbines, regardless of where the accretion happens. Rime and glaze accumulate when super-cooled drops impact the freezing surface of the wind turbine. Snow can also accumulate by being blown onto the structure and freezing (PRYOR & BARTHELMIE 2010).

Figure 3: Ice accretion on the blade of a wind turbine (photo: CATTIN 2008)

Icing situations can lead to numerous operational problems for wind turbines, including:

- Turbine performance and operability due to increased material stress (see 2.2.1 Temperature-related Impacts) and the freezing of flexible parts (PRYOR & BARTHELMIE 2010);
- ice throw or ice shedding, when ice parts/blocks are thrown from an operating wind turbine (PRYOR & BARTHELMIE 2010, ACKERMANN & SÖDER 2000); and
- reduced electricity generation due to mechanical and required down times in freezing conditions (TAMMELIN ET AL. 2003).

These impacts are not only reported from arctic latitudes, especially Finland and Sweden, but also from high altitudes in Mid-European countries like Germany (e.g. Black Forest) and Switzerland. A pilot project in Sweden and Finland showed, that between 9 and 45 % of wind turbine downtimes are a result of freezing conditions (RADEMAEKERS ET AL. 2011). Additionally, freezing conditions over the sea are common and may lead to significant reductions in electricity generation in offshore wind energy parks. TAMMELIN ET AL. (2003) state that about 20 % of the newly installed wind turbines in Europe will be subject to regularly occurring freezing conditions and that up to 10 % of the new structures are built within extreme conditions where an adopted technology is necessary.

Snow can cover the **solar panels** and reduce efficiency. A study from Scandinavia showed that due to rising average air temperatures in a changing climate, snow coverage decreases and reduces the reflection that can lead to a decrease in irradiation of about 2 %. Together with rising air temperatures and the influences described in Section 2.2.1, a total reduction of 6 % in efficiency, even in northern latitudes, is possible. In southern Europe, however, efficiency is expected to rise due to an increase in irradiation and less cloud cover

(RADEMAEKERS ET AL. 2011). Besides the effects of irradiation changes, the mechanical load of snow on the installation can lead to the breaking of the module or the carrying construction (*GERMAN INSTITUTE FOR STANDARDS*/Deutsches Institut für Normung e.V. DIN 2005b). Environmental impacts on PV installations are to be tested according to International Standards No. IEC 61215 (crystalline cells) and IEC 61646 (thin-film cells) including the so-called hail test with hailstones of a diameter ∅ = 25 mm with a speed of 23 m/s on eleven spots of the module (*TECHNICAL INSPECTION ASSOCIATION* TÜV RHEINLAND 2009). Above this threshold, PV modules are not necessarily resistant to hailstone impacts.

YU, JAMASB & POLLITT (2009) describe hail as a special threat to **transmission lines** if individual hailstones are 15 mm or more in diameter. Even more so, ice coatings have a significant impact on transmission lines as well as on wind turbines. Moreover, JU, XUE & LI (2009) address four types of failures due to ice coated cables. First of all, ice coatings can lead to a physical overload of the structures. Due to heavy weights, transmission towers can collapse. Second, uneven distribution of ice on cables can lead to an unbalanced system with increased tension on cables, insulators and clamps which might lead to cables disruptions or flashovers. The third point identified is flashovers due to iced insulators. Here, the ice accretion on the insulators and intrusion of moisture promotes changes in the electric field and increases the possibility of flashovers. The last aspect is conductor galloping, which means that the cable is subject to free vibration and affects conductors and towers and can cause a cut-off from the grid. In 1998, North America experienced huge ice loads and 1,300 masts broke under high ice loads. A much better known example from Germany is the 2005 Münsterland event, where ice loads lead to several weeks of disrupted electricity distribution. 82 masts were damaged, several completely broken (FEDERAL INSTITUTE FOR MATERIALS RESEARCH AND TESTING 2006). Depending on the density of the ice accretion of 200 - 990 kg/m³, several tonnes of ice can surround the cables as additional weight (WAGNER & PEIL 2009). During the Münsterland event, the *German Weather Service* calculated an additional load of 51.1 ± 22.5 N/m. Not only ice accretion but also strong wind gusts of up to 20 m/s lead to the total impact (GERMAN FEDERAL NETWORK AGENCY 2006).

Coal stockpiles in coal-fired power plants are particularly subject to impacts from extreme precipitation. According to CHAKRABORTI (1995), the drainage system of a coal stockpile is designed for a 1-in-10-years, 24-hour rainfall event. If this threshold is exceeded, the stockpile is drenched. Wet coal has a reduced heating value because the additional moisture in the coal is converted to steam which uses additional energy for this process (HATT 2001). For example, per 10 % increase in moisture content, the boiler efficiency of a coal-fired power plant is reduced by 1 % (HATT 2004). Wet coal during freezing conditions can accumulate into lumps which may not be usable and would need to be cracked before entering the hoppers (CHAKRABORTI 1995).

2.2.3 Wind-related Impacts

PIRKER & WIESINGER (2005) analysed the impacts of the "Anatol", "Lothar" and "Martin" winter storms and found most of the damage was to roofs and building faces of **thermal power plants**. The same conclusion is reached by BINDER ET AL. (2005). Accordingly, damages to the insulation of towers and the uplifting of roofs are reported by BAILEY & LEVITAN (2008) and O'CONNELL & HARGREAVES (2004).

Wind turbines (poles and masts) are subject to the influence of storms, tornadoes and hurricanes. Since they are placed in high wind speed corridors to guarantee high efficiency, wind turbines can bend and be broken (MILLS 2007). Manufacturer guarantees cover wind speeds of up to 30 m/s (REPOWER SYSTEMS AG 2009, VESTAS 2009, and NORDEX 2009) after which electricity generation is cut-out.

Table 4 shows some technical specifications concerning cut-in/cut-out speeds as well as rated wind speeds for three main manufacturers. The cut-out wind speed usually lies within the range of a heavy storm as defined in Table 1. In this analysis, several types of wind turbines from the constructors Repower Systems, VESTAS and NORDEX are compared in an own compilation, which does not claim to be complete.

Table 4: Technical specifications of selected wind turbines according to the manufacturers, on =onshore, off=offshore

Wind turbine	Cut-in speed [m/s]	Rated wind speed [m/s]	Cut-out speed [m/s]
MM82 (Repower Systems)	3.5	14.5	25.0
MM92 (Repower Systems)	3.0	12.5	24.0
6M (Repower Systems)	3.5	14.5 (on), 14.0 (off)	25.0 (on), 30.0 (off)
3.2M114 (Repower Systems)	3.0	12.0	22.0
3.4M104 (Repower Systems)	3.5	13.5	25.0
5M (Repower Systems)	3.5	14.0	25.0 (on) 30.0 (off)
V80-2.0 (VESTAS)	4.0	16.0	25.0
V90-1.8/2.0 (VESTAS)	4.0	12.0	25.0
V90-3.0 (VESTAS)	3.5	15.0	25.0
V100-1.8 (VESTAS)	3.0	12.0	20.0
V112-3.0 (VESTAS)	3.0	12.0	25.0
V112-3.0 offshore (VESTAS)	3.0	12.0	25.0
V52-850 (VESTAS)	4.0	16.0	25.0
V82-1.65 (VESTAS)	3.5	13.0	20.0
N117/2400 (NORDEX)	3.0		20.0
N150/6000 (NORDEX)	3.5		25.0

The most apparent impact of wind on power plants and connected structures is wind load pressure. Wind load pressure can cause:

- the uplifting of tiles and roofs (O'CONNELL & HARGREAVES 2004; SWISS RE 2005);
- damage to overhead power lines (SWISS RE 2005; HEYMANN 2007);
- damage to storage tanks (CHANG & LIN 2006);
- bending and failure of pylons, masts and towers (Figure 4, Figure 5);
- destruction of relay and transformer stations, disruption to distribution systems, offshore oil rigs and pipelines (SWISS RE 2005); and
- damage to insulation and cooling towers (BAILEY & LEVITAN 2008).

After the winter storms "Lothar" and "Martin", more than 200 destroyed pylons were found in Northern France, Southern Germany and Switzerland, where the storms hit with the highest wind velocities (CRUZ ET AL. 2004).

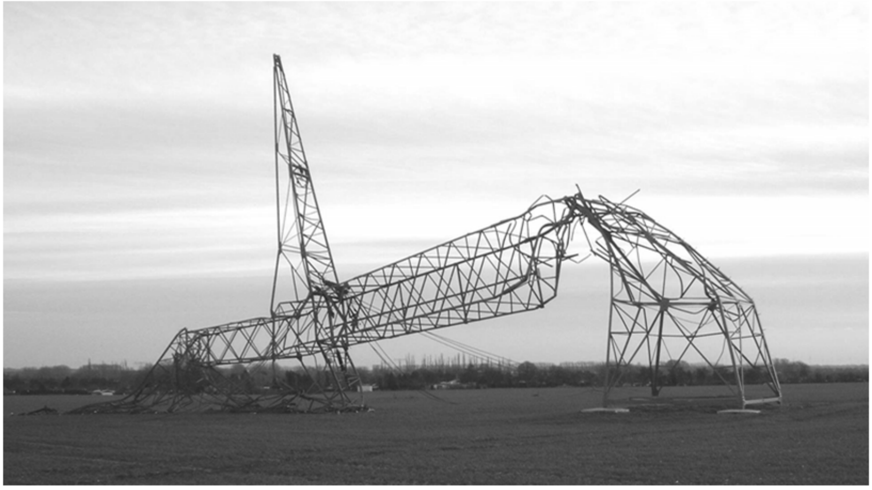


Figure 4: Failure of a power mast due to winter storm Kyrill (photo: OLAF2)

Figure 5: Complete failure of a wind turbine pole (photo: GEGENWIND SH)

During storms, inaccurately mounted solar panels can be blown away (SCHMITT 2005, *GERMAN INSTITUTE FOR STANDARDS*/Deutsches Institut für Normung e.V. DIN 2005a). Therefore, the *German Insurance Association*/Gesamtverband der Deutschen Versicherungswirtschaft e.V. (*GERMAN INSURANCE ASSOCIATION* GDV 2003) reminds operators of PV modules that stable construction is of importance. There are no international standard tests for wind speeds and mounting requirements.

BUDNITZ (1984) analysed power plant structures on their resistance to wind pressure. He came to the conclusion that concrete-sided structures and buildings are more resistant to wind pressure than metal-sided ones. Figure 6 shows tank damages after Hurricane Katrina, where the walls of a storage tank are dented. Likewise, in 1989 Hurricane Hugo demolished several storage tanks on the Virgin Islands and in 1970 Hurricane Celia destroyed 30 storage tanks in Texas, USA (CHANG & LIN 2006).

Figure 6: Tank damages after Hurricane Katrina in Louisiana 2005 (M. NAUMAN, FEMA photo library ID No. 20548)

Usually, smaller tanks are subject to denting and debris impacts; smaller parts of the walls are pressed inwards or topple over. Walls collapse in larger tanks due to strong lateral wind pressure (BAILEY & LEVITAN 2008).

The following Table 5 contains some damages reported after severe storms in Europe.

Table 5: Damages to electricity generation and distribution structures after severe storms in Europe

Storm and occurrence date	Area of highest impact	Damages	Source/Reference
Lothar/Martin (December 25/26, 1999)	Northern France, Southern Germany, Switzerland	200 electricity pylons	SWISS RE (2000) in CRUZ ET AL. (2004)
Kyrill (January 18-20, 2007)	Germany, Austria, Poland, Czech Republic	Disruptions in electricity network (2 million households without electricity)	EEA (2010)
Klaus (January 2009)	France	Loss of electricity pylons, interruption of supply for 1.5 million households	EEA (2010)
Anatol (December 03, 1999)	Denmark, Scotland, Southern Sweden	Electricity supply failed for 165,000 households due to damaged network	MUNICH RE (2001)
Erwin (January 07-09, 2005)	Scandinavia, Baltic States	Loss of electricity, shut down of five NPPs in Sweden	MUNICH RE (2006)
Thorsten (November 25-27, 2005)	Germany	Bending of network masts	MUNICH RE (2006)
Xynthia (February 26-28, 2010)	Northern France, The Netherlands, Northern Germany, Denmark, Southern Sweden	Damages to network, loss of electricity	RUHNAU, SÄVERT & LAPS (2010)
Jeanette (October 27, 2002)	UK, Northern Germany, Denmark, Poland	At least one wind turbine broken	STUTTGARTER NACHRICHTEN ONLINE (October 28, 2002), MAHRENHOLZ (2006)
Karla (December 30-31, 2006)	Southern England, Northern France, Northern Germany	Loss of electricity supply	SPATZIERER & LAPS (2007)
Lotte (December 31, 2006 – January 01, 2007)	Germany	Loss of electricity supply	RP ONLINE (December 31, 2006)
Franz (January 12, 2007)	Germany	Damages to overhead wires	SPIEGEL ONLINE (January 11, 2007), SPATZIERER & LAPS (2007)
Annette (February 22, 2008)	Northern Germany, Scandinavia	Bending of masts and towers, loss of electricity supply	N-TV PANORAMA (February 23, 2008a)
Emma (March 01, 2008)	North Sea, Northern Germany, Southern Sweden	Damages to ~ 5.000 transformer stations	N-TV PANORAMA (March 01, 2008b)

Furthermore, BAILEY & LEVITAN (2008) list a number of examples of damage to power plant infrastructure by storms and hurricanes, for example:

- partial collapse of cooling towers;

- collapse of utility poles;
- denting of supply and storage buildings, mostly metal-sided ones; as well as,
- exfoliation of insulation of process towers by causing failures of straps and fasteners.

A positive impact of wind speeds is wind chill on overhead wires for electricity transmission. Wind chill can increase the capacity of transmission lines by up to 20 % per meter per second in wind velocity, as wind keeps the temperature limits of 80 °C for a longer time span and cools the wires due to increased convection (RADEMAEKERS ET AL. 2011).

2.2.4 Impacts of Combined Events

2.2.4.1 Thunderstorms including Lightning

Only one of the articles reviewed addresses the impact of lightning on **nuclear power plants** (BUDNITZ 1984). Lightning is described as an extreme external event, in addition to man-made accidents, external fires and pipeline accidents. Lightning strikes mainly hit the connected infrastructure, usually the highest buildings and structures on a power plant site. According to CHANG & LIN (2006), lightning strikes are the most common cause of **storage tank** accidents with 80 registered incidents between 1960 and 2003. Other natural disasters accounted for seven cases over the same time period. STOCK (2009) reports a total of 480 registered tank accidents between 1951 and 2003, 150 of them due to lightning strikes. The changing climate has seen an increase in the frequency of lightning in Germany between 2004 and 2007, changing from 4.9 to 7.5 lightning strikes per square kilometre per year. This can also be attributed to a denser, improved observational network (STOCK 2009). It is important to note that when a lightning strike hits the tank, off-tank fluids may be inflamed. This can lead to huge damages in the infrastructure as well as in economic planning.

Wind turbines are subject to lightning strikes because of their exposed location. Both direct strikes and strikes of nearby objects or structures can impact wind turbines by creeping currents (COTTON & JENKINS 1997). Every part of the wind turbine – nacelle, gearbox, blades and tower – could be hit by lightning but only 1/3 of damage is generally caused by a direct hit. Most damage can be attributed to lightning strikes on communication or grid lines (GLUSHAKOW 2007).

In general, four effects of lightning on wind turbines were identified: Peak currents, changes in specific energy, overvoltages and charge transfer. Peak currents and changes in specific energy can cause materials heating and shock effects due to impact. In these cases, mostly the blades, the nacelle and the wiring are vulnerable. Concerning overvoltages, flashovers and shock effects affect the electronic control system of a wind turbine. Moreover, the charge transfer can affect the bearings and the blades by inducing creeping currents along the lightning conductors (COTTON & JENKINS 1997).

Usually the blades are constructed to withstand damage by high amperages of several 1,000 A (JONAS 2000). Nevertheless, lightning impacts often lead to the burning down of the wind turbine as it can be difficult for the fire brigade to reach the heights of the nacelle and other burning parts (Figure 7).

Figure 7: Burn down of a wind turbine. Black smoke comes out of the nacelle. The reason for the damage is not known (photo: ©GESAMTVERBAND DER DEUTSCHEN VERSICHERUNGSWIRTSCHAFT)

NASA maps indicate a correlation between high wind density and thunderstorm activity, showing high wind density areas to have 30 or more thunderstorms per year. However, high wind density areas are favourable for installing wind turbines. Moreover, following the mapping by the NASA, studies in Germany have shown that 8 out of 100 wind turbines are expected to be hit by lightning each year. This study also shows statistics of 124 direct hits to turbines and 269 incidents of damage from the grid leading to destruction of wind turbines between 1992 and 1995. Within four years a total number of 393 failures occurred (GLUSHAKOW 2007).

Lightning strikes to **PV installations** usually induce failure due to overvoltage. Lightning conductors are not required for residential buildings in Germany, however. During PV module installation, existing lightning protection has to be integrated into the PV system. Lightning protection can be provided through grounding the installation (*GERMAN INSURANCE ASSOCIATION* GDV 2003). There can be both external and internal lightning protection for PV installations. External lightning protection includes the capture of direct lightning hits and discharging the electric currents into the ground thus avoiding damage to the installation or the public. Internal lightning protection must avoid sparking through potential equalisation meaning that metallic and conducting parts of the module are protected against currents from the external lightning protection (*GERMAN SOLAR INDUSTRY ASSOCIATION*/Bundesverband Solarwirtschaft e.V. (BSW) & *CENTRAL ASSOCIATION OF THE*

GERMAN ELECTRIC POWERED AND IT CRAFTS/Zentralverband der Deutschen Elektro- und Informationstechnischen Handwerke (ZVEH) 2008). In case of fire, fire extinguishing at PV installations is challenging. The fire brigade needs to take into account several guidelines and instruction in handling high voltages and conductors (A.U. 2011; WILLE 2005; A.U. 2009) (Figure 8).

Figure 8: Fire damage of a PV installation (photo: ©GESAMTVERBAND DER DEUTSCHEN VERSICHERUNGSWIRTSCHAFT)

In an overall comparison between the effect of lightning, wind and precipitation on **transmission lines**, SHEN, KOVAL & SHEN (1999) found that the impact of wind and precipitation are not proportional to line length, but that the impacts of lightning strikes are. Lightning strikes are major causes for outages in electricity distribution systems. The consequences of lightning strikes might include – as with PV installations – direct damages through an increase in peak current, charge transfer, specific energy and rate of current rise (COTTON & JENKINS 1997) and indirect damage from overvoltage, electromagnetic pulses, electrostatics and creeping currents (CHANG & LIN 2006).

2.2.4.2 Water Temperature

Thermal power plants are equipped with cooling systems to condense process water and to return it to the steam cycle. Therefore, the efficiency of a cooling system that uses surface water for cooling depends on ambient water temperatures. Basically, two types of cooling water systems are used. In the once-through cooling system, water is withdrawn from a nearby water body and discharged back, either after passing through cooling towers or not. In the closed-circuit cooling system, water is withdrawn from the water body and circulated through the system several times before a considerably reduced amount of water is discharged. Consequently, the once-through cooling system has higher water withdrawal but lower consumption and the recirculation cooling system has lower water withdrawal but a relatively higher water consumption (FEELEY III ET AL. 2008; STRAUß 2009). Rising water temperatures lead first to an increase in water withdrawal to meet legal and environmental thresholds for the temperature of discharged water without reducing efficiency. The ensuing decrease in plant efficiency results in a further reduction of electricity output to meet environmental thresholds because if limits on water use and pollution (KIRKINEN ET AL. 2005; KRYSANOVA & HATTERMANN 2007; MILLS 2007; EPRI 2009). There are numerous examples of this. In the United States, high ambient water temperatures in the south-eastern part of the country in 2002 resulted in reduced power output at several thermal power plants (US DEPARTMENT OF ENERGY [DOE] / NATIONAL ENERGY TECHNOLOGY LABORATORY [NETL] 2007). Second, in the 2003 European heat summer, power plants in Switzerland (SWISS AGENCY FOR THE ENVIRONMENT, FORESTS AND LANDSCAPE [BUWAL], SWISS FEDERAL OFFICE FOR WATER AND GEOLOGY & METEOSWISS 2004), in Southern Germany (FEDERAL INSTITUTE OF HYDROLOGY [BfG] 2006) and France reduced their electricity generation due to high water temperatures. Again, in the summer of 2006, several power plants in France, Spain and Germany had to reduce their power output due to high water temperatures and the need to meet water discharge thresholds. Some power plants were shut down (DOE/NETL 2007). No further analysis will be carried out on the effects of ambient water temperature but the author refers to STRAUCH'S doctorate thesis (2011), in which this topic is analysed in detail.

2.2.4.3 Floods and Low Water

In general, **thermal power plants** depend on water supply. Water is used for cooling purposes, as process and other supply water (e.g. for sanitation, the lunchroom and washer systems). Therefore, a shortfall in quality (through chemical or thermal pollution) and quantity (amount) of water has the most important direct impact on thermal power plants. Electricity generation through thermal power plants requires about 100 litres of freshwater per kilowatt-hour (FEELEY III ET AL. 2008), most of it used for cooling.

There are two types of flooding: internal (e.g. from broken pipes or tank ruptures) and external (from high water levels in rivers, lakes, ocean or from intense rainstorms or flash floods) (BUDNITZ 1984). This work only analyses the external flooding. Most of the impacts of site flooding are on the connected infrastructure. STEININGER ET AL. (2003); YOUNG, BALLUZ & MALILAY (2004) and KRAUSMANN & MUSHTAQ (2008) list several impacts on power plant infrastructure as being:

- uprooting and displacement of storage tanks;
- rupturing of pipe and cable connections, even underground gasoline and oil pipes;
- breaching of tanks due to collision with debris;

- impacting indirectly such as through disruption of water purification and sewage disposal systems; as well as
- short-circuiting and power outages resulting in malfunctioning of cooling systems, pumps and safety systems.

These impacts on power plant infrastructure are also called NaTechs – Natural Hazards triggering Technological Accidents (KRAUSMANN & MUSHTAQ 2008).

Figure 9 shows a flooded coal-fired power plant in the United States during a river flooding of the Mississippi river in 1993. Clear to see are the flooded and eroded coal stockpiles in the middle of the picture.

Figure 9: Flooded coal-fired power plant at the Mississippi river, 1993 (photo: A. BOOHER, FEMA photo library ID No. 3429)

Causes of damage are inundation, flow resistance and deposit of sediment loads (STEININGER ET AL. 2003). For example, during flooding in Austria in August 2002 damage was reported to transformer stations, relay stations, cables, pylons and cable boxes (HABERSACK & MOSER 2003, PIRKER & WIESINGER 2005). In 1993, a rainfall induced flooding affected 1,300 US Union Electric power stations. Most components needed extensive cleaning due to accumulated mud in circuit breakers, motors and switchgears (ABI-SAMRA & HENRY 2011).

Several power plant case studies show the following impacts of flooding (IAEA 2003 if not indicated otherwise):

- 1980: increased water level and leakage lead to the contamination of groundwater because of defective storage tanks in Garigliano, Italy.
- 1993/1994: water levels at the US Cooper power plant surpassed the 10,000-year flood design water level. As a result, increased groundwater damaged cable tunnels,

electrical equipment and contamination occurred. The power plant's emergency routes were not usable.

- 1999: the nuclear power plant in Blayais, France was flooded. Several emergency systems failed and two of four units needed to be shut down due to encroaching water (GORBATCHEV n.d.).

Hydropower plants are extremely vulnerable to changing runoff as they depend on it for water supply. A reduction of 1 % in precipitation will result in a reduction of 1 % of electricity generation by hydropower plants and vice-versa (RADEMAEKERS ET AL. 2011). Floods can cause damage to hydropower plants: structures and buildings can be directly damaged by the mechanical load of the water body. Electrical devices could be inundated by water and short-circuiting would disable electricity generation and distribution. Furthermore, sedimentation and deposition of debris can lead to damages as well as blocking water inlets and turbines (PIRKER & WIESINGER 2005).

An increase in sea levels is usually mentioned as having a negative impact on power plants and their connected infrastructure but the effect has never been quantified (PARKPOOM, HARRISON & BIALEK 2004; DOE/NETL 2007; KRYSANOVA & HATTERMANN 2007; EPRI 2009; PASKAL 2009). Moreover, increases in sea levels can be considered to be an impact of a changing climate and changing mean patterns, therefore it is not included in this research on the influence of extreme weather events.

RENNI ET AL. (n.d.) conducted a study on **storage tanks** and their interference by flood events. They list the following aspects:

- catastrophic failure would be the complete collapse of the tanks due to pressure or to the collapse of the pipeline system;
- additional failure could be the disruption of connections and flanges (overload, debris impact);
- shell rupture and destruction of roofs, as well as minor failures of connections and pipelines, could also result from the impact of waves and water masses.

Consequences of low water and drought include reductions in summer runoff in Germany, especially along the River Rhine. Here, a decrease in runoff may be by up to five to twelve percent by 2050 (BATES ET AL. 2008). The most obvious consequence of low water levels is the reduction in the supply of cooling water; although thermal power plant shutdown has not yet been attributed solely to a shortfall in water supply (SCHMIDT-THOMÉ & KALLIO 2006). Low water levels are usually not a threat to the environment because power plants must reduce their water withdrawal or even shut down in the case of an insufficient amount of cooling water (OTT & RICHTER 2008). Several authors concluded that a shortfall in water negatively affects electricity generation in thermal power plants whether nuclear or conventional (STEININGER ET AL. 2003; DOE/NETL 2007; EPRI 2009).

On the other hand, impacts on power networks have been reported and analysed by the ENERGY NETWORKS ASSOCIATION (2009). Therein, the impact of soil movements and crackling due to missing water supply is described on gas networks and, in particular, on pipelines. Masts for overhead wires could be exposed to soil movement resulting in a so-called leaning of the masts. Soil shrinkage also affects substations and electricity distribution buildings due to internal displacement.

2.3 Adaptation Options

Generally speaking, adaptation should increase the strength and preparedness of power plants to cope with future climatic conditions and therefore, be beneficial to power plant operators and to the public. These benefits – an increase in robustness, an increase in the flexibility of management and an improvement in awareness and preparedness – are highlighted by WILLOWS & CONNELL (2003).

There are several ways to define adaptation measures. These include type of measure: hard/structural and soft/non-structural measures (e.g. WILLOWS & CONNELL 2003; KUNDZEWICZ & KACZMAREK 2000) and the time frame of adaptation: no regret/low regret/short/medium/long-term measures (AULD, MACIVER & KLAASSEN 2007). In the following sections, all of these adaptation measures will be mentioned in the context of power plant adaptation, from the adaptation of building structures for thermal power plants and power plant sites to adaptation of connected infrastructures, mostly on-site. Appendix A gives an overview of adaptation measures that cannot be attributed to one application but only be sorted by type.

2.3.1 Adaptation of Thermal Power Plants

Two main options of adaptation of **cooling options** are the use of so-called non-traditional waters and the re-use of process water. Non-traditional waters, in this sense, is waters not withdrawn from a river, lake, the ocean or from groundwater sources but is otherwise obtained from the environment. For instance a percentage of a power plant's water requirements can be obtained by:

- recirculation of produced water from oil and gas fields or coal mines which are needed during the extraction;

- usage of treated sewage water from nearby cities;
- or treated coal mine or extraction of coal stockpile and ash pond effluents (UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE [UNFCCC] 2006; DOE/NETL 2007; FEELEY III ET AL. 2008).

In a test site 25 % of the cooling water requirements for a 1,800 MW coal-fired power plant were met by produced water from oil and gas fields. The entire requirement for cooling water for a 600 MW coal-fired power plant at Pittsburgh, USA was met by mine discharges (DOE/NETL 2007). Furthermore, the nuclear power plant at Palo Verde in Arizona, USA receives 100 % of its cooling water from the Phoenix City Sewage Treatment Plant. The last example is not a case study for climate change adaptation, nevertheless it shows that alternative technologies for water recovery already exist and can be adapted and implemented to meet new objectives.

The re-use of process water covers the mechanisms of the recycling of water from flue gases through heat exchangers, the use of hot water from the condenser to dry coal and subsequent use of the evaporated water from the coal as well as the reduction of evaporation losses in flue gas desulphurisation systems. As illustrated by the example of using produced water, recycled water from condensed flue gases can cover 25 - 37 % of the power plants water requirements (DOE/NETL 2007; FEELEY III ET AL. 2008), though this is only suitable for the external cooling process. Using hot water from the condenser to dry coal has two major advantages: first, coal that enters the combustor has an increased heating value (LAMBERTZ & EWERS 2006) and secondly, water that enters the cooling towers is already cooler. Moreover, steam generated by the evaporating coal could be condensed and used.

Another practice is to channel air over blocks of ice for cooling before it passes through the gas turbine air inlet. Regardless of the additional costs, this increases power output and also reduces the heat rate. Secondly, the melted ice can be collected and re-used in the cooling towers (DOE/NETL 2007). Furthermore, evaporation losses in the cooling towers can be reduced through condensing equipment at the cooling tower outlet. This may meet up to 20 % of evaporation loss (DOE/NETL 2007), so that more water can be re-circulated or discharged back into the water body. The retrofit of four cooling towers in order to achieve a discharge water temperature reduction of 2 - 3 °C will cost about 2.5 M€ (~ 2.5 €/kW) (RADEMAEKERS ET AL. 2011).

Other options for the adaptation of the cooling process are to use alternative cooling towers and technologies (e.g. OTT & RICHTER 2008; DE BRUIN ET AL. 2009). Dry cooling towers using air as a heat exchanger with, or without, fans to create air-flow are one option. Furthermore, regenerative cooling can be used, whereby compressed steam cools because it expands. Heat pipe exchangers allow the steam they carry to release heat to the environment without direct contact; then the cooled/condensed steam can be re-circulated.

A study by VAURIO (1998) on **power plant modifications** showed that improved drainage, re-routed service water pipes, and improved isolation of water pipes are effective and cost-efficient ways to protect a power plant from flooding. In comparison, building of a cooling tower costs about 50 - 60 M€ and the costs of modifying coastal water inlet system may be up to 100 M€ (RADEMAEKERS ET AL. 2011).

As demonstrated by the examples of wind-related impacts, the use of concrete-sided buildings rather than metal-sided buildings could be an adaptation measure against strong winds and increased corrosion from increased precipitation (BUDNITZ 1984).

Thermal power plant sites can be **adapted against flooding** by installing flood control measures. Several options are shown in THOMALLA ET AL. (2006), for example embankments where the site is totally surrounded by a dam. In KUNDZEWICZ & KACZMAREK (2000) and UNFCCC (2006) for example, the use of dams, dikes, flood control reservoirs, polders, ponds and the improvement of channel capacity is demonstrated. All these measures count as *hard* measures or physical protection (see Figure 10). MAI, OHLE & ZIMMERMANN (2002) propose upgraded or new protection measures, especially for nuclear power plants. They suggest dikes that should be, even after a partial breach, high enough to protect the NPPs from flooding regardless of the probability of occurrence (in LEIPPRAND ET AL. 2008). According to MILLS (2007), land restoration and forestation lead to a reduction in flood peaks and mudslides and are therefore appropriate measures against the negative effects of climate change. KUNDZEWICZ & KACZMAREK (2000) also list a number of *soft* measures for flood protection such as zoning, improved building codes and flood insurance. Whereas zoning and improved building codes place the responsibility with public authorities, as they not only protect power plants but also common goods and public infrastructure, flood and/or weather insurance is the responsibility of the individual; although not every country or community offers insurance against flood risk. An overview on hard and soft flood protection measures is given in Table 6 and Table 7. Figure 10 shows temporary stop log systems for entrance protection.

Table 6: Overview of hard/structural and soft/non-structural flood protection measures. The arrangements are not only feasible for thermal power plant protection but may also work for other electricity generating facilities. The first column represents the measurement category (hard, soft, other), the second column contains the function, the third column indicates the sources (continued on following page with soft options)

Flood protection measures	Function of protection measure	Sample Source/Reference
Hard/structural options		
Dams, dikes	Keep flood water from land which needs to be protected (e.g. industrial or residential areas)	KUNDZEWICZ & KACZMAREK (2000), HOOIJER ET AL. (2004), THE ASSOCIATED PROGRAMME ON FLOOD MANAGEMENT (2004), ECONOMIC COMMISSION FOR EUROPE (2009), MANSANET-BATALLER ET AL. (2008)
Flood control reservoirs	Reduction and delay of runoff	KUNDZEWICZ & KACZMAREK (2000)
Floodways	Channeling runoff	KUNDZEWICZ & KACZMAREK (2000), HOOIJER ET AL. (2004)
Increase of channel capacity	Improvement of channeling runoff	KUNDZEWICZ & KACZMAREK (2000), THE ASSOCIATED PROGRAMME ON FLOOD MANAGEMENT (2004)
Polders, retardation ponds, water storage	Storage of flood water, delayed re-feed into water body	KUNDZEWICZ & KACZMAREK (2000)
Flood proofing	Building flood-secure structures	KUNDZEWICZ & KACZMAREK (2000), THE ASSOCIATED PROGRAMME ON FLOOD MANAGEMENT (2004)
Retention areas	Storage of flood water, delayed re-feed into water body	HOOIJER ET AL. (2004), ECONOMIC COMMISSION FOR EUROPE (2009)
Renaturation/rejuvenation of floodplains	Increase capacity of natural flood storage, decrease flow velocities, reduce runoff	HOOIJER ET AL. (2004)
Barriers (temporary or permanent)	Prevent the inundation of structures, keep water from intruding	VAN DER VAT (2007)

Table 7: Overview of hard/structural and soft/non-structural flood protection measures (continued from previous page)

Flood protection measures	Function of protection measure	Sample Source/Reference
Soft/non-structural options		
Zoning	allocation of land with restricted or prohibited usage (priority and retention areas)	KUNDZEWICZ & KACZMAREK (2000)
Implementation of building codes	Regulatory preparation of flood proofing	KUNDZEWICZ & KACZMAREK (2000), THE ASSOCIATED PROGRAMME ON FLOOD MANAGEMENT (2004)
Flood insurance	Transfer of flood risk on many parties	KUNDZEWICZ & KACZMAREK (2000), THE ASSOCIATED PROGRAMME ON FLOOD MANAGEMENT (2004)
Development and adaptation of policies	Regulatory approach	THE ASSOCIATED PROGRAMME ON FLOOD MANAGEMENT (2004)
Flood forecasting and warning	Preparation of public, launching of installation of protection measures	THE ASSOCIATED PROGRAMME ON FLOOD MANAGEMENT (2004), ECONOMIC COMMISSION FOR EUROPE (2009)
Information and education	Preparation of public or staff, mapping of possible events	THE ASSOCIATED PROGRAMME ON FLOOD MANAGEMENT (2004)

Another case is the adaptation in coastal zones. Among others, LEARY (2004) and the UNFCCC (2006) recommend protection through hard measures such as dykes and sea-walls. Recommendations for the retreat include establishment of set-back zones, relocation and accommodation, better warning and evacuation systems, insurance, improved building codes as well as improved drainage systems.

Figure 10: Stop log system as mobile flood protection (©IBS INDUSTRIEBARRIEREN UND BRANDSCHUTZTECHNIK PLANUNGS- UND VERTRIEBSGESELLSCHAFT MBH n.d.)

Since the vulnerability of a site is considerably influenced by its exposure to threat, LEARY (2004) proposes the relocation of power plant sites to less exposed places. Especially in the case of existing power plants, this might not be an adaptation option. During the planning phase changed conditions in weather and resulting in the availability of cooling water for thermal electricity generation should be compared to the resilience of existing structures and long-term location should be adapted to new recommendations (TIERNEY 2007).

2.3.2 Adaptation Options for Renewable Energies

Hydropower plants are dependent on water and subject to its fluctuations in availability. Adaptation options are to ensure that standards for strength are met and operation can be timed accurately. THE GOVERNMENT OF CANADA (2009) suggests several options for adapted hydropower plant operation:

Table 8: Adaptation options for hydropower plant operation, samples of structural and non-structural measures as proposed by the GOVERNMENT OF CANADA (2009)

Adaptation measures/options	Functionality
Non-structural instruments	
Adapted operating rules	Optimized operation during flood or drought situations
Revised runoff forecasting	Changes in runoff patterns need to be recognized
Coordination of power plants and other usage in catchment area	Set priorities for power plant operation or other usage, e.g. irrigation
Revision of design and engineering practices	Modifications of turbines could be feasible in changed runoff patterns, e.g. more low water levels may need turbines with lower capacity
Structural instruments	
Rerouting of upstream tributaries	Regulation of amounts of runoff
Storage reservoirs	Storage of flood water, delayed re-feed into water body
Construction of dams	Keep flood water from land which needs to be protected (e.g. industrial or residential areas)
Increase channel capacity	Improvement of channeling runoff
Retrofitting of installed capacity	Improvement of utilization, optimizing electricity output when adapted to runoff amounts

Structural damage can be avoided for hydropower plants through structural adaptation options such as dam safety, enhanced discharge or water storage (LEIPPRAND ET AL. 2008). If flooding conditions result in the shut down of a hydropower plant, it can be used as a weir to protect facilities downstream. Blockage from flood debris can be avoided by filter installation. Especially hydropower plants can reduce the risk of small and medium floods because of their location in the stream and pre-existing runoff pattern regulation (RADEMAEKERS ET AL. 2011). As in the case of thermal power plants, hydropower plant adaptation measures can be separated into structural and non-structural options (see Table 8 above).

Several approaches for adaptation options for **wind turbines** can be considered. First, that towers could be built either as a latticed steel pylons, on which wind pressure has less surface to attack or as secured metal or concrete poles that can avoid tipping over and breaking (BAILEY & LEVITAN 2008, see Figure 11). One general approach is to plan wind farms with sufficient distances between turbines to avoid too much turbulence. A result of wind turbulence and gusts is high structural load as well as an increase in maintenance (RADEMAEKERS ET AL. 2011). A well-planned and constructed wind farm may therefore help to reduce downtimes and a resulting reduction in electricity generation.

Figure 11: Lattice steel masts for wind turbines (photo: SIEBER 2011)

Several options are available to protect against damage from frost and ice accretion. The most obvious would be to install heating wires and other heating devices to de-ice the blades. However, these heating systems are relatively costly because of their own high levels of energy consumption (LAAKSO ET AL. 2003). One lower priced solution could be to install inflatable membranes along the blades and fill them with air to blow up ice accretions (LAAKSO ET AL. 2003). However, all these systems work after ice has built upon the blades and system components of the wind turbine. None of these measures is able to avoid the initial ice accretion itself. Research is being performed on solutions like a cover of nanostructured materials where waterdrops or ice particles cannot accumulate (BASF 2010; CLARIANT 2010; PARRISH 2009). But, the author assumes that when air-borne particles hit the rotating blades at a high velocity, they damage the surface of the blades in dimensions bigger than nanostructures, so that the coating would now be affected. This reduces the benefits of this option for adapting the blades.

Lightning conductors are already installed on all wind turbines. Most new wind turbines are equipped with lightning rods at the nacelle. Some manufacturers, like Enercon, have lightning protection in the blades (e.g. ENERCON GMBH 2011). Nordex offers systems that conform to DIN EN 62 305 for the protection of the entire wind turbine (e.g. NORDEX SE 2011). RePower Systems describes their lightning protection system as follows: The lightning protection fits the standards of the IEC for interior as well as exterior systems. Moreover, bypasses, galvanic separation and overvoltage arresters protect the whole wind turbine and the installed grounding shields the generator (REPOWER SYSTEMS 2011). Those measures prevent wind turbines from catching fire from direct lightning strikes and protect sensitive electric devices. In addition, the best possible protection against indirect effects is insulation.

Corrosion of materials can be prevented through the use of specific types of steel for turbine masts (LAAKSO ET AL. 2003). Also, special types of glass-fibre and fillers reduce sensitivity to severe weather impacts.

PV systems are either subject to unavoidable consequences of weather events (snow coverage for example) or can avoid others by adhering to safety standards and rules. Even though PV installations are influenced by many hydro-meteorological impacts, adaptation options are rare. However, it is recommended to integrate lightning protection with PV installations into the building protection system if available, because residential buildings are not obliged to do so (*GERMAN INSURANCE ASSOCIATION* GDV 2003).

2.3.3 Adaptation Options for Connected Infrastructures

One of the easiest ways to adapt infrastructures to climate change is through the use and renewal of standards. Increasing uncertainty in climate change research and extreme weather data may lead to implementing and adjusting standards for construction and protection of power plants and connected infrastructure (AULD, MACIVER & KLAASSEN 2007). There are currently several different institutions originating standards, design codes and rules to ensure the best possible protection for newly built and pre-existing power plants. Amongst these institutions are the *German Institute for Standards* [Deutsches Institut für Normung e.V. DIN], the *Association of German Engineers* [VDI] and the *German Nuclear Safety Standards Commission* [KTA], the American Standards Association, the British Standards and, above all, the International Federation of the National Standardizing Associations [ISA] and the International Organization for Standardization [ISO] with their internationally binding regulations. Usually, these rules and codes contain an extrapolation of the extreme value statistics for design bases; those values should become an integral part of construction and renovation. Nevertheless, these different regulations often do not contain the same basic information and diverge from each other.

The most effective way to reduce the number of newly built power plants in hazardous areas is through zoning and the disclosure of restricted, or prohibited, building zones in flood-prone areas (KUNDZEWICZ & KACZMAREK 2000). However, because thermal power plants need large quantities of water and their need to be close to a water body makes this solution not practical.

Temperature-related adaptation options of distribution infrastructures are described for **transformers and cables**. Transformers need to be cooled, most often by using copper as a conductor. Other materials might be more conductive, allowing heat from increasing air temperatures to be transferred more easily, but they tend to be more expensive. RADEMAEKERS ET AL. (2011) assume that copper will remain the primary heat conductor for the next ten to twenty years because of its reliability. Another option discussed in RADEMAEKERS ET AL. (2011) is the insulation of cables and wires. So-called gas insulated lines (GILs) are more efficient because the increasing temperatures do not affect transmission. Yet, costs for GILs are nine to twelve times higher than for common cables. A positive side effect of GILs is the reduction of cable sagging from high temperatures and reduced cable expansion in diameter.

OTT & RICHTER (2008) suggest an increased installation of underground cables instead of overhead wires, because they are less vulnerable to storms, wind throw and freezing/ice loads, but more vulnerable to flooding. This would suggest that using underground cables might not offer a measurable improvement in flood-prone areas. Still, there are some aspects to be considered in the installation of underground cables. Though underground cables are less vulnerable to storm damages, cables with a voltage of more than 150 kV are at risk of over-voltage when put underground. Furthermore, low-voltage underground cables are about four to five times more expensive, high-voltage underground cables are about ten to twenty times more expensive than overhead wires. This is due to higher inspection, hauling and operating costs (RADEMAEKERS ET AL. 2011). Compared to only two to three times the cost of other measures (i.e. strengthening pylons and lines) underground cabling seems technically less profitable.

The ENERGY NETWORKS ASSOCIATION (2009) addresses the impact and potential protection of network structures against thunderstorms and lightning strike. Here, the redesign of structures is mentioned but not explained further. One possible implication could be the use of more weather-resistant materials or the relocation of structures to reduce exposure as before. Clearing vegetation (i.e. trees and over-hanging branches) around the network structures ensures that in case of a storm event, these branches cannot fall onto the wires and cause short-circuits. Again, the most obvious option of relocating the network underground is mentioned.

A combination of temperature, water and salt intrusion can lead to corrosion of the electricity network and of concrete structures, like **storage tanks**. Concrete structures can be repaired by the removal of damaged parts and the application of waterproof textures afterwards. Salt intrusion, however, remains in the concrete and continues to corrode the structure (AULD, KLAASSEN & COMER 2006).

Transmission stations can also be affected by flooding. ABI-SAMRA & HENRY (2011) propose the protection of these structures by ring-shaped barrages constructed around the transmission station to a minimum height of the worst flood event. One easy way to adapt is by storing sensitive equipment or liquids above flood level. Another measure showed that relocation of transmission stations must be considered. Location security should already be considered during the planning phase rather than re-locating existing stations. A relocation of transmission stations was considered in Rosenburg at the Elbe after flooding in 2002 (PIRKER & WIESINGER 2005).

Another important point is the adaptation of **coal stockpiles**. They are vulnerable to precipitation, wind and both high and low temperatures. Therefore, an optimal orientation as well as an improved stockpile shape might lead to reduction of storm loss. This can be achieved through using barriers and windbreaks (CAL, CHEN & SOO 1983) or by spraying agents to create a crust on the stockpiles (CHAKRABORTI 1995). CAL, CHEN & SOO (1983) account for losses up to several thousand tons per year through the loss of coal particles with a diameter < 30 µm.

Crusts can also protect stockpiles from the impact of severe precipitation and additional freezing. Even plants and grass cover can help to reduce coal losses from severe weather (HATT 2003). Building wind barriers and additional compacting the coal stockpile prevents spontaneous combustion during high temperatures (FIERRO ET AL. 1999). Agglutination and freezing can be prevented primarily by using sprayed agents and compacting the coal to prevent water intrusion into the stockpile and secondly by circulating coal within the stockpile to avoid ground frost (CHAKRABORTI 1995, FIERRO ET AL. 1999).

2.4 Management Concepts and General Decision Making

Management concepts consist of several steps of decision making processes which include amongst other things data collection and processing, risk analysis of pros and cons and the final decision according to best practice. Typically, a three to four step chain describes the general risk management concept.

WANG (2002) established a classical engineering project management chain with the four steps of “Analysis”, “Planning”, “Implementation” and “Evaluation”. Therein, further sub-topics are defined as shown in the following Table 9:

Table 9: Management steps according to WANG (2002) [shortened by author]

Management Phase	Sub-topics
Analysis	• Identification of the goals (regarding general target and external expectations) • Determination of the involved processes • Recognition of possible risks
Planning	• Strategic orientation and development of goals • Structuring of processes and establishment of project management • Investigation of risks and subsequent search for problem solutions
Implementation	• Realization of the project • Management of conflicts and risks
Evaluation	• Finalisation of the project • Lessons learned • Improvement of the management processes for follow-up projects

Even though WANG focuses on customer relationships in this description, the main stages and questions fit to a variety of applications. The management chain is subject to decision making in each of the phases. This leads to an assessment and comparison of alternatives and the estimation of consequences. For these processes, WANG recommends the use of decision trees and other decision support tools. Moreover, he introduces the cycle of "plan-do-check-and-act" for a continuous improvement.

PLIEFKE, SPERBECK & URBAN (2006) draw a framework of risk management with the steps "Risk Identification", "Risk Assessment" and "Risk Treatment" which is complemented by the "Risk Monitoring". Within the step "Risk Identification" attention is paid to the risk itself and the perception of the risks that might influence the core processes of a facility or project for example. Moreover, these core processes and the hazards are described to answer the vulnerability question of this work: "what can happen where?". This essential question leads over to the next step or phase in risk management called "Risk Assessment". Here, analysis and evaluation of the situation are the main topics where the risk is mostly quantified in monetary terms by analyzing the intensity and the frequency of the identified negative impact. Subsequently, the evaluation phase is conducted by comparing various risk situations and values to the goals of the core processes. The last phase of "Risk Treatment" is based on decision making processes on how the identified risk should be handled and managed. PLIEFKE, SPERBECK & URBAN (2006) call this risk mitigation because the focus is to avoid risks. Nevertheless, structures, processes and facilities need to be adapted.

The National Communications Support Programme collected several approaches for adaptation decision frameworks which imply climate change information in the assessment (LU n.d.). The table reflects the adaptation framework as well as main objectives, target end-users and key components respectively steps or phases of the decision process. Basically, all of the described approaches contain the phases as mentioned above though some of the concepts differ in number of steps. Still, all the concepts have the definition and identification of the problem, the assessment of the risk and alternative action as well as some type of implementation phase in common.

In Germany, the *Federal Ministry of the Interior* (BMI/Bundesministerium des Inneren) and the Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS/*Association for facility and reactor safety*) suggest that the four-step planning process should be structured as a so-called plan-do-check-act cycle similar to other management cycles (OLTMANNS ET AL. 2007; FEDERAL MINISTRY OF THE INTERIOR 2008). The overall approach can be seen in Figure 12:

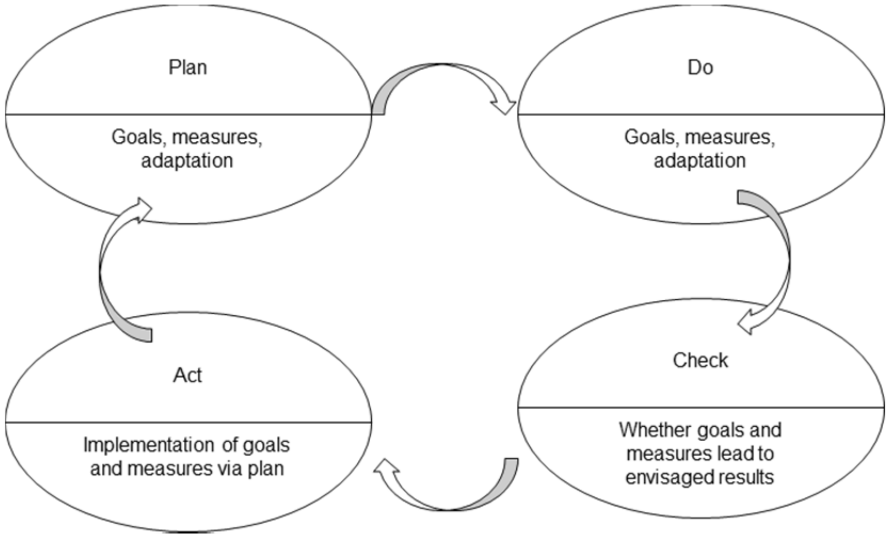


Figure 12: Cycle of plan, do, check and act according to GRS (2007) and FEDERAL MINISTRY OF THE INTERIOR (2008)

Moreover, Schmidt-Thomé (in Greiving and Fleischhauer 2006) use a chain of “Problem Analysis”, “Assessment of Alternatives”, “Decision-Making” and “Implementation” which will be compared to the approaches described before. An adapted diagram for the application of this approach can be found in Section 5.1 (see Figure 13).

The first step “Plan” in the planning process can be equated with Step 1 “Problem Analysis”. Here, the visions and goals of the company and/or the power plant operator are defined and measures on how to reach these goals are formulated (OLTMANNS ET AL. 2007).

The second, or “Do” step encompasses the precise planning of these measures. This can only be done when the “Assessing Alternatives” step is carried out (OLTMANNS ET AL. 2007). At this point, it is important to find a feasible solution for the impacts of extreme events on the affected power plant structures in order to reach the defined goals.

“Checking” can be compared to the “Decision Making” step as alternatives are analysed in order to reach the goals. Moreover, the goals are analysed for adequacy. One result of this “Check” could be that the goal of full protection for the power plant site was set too high for the budget and that expenditures to adapt a site to be protected against extreme events does not amortise during the time of operation. Or, on the other hand, that the desired measures exceed the goals and that less expensive measures are sufficient. If this analysis is not carried out, maladaptation could occur.

The last step "Act" includes the implementation of the goals and measures at the power plant site and is therefore equal to the step of implementation. Nevertheless, if the goals have changed during the planning phase or if an occurring event reveals gaps in the process or the emergency plan, the cycle has to be repeated in order to create an integrated risk management approach.

How the plan-do-check-and-act cycle is implemented into practical approach is shown in Section 3.1.5 and in the Case Study in Section 5.3 as example of flood risk management for thermal power plants.

In their workshop on the assessment of disaster risk management guidelines and tools, the working group ICLEI - LOCAL GOVERNMENTS FOR SUSTAINABILITY reveals that "tools" are usually manuals, guidelines and books, but none of the organisations uses GIS actively (ICLEI 2007). A comprehensive collection of handbooks, manuals and guidelines underlines the lack of the use of Geographical Information Systems especially by decision makers. On the other hand, GUNES & KOVEL (2000) point out that a Geographical Information System is of use due to its strengths concerning the possibility of handling spatial and temporal data through all phases in a decision making process or cycle.

The steps of the risk management chain and the consequential decision making cycle in planning processes, whether local planning and climate mitigation or corporate risk management and infrastructure adaptation, represent the main questions in this work:

Within the phase of risk identification (WANG 2002), plan (FEDERAL MINISTRY OF THE INTERIOR 2008) or problem analysis (OLTMANNS ET AL. 2007) the vulnerability question is described in detail: which regions or districts in Germany and which electricity generating units are especially affected by extreme hydro-meteorological events?

The following phase of risk assessment (WANG 2002), do (FEDERAL MINISTRY OF THE INTERIOR 2008) or assessment of alternatives (OLTMANNS ET AL. 2007) encompasses the adaptation and mitigation question: how can electricity generating units and regions be protected against the identified extreme hydro-meteorological events?

And the last phase of risk treatment (WANG 2002), check and act (FEDERAL MINISTRY OF THE INTERIOR 2008) or decision-making and implementation (OLTMANNS ET AL. 2007) comprises the decision making question: how do local planning and corporate risk management deal with the vulnerability?

Section 2 gave a comprehensive overview on extreme hydro-meteorological events and how they affect electricity generating infrastructure. Moreover, adaptation options for each of the infrastructures in the context of the impacts were highlighted. The introduction to risk management showed the established systems as well as gaps in application and integration of the above mentioned events into general planning approaches. This will be used as a basis for the following discussion on the methods used in this work to reduce these deficits.

3. Methods and Data

After the identification of the extreme hydro-meteorological events which may negatively affect electricity generating infrastructures and the lack of use of this data in management processes in Section 2, Section 3 aims at bridging these gaps. Therefore, this section will adjust the general risk management approaches as described in Section 2 for environmental risk management of extreme hydro-meteorological impacts on electricity generating infrastructure. Attention is paid to the needs of operators of large, centralised electricity generating facilities and power plants but also to the different renewable and distributed energies of hydropower plants, PV installations and wind turbines. Moreover, the data bases of extreme hydro-meteorological events, originating from the *German Weather Service*, the European Severe Weather Database and the URBAS project on flooding in cities are described. The power plant site database is accomplished by a collection of publically available renewable energy infrastructure information and conventional power plant site information. Statistical evaluations of the databases are the foundation as temporal analyses for future research and developments in this work.

3.1 Methods

So far, there is no general concept available in Germany for a Geographical Information System (GIS)-based approach for mapping and managing hydro-meteorological risks for power plant sites, neither for thermal power plants and flood risks nor for renewable energies and the identified impacts. Instead, climate mitigation concepts are narrowed down to mitigation without taking into account adaptation (see Section 4.1) and corporate risk management includes the risks that power plants pose to the environment (see Section 5.1). One related example is the “CEDIM Risk Explorer Germany” (2012) which displays winter storm, earthquake, flood and man-made hazards with risks and expected losses for systems. These systems are specified as structures, plants, facilities, countries or companies. That means, the “CEDIM Risk Explorer Germany” is not as focused on electricity generating unit as this study and does not take into account as many extreme hydro-meteorological events. The German Climate Atlas as established by the GERMAN WEATHER SERVICE (2012) focuses on regional climate projections and therewith on mean parameters instead of extreme events. The advantage of a GIS-based approach is the storage, handling and visualisation of all available data on specific power plant sites, on extreme hydro-meteorological events as well as on legislation and regulations.

Since this lack of GIS-based approaches in risk management for power plants or local planning, the following work focuses on the phases of risk management and where GIS can be integrated of value. As highlighted in Section 2.4 this has not been practised yet so that the concepts of risk management need to be adjusted and enhanced for the goals of this study. According to Schmidt-Thomé (GREIVING & FLEISCHHAUER 2006, see Figure 13), the four phases of risk management planning are adjusted for the use in a GIS. Here, the scheme is only exemplified for the use of flood risk management at a thermal power plant. The four relevant aspects of the scheme of damage assessment are as follows:

- Problem analysis: power plant sites are supposed to be protected against flooding. Therefore, all relevant data is collected and integrated into a GIS. This implies the selection of the investigation area as well as the identification and cataloguing of each building in that area. Furthermore, the design water levels need to be combined with the terrain levels, which can be extracted from a Digital Elevation Model (DEM).
- Assessment of alternatives: different design water levels are illustrated for the different sites. Afterwards a comparison is made.
- Decision-making: based on the illustrated water levels, an individual emergency plan is established and tested. A first assessment of damage according to the degree of utilisation can be provided.
- Implementation: the emergency plan gets implemented at the sites. In this phase, missing protection measures, storage places for mobile protection measures and access routes can be identified within the GIS.

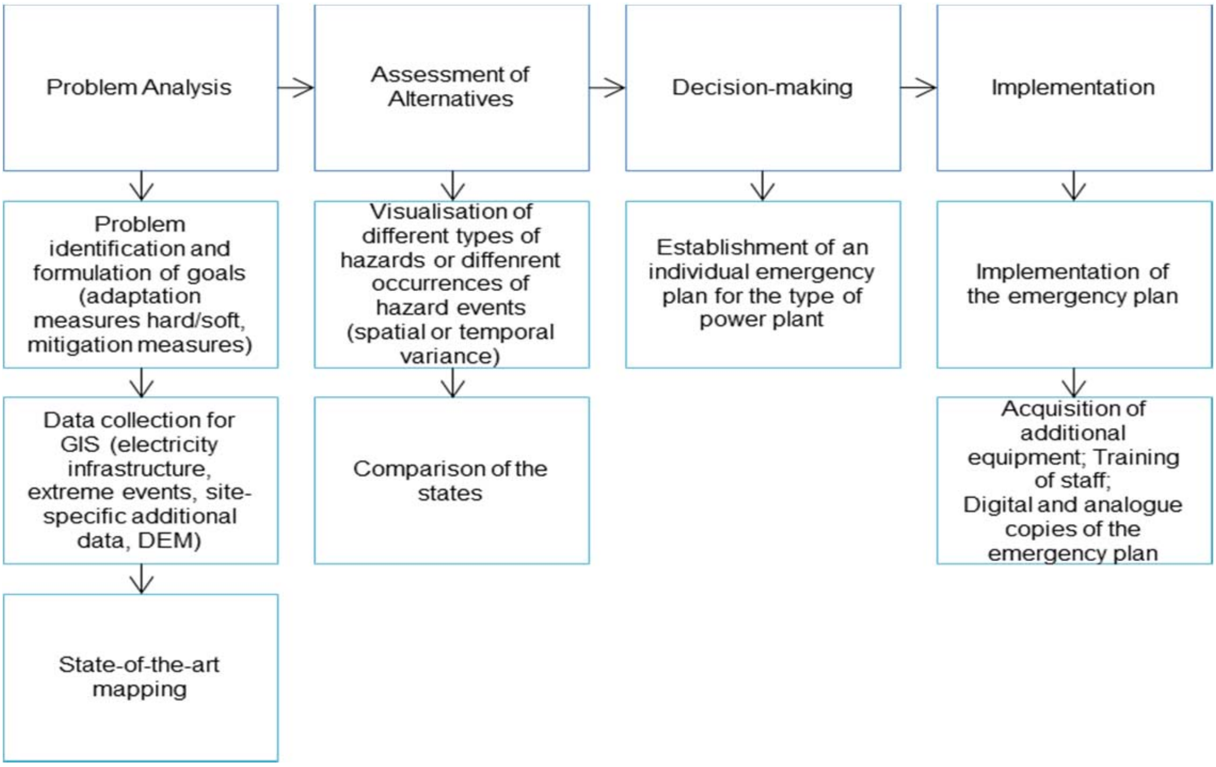


Figure 13: Planning process according to Schmidt-Thomé in GREIVING & FLEISCHHAUER (2005), depicted are the four steps of the planning process and the relevant aspects of realisation

Most disaster risk management approaches use similar four step approaches, like collected by the IPCC (2012, see also Section 2.4). Here, the four steps consist of the (1) risk identification which corresponds to step 1 “problem analysis”; (2) risk reduction; (3) risk transfer and (4) disaster management which comprises the other steps of the above characterized scheme. It becomes clear that depending on the focus of the analyses also the focus of the risk management cycle shifts. Using the scheme by Schmidt-Thomé as a basis, the steps (3) and (4) of the IPCC approach would follow the implementation phase as a complementation of public relations.

According to this scheme, a standardised GIS-based extreme event management system for power plants should combine significant background information, as well as a practical approach for all types of power plants. The Federal Ministry of the Interior describes risk management as a cycle of “plan, do, check and act” (FEDERAL MINISTRY OF THE INTERIOR 2008, see Section 2.4). This means that the preparation of a site-specific plan should result in implementation that the plan must be checked after a flood to assess its performance and that again, action is needed to improve the plan. A practical application of this approach is shown in Chapter 5.3. In the following subsections, the four steps of the planning process are described in more detail and an insight is given into the planning process for the flood event management.

3.1.1 Problem Analysis

In GIS-based hazard management, four different analyses are carried out. To establish a complete problem analysis, modelling must be prepared and a first concept should be set up. In the preparation phase, goals and methods are specified. Technical terms, as well as the degree of detail, should be defined (GREIVING & FLEISCHHAUER 2006; OLTMANNS ET AL. 2007).

First of all, a hazard analysis describes the characteristics of the hazard. This includes probability of occurrence, magnitude, intensity, place and influence of geological as well as meteorological components (CHEN ET AL. 2004; GRÜNTHAL ET AL. 2006). Exposition analysis includes the identification and mapping of all elements at the site, especially constructions and plant components as well as buildings and other infrastructural constructions, for example access routes, communication, supply and disposal of resources (CHEN ET AL. 2004). The storage and handling of hazardous materials and substances should be implemented in the GIS (GUNES & KOVEL 2000; GRÜNTHAL ET AL. 2006). A vulnerability analysis detects the degree of vulnerability of one of the aforementioned components to the influence by an extreme event (CHEN ET AL. 2004; GRÜNTHAL ET AL. 2006).

A specific goal could be protecting the power plant site against the calculated design flood level, e.g. the HQ_{100} or the $HQ_{10,000}$. This includes the protection of construction and buildings against water intrusion and also the operational maintenance, i.e. access to personnel as well as fuel and lubricants. The differences between variable water levels are of special interest, because not every water level has an impact on the same part of the site. The risk analysis consists of a combination, analysis and assessment of these three analyses (CHEN ET AL. 2004; GRÜNTHAL ET AL. 2006). As a result, maps and diagrams are generated to display the impact of flood risk on affected parts of the power plant site. With the help of maps, which contain terrain as well as site-specific information and the expected water levels, critical phases and places can be detected. To provide constant protection, specified water levels result in pre-assigned measures. The concept involves the basic duties of the company (OLTMANNS ET AL. 2007). Those duties of conventional thermal and nuclear power plants are to provide electricity for base and medium load and need to be protected. Mostly however, the capacity for electricity production is reduced due to high water levels. Such regulations are part of the operating manual.

3.1.2 Assessing Alternatives

For an assessment of alternatives, the actual condition, as well as the target condition, needs to be modelled. Therefore, the actual state of the industrial site needs to be registered to realise weak points and to identify the room for improvements in preparing for the next step. These improvements are implemented during the step of target modelling; during which every operation in the facility must be adapted to the new situation (OLTMANNS ET AL. 2007). For a power plant site, this means that an emergency plan needs to be created and afterwards implemented.

The first step is to display the basic map even before the calculated design water levels are applied to the site. Within process-oriented management, the modelling of actual state encompasses a display of calculated design water levels in the GIS so that the planning of temporary flood protection measures can be carried out. During the flood event this emergency plan should be employed. The GIS helps to inform the personal and shows still actual weaknesses and solutions.

3.1.3 Decision Making

According to Oltmanns et al. a structural organisation for the decision making process means a rearrangement of the present organisation of the facility to meet the challenges of an emergency (OLTMANNS ET AL. 2007). During the decision-making process the power plant operator needs to determine which measures are to be introduced (GREIVING & FLEISCHHAUER 2006). Here, the goals defined during Step 1 “Problem Analysis” should be kept in mind.

Therefore, all existing measures are planned to guarantee the operation of the power plant in case of floods and to respond to the potential damages as soon as possible. In this step, a GIS is used for orientation and to display the structures and installations in their original condition. Furthermore, safe storage places for tools and dry places for supply and disposal can be displayed. These places should never be affected by flood.

3.1.4 Implementation and Continuity

In this phase all suggestions for improvement as well as perceptions of the extreme event will be implemented (OLTMANNS ET AL. 2007). It will include training for and implementing an emergency plan at the power plant site as well as purchasing missing or additional protection measures and structuring of soft adaptation measures (see Appendix A). The emergency plan will finally be stored in digital, as well as in analogue form, as digital plans might not be accessible during an emergency. The last step of the planning process leads back to the initial modelling preparation point because the process-oriented management is a cycle of perception.

This means that in case of a flood of equal dimension potentially emerging threats can be recognised as early as possible and the site can be protected according to projected conditions. In a GIS, changes to the terrain and infrastructure (such as accumulation of material on the terrain, construction of dams) are updated to the database. The goals of the company can be revisited after a flood event and the cycle begins again with the modelling cycle (OLTMANNS ET AL. 2007).

3.1.5 Planning Process as a Cycle

Risk management chains as described in Section 2.4 usually end with some type of implementation of the findings of the analyses. In order to prepare for changing environmental conditions, management chains need to be enhanced to a management cycle if there is new awareness on influencing factors. This enhancement is carried out by the application of the plan, do, check and act cycle which allows for continuous improvement of plans and measures. As GUNES & KOVEL (2000) point out, Geographical Information

Systems are best suitable for data handling and decision support concerning every phase of the management process.

During the adaptation management process, power plant operators need to answer the following questions as proposed by THOMALLA ET AL. (2006). The bullet points specify to some extent the overall questions with regard to thermal power plants as well as to renewable energies and the adaptation process as implemented here.

- “*Who and what are the exposure units?*”
  - Here a definition of the exposure units is needed
  - For thermal power plants these could be the boiler/reactor, buildings like offices and recreational areas, access roads, cooling towers, storage rooms, security places and cooling water intake/discharge structures.
  - Concerning renewable energies the exposure unit is the installation itself but subcategories such as blades and mast for wind turbines, panel or frame for PV installations or turbine or building for hydropower plants might be separated.
- “*What hazards and stresses are they exposed to?*”
  - Identification of the impacts of extreme weather events on power plant structures (see Section 2.2)
  - Mapping of possible exposure (see Section 4.2 and Section 5.2)
- “*How resilient are the exposure units to current stresses?*”
  - The resiliency might be set by standards/regulations.
  - Already existing measures should be taken into account at that point.
- “*Are the exposure units and stresses changing? In what ways?*”
  - Change due to climate change
  - DPSIR[6]: pressures are changing → more frequent, more severe weather events
- “*What is a core set of indicators?*”
  - Are the parameters of the extreme events reasonable indicators for the occurrence of possible damages?
  - Is the district where installations are planned under influence of certain extreme events or do all types of extremes need to be taken into account?

[6] DPSIR: driving forces, pressures, state, impact and response. A framework operated by the European Environment Agency for describing environmental impacts and societal coping.

3.2 Data Acquisition and Handling

Four main types of data were used for the analyses: data from the European Severe Weather Database, data from the *German Weather Service*, data from the URBAS project on urban flooding and data about power plant sites.

3.2.1 Data from the European Severe Weather Database (ESWD)

The European Severe Weather Database (ESWD) project collects and evaluates extreme weather phenomena in Europe. The consortium consists of several meteorological and hydrological services (i.e. German, Spanish, Austrian and Finnish Meteorological Institutes or Services) and voluntary observers, like Skywarn or the public (ESWD ONLINE). The data is freely available under quoting conditions.

From this service, data concerning the occurrence of the following extreme weather events dust devil, funnel clouds, gustnado, heavy rain, large hail, severe wind and tornado were taken in the qualities of “report confirmed by reliable sources QC1” and “event fully verified QC2” from January 1, 1980 - December 31, 2009 (criteria see Table 10).

Table 10: Criteria for extreme weather events (according to ESWD)

Type of event	Criteria
Dust devil	Itself extreme
Funnel cloud	Itself extreme
Gustnado	Itself extreme
Heavy rain	Exceptional amounts of rain for a specific region, no threshold given
Large hail	Diameter > 2 cm
Severe wind	Wind speed > 25 m/s
Tornado	Itself extreme

The information available was either assigned by one of the partner organisations of the European Severe Weather Database, or that all information about occurrence, time and place (ESWD ONLINE) is fully verified.

The data retrieved was tested for double information and accuracy of occurrence date. Duplicated data was replaced by one single event. The accuracy of the occurrence date has not been taken into account. It was obvious that uncertain data were set to the first day of the month of occurrence. Since the exact date is not important for further analysis, the author kept the information as received. Data was obtained from the website and put into a standard Excel File Format. Gauß-Krüger coordinates were calculated from the original latitude/longitude coordinates by using the internet based transformation platform “Transformation of Terrestrial Coordinates between Reference and Projection Systems” of the Leibniz Institute for Applied Geophysics (online application GORLING 2011).

3.2.2 Data from the German Weather Service (GWS)

The WebWerdis database from the *German Weather Service* (GWS) was consulted for temperature data. Here, data on the daily minimum and maximum air temperature for 51 German weather stations over the period from January 1, 1980 to December 31, 2009 were selected, 30 years in total. The number of days in this frame is 10,958, but a minimum of 9,741 records was accepted (Reit im Winkl). The data was downloaded and entered into an Excel spreadsheet for further analyses.

3.2.3 Data from the URBAS Project

The URBAS project collected and analysed flooding events in urban areas. The project was part of a Federal Ministry of Education and Research funded programme run between 2005 and 2008, with partners from engineering organisations, universities of applied sciences, the *German Weather Service*, the German Re-Insurance and cooperating cities. The URBAS database consists of a total of 415 events that occurred from 1900 to 2007. Only those events which occurred during in the 28-year time span from January 1, 1980 to December 31, 2007 were taken, in accordance with other data sources (URBAS online). “Downburst”, “flash flood”, “flood”, “lightning” and “thunderstorm” events were taken from this project and used in the analysis. The event coordinates used in this research were taken from the URBAS website homepage and Gauß-Krüger data for the region/city was used for the first occurrence described.

3.2.4 Power Plant Site Data

Data on thermal and nuclear power plant sites are easily acquired as they are available online for example from the *Federal Environmental Agency* (Umweltbundesamt/UBA 2011). Additionally, a database of site information was created (Gauß-Krüger-coordinates, type, capacity). Only the coordinates are relevant in this analysis. Renewable Energy operators in Germany are required to register their power plant in accordance with the German Renewable Energy Act. Power input from those power plants is registered with the four network operators EnBW Transport Net Cooperation, Amprion (former RWE Net limited company), TenneT TSO limited company and 50Hertz Transmission (former Vattenfall Europe Transmission limited company). These network operators collect information on the type of resource (biomass, photovoltaic installations, wind, hydropower plant), the address, the year of installation, the original operator, the capacity and several other parameters. Each database was separated into databases appropriate to this work (photovoltaic installations, wind turbines and hydropower plants) and therein reduced to network operator, name of the power plant (numbered), address and capacity information. For further analysis, addresses were kept as spatial information based on zip codes, with no need for a more detailed location.

The impact of tropical days, fog and ice fog, heavy snow, blizzards and water temperature are not included in this analysis. No direct impacts were identified from tropical days, therefore this parameter is not considered. No data was found on fog and ice fog, heavy snow or blizzards. Water temperatures are covered in detail in Strauch's thesis (2011).

3.3 Statistical Analyses

The statistical analysis shows how extreme hydro-meteorological events developed in time and how many extreme events occurred in the period 1980 to 2009. This 30 year time frame was chosen due to climatological reasons. A description of the databases used in this chapter is included in Section 3.3 on Data Acquisition and Handling. As extreme hydro-meteorological events are rather poorly registered for the first time frame between 1980 and 1989, this period was not considered for further analyses in the upcoming sections.

3.3.1 Air Temperatures

For the overall assessment in this work some basic statistical analyses concerning the extreme weather events were made. To analyse the differing air temperatures over time, the data from several monitoring stations by the *German Weather Service* (GWS) was used. Statistical analyses were then implemented, to assess the received data.

Each station recorded a total of 10,958 days between January 01, 1980 and December 31, 2009, covering a period of 30 years. The Reit im Winkl station is the sole exception, with only 9,741 days recorded. In spite of the reduced amount of data, the station was accepted due to the favourable geographical location. With 50 stations covering 10,958 days and one station with 9,741 days, a total number of 557,641 temperature measurements were used for the air temperature analysis. The complete table can be found in Appendix C. This table contains the station name, the original data on latitude, longitude and station height and the transformed Gauß-Krüger coordinates of eastings and northings.

The icing days encompass a total number of 41,085 days, so 7.36 % of all days can be classified as such. Icing days are defined by maximum air temperatures of ≤ 0 °C. The distribution of icing days per year can be found in Table 11 and Figure 14 and Figure 15.

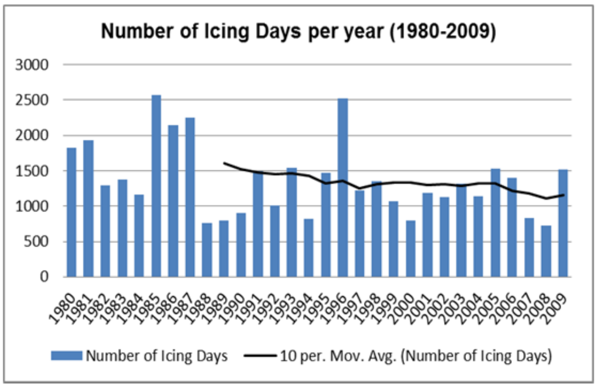


Figure 14: Distribution of icing days per year from 1980 to 2009 at the 51 GWS monitoring stations

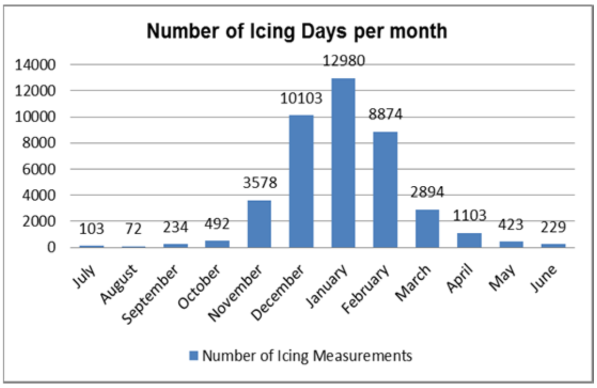


Figure 15: Distribution of icing days on a monthly basis, 1980-2009 at the 51 GWS monitoring stations

Table 11: Number of icing days per year 1980 - 2009 at the 51 GWS monitoring stations

Year	Number of icing days	Year	Number of icing days	Year	Number of icing days
1980	1,830	**1990**	901	**2000**	797
1981	1,926	**1991**	1,498	**2001**	1,190
1982	1,290	**1992**	1,012	**2002**	1,133
1983	1,373	**1993**	1,537	**2003**	1,317
1984	1,167	**1994**	823	**2004**	1,142
1985	2,568	**1995**	1,475	**2005**	1,527
1986	2,144	**1996**	2,517	**2006**	1,405
1987	2,251	**1997**	1,218	**2007**	834
1988	756	**1998**	1,351	**2008**	721
1989	802	**1999**	1,064	**2009**	1,516
			Sum 41,085		

The graph shows that the number of icing days decreases over time, having an absolute minimum in 2008 with only 721 icing days and an absolute maximum with 2,568 icing days in 1985. This trend is also clearly indicated by the ten year moving average trend line. It is important to note that these numbers represent the total days measured over all 51 of the monitoring stations and thus can be larger than the number of days in a single year.

The number of frost days (days with a minimum air temperature of ≤ 0 °C) can be seen in Table 12 and the distribution can be taken from Figure 16 and 17. In the aforementioned time frame, there was a total of 138,129 measured frost days, which represents 24.77 % of all measured data.

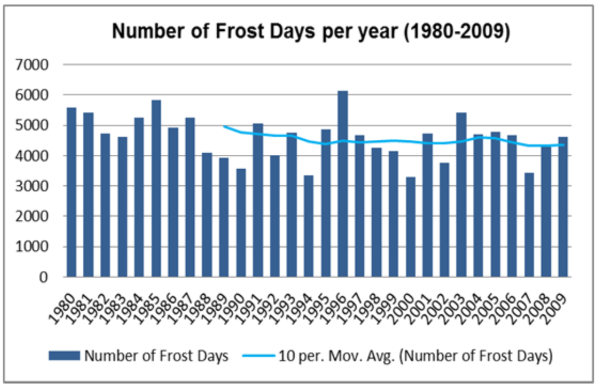


Figure 16: Distribution of frost days per year from 1980 to 2009 at the 51 GWS monitoring stations

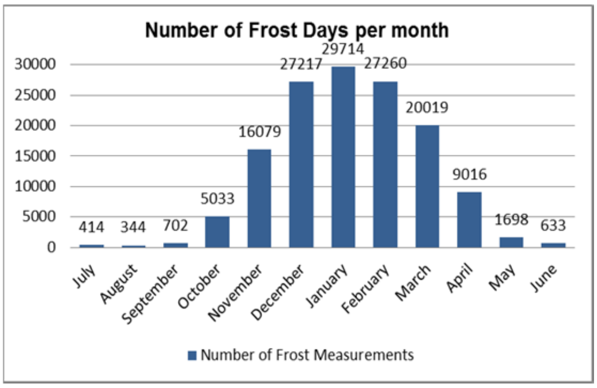


Figure 17: Distribution of frost days on a monthly basis, 1980-2009 at the 51 GWS monitoring stations

As frost days encompass also the number of icing days, no conclusions are made concerning the total number of days between 1980 and 2009 with temperatures ≤ 0 °C.

Table 12: Number of frost days per year 1980 - 2009 at the 51 GWS monitoring stations

Year	Number of frost days	Year	Number of frost days	Year	Number of frost days
1980	5,571	**1990**	3,579	**2000**	3,293
1981	5,422	**1991**	5,049	**2001**	4,734
1982	4,739	**1992**	4,013	**2002**	3,755
1983	4,621	**1993**	4,747	**2003**	5,429
1984	5,261	**1994**	3,356	**2004**	4,694
1985	5,830	**1995**	4,879	**2005**	4,775
1986	4,931	**1996**	6,144	**2006**	4,663
1987	5,251	**1997**	4,674	**2007**	3,430
1988	4,082	**1998**	4,251	**2008**	4,275
1989	3,928	**1999**	4,146	**2009**	4,607
			Sum 138,129		

For the frost days, the trend is not as obvious as for icing days but nevertheless the number is continuously decreasing. As for the icing days, the ten year moving average trendline shows a decrease. The minimum number of frost days was measured in 2000 with 3,293 measured frost days, whereas 1996 had the greatest amount of measured frost days with a total number of 6,144.

Summer days are defined by a maximum air temperature ≥ 25 °C. For the analysis, the air temperature was only exceeded to 29.98 °C in order to separate the summer from the heat days (definition see Table 1). Here, a total number of 42,167 summer days were measured between 1980 and 2009. The number of summer days per year and the distribution can be taken from Table 13 and Figure 18. As per definition summer days also encompass the number of heat days, only a percentage will be given for their share of the data.

Table 13: Number of summer days per year 1980 - 2009 at the 51 GWS monitoring stations

Year	Number of summer days	Year	Number of summer days	Year	Number of summer days
1980	769	**1990**	1,290	**2000**	1,383
1981	1,108	**1991**	1,451	**2001**	1,361
1982	1,726	**1992**	1,688	**2002**	1,400
1983	1,833	**1993**	1,366	**2003**	2,230
1984	772	**1994**	1,311	**2004**	1,293
1985	1,177	**1995**	1,553	**2005**	1,466
1986	1,467	**1996**	1,105	**2006**	1,743
1987	980	**1997**	1,718	**2007**	1,488
1988	1,146	**1998**	1,015	**2008**	1,403
1989	1,614	**1999**	1,714	**2009**	1,597
			Sum 42,167		

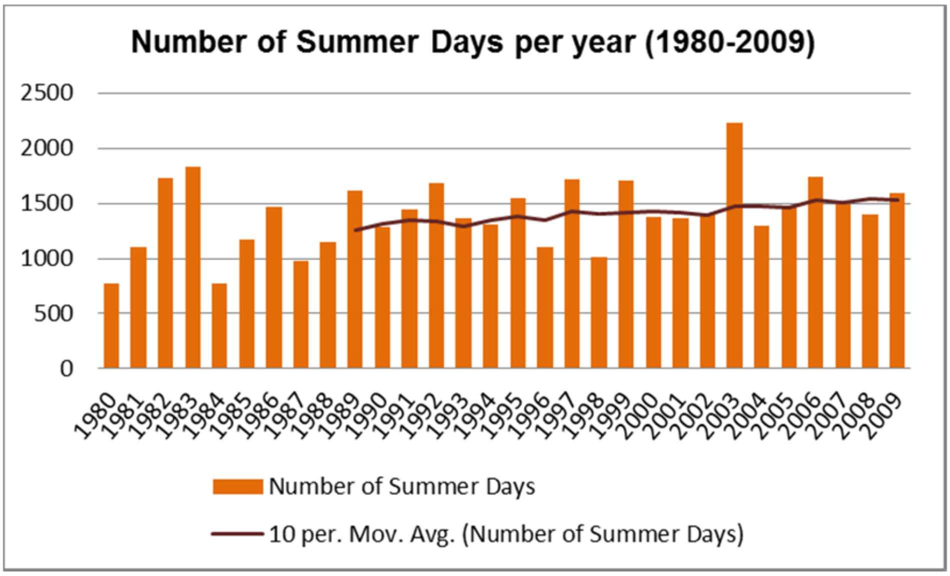


Figure 18: Graph of the temporal distribution „summer days per year“ between 1980 and 2009 at the 51 GWS monitoring stations

In contrast to the cold characteristic days, the number of summer days has increased slightly in the past 30 years. The year with the least number was 1980 with 769 summer days, whereas in 2003 a total number of 2,230 summer days was counted. The ten year moving average trendline underlines the increase in number of summer days during the 30 year time span under investigation.

The following Table 14 contains an overview on the number of heat days between 1980 - 2009.

Table 14: Number of heat days per year 1980 - 2009 at the 51 GWS monitoring stations

Year	Number of heat days	Year	Number of heat days	Year	Number of heat days
1980	83	**1990**	323	**2000**	270
1981	114	**1991**	289	**2001**	385
1982	348	**1992**	470	**2002**	297
1983	536	**1993**	122	**2003**	990
1984	182	**1994**	779	**2004**	240
1985	147	**1995**	527	**2005**	388
1986	221	**1996**	141	**2006**	655
1987	90	**1997**	255	**2007**	224
1988	144	**1998**	415	**2008**	369
1989	239	**1999**	263	**2009**	247
			Sum 9,753		

Heat days, defined by maximum air temperatures ≥ 30 °C, make up a major part of the number of summer days. With a total of 9,753 heat days measured, the summarised summer days take up 9.31 % of all measured days. Figure 19 shows the distribution of heat days in the analysed period.

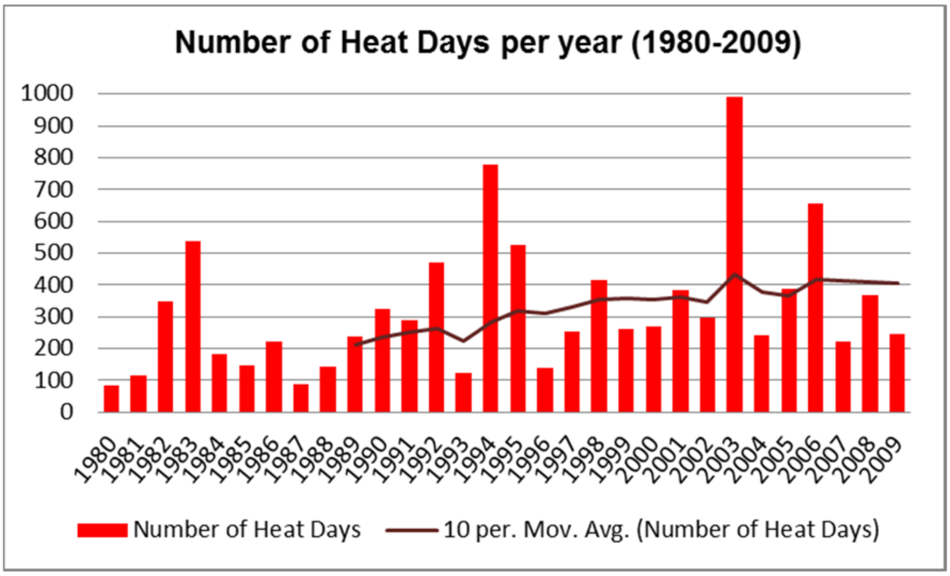


Figure 19: Graph of the temporal distribution „heat days per year“ between 1980 and 2009 at the 51 GWS monitoring stations

The amount of heat days, as well as summer days, has increased per year (see also ten year moving average trendline). The temporal distribution, however, is more irregular than the others. In 1980, only 83 heat days were measured, whereas in 2003, 990 heat days occurred. The highest temperature measured was 39.2 °C in 2003 at the station of Rheinfelden.

In the analyses, tropical days (a minimum air temperature of ≥ 20 °C) have not been included, as maximum air temperatures seem to have a greater influence on structures and buildings - in the case of high temperatures - than minimum ones.

The data derived from the European Severe Weather Database is based on observation rather than consequent monitoring at GWS stations. With this in mind, it is important to note that any increase in data might be based on an increase in observations rather than actual readings. Consequently, for the further analysis only the maximum and minimum numbers will be given without reference on trends.

3.3.2 Precipitation-related Events

In this section, statistical analyses of precipitation-related events, such as heavy precipitation and hail are discussed. Heavy precipitation encompasses rain as well as snow, so where possible, indication is made which type of precipitation has been measured. If it is not clear, no difference was made. The distribution of heavy precipitation events per year is given in Table 15 and Figures 20 and 21.

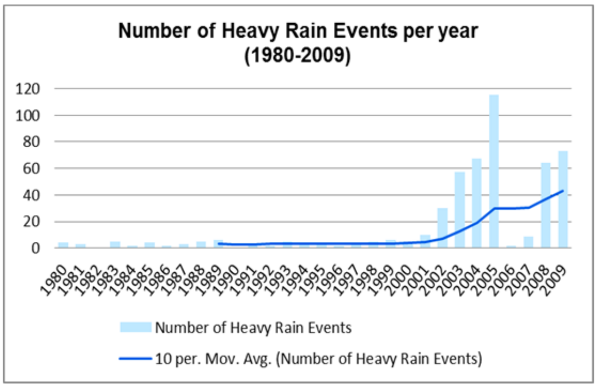


Figure 20: Distribution of heavy precipitation events 1980-2009, in total 499 heavy rain events are registered in Germany (compilation according to ESWD)

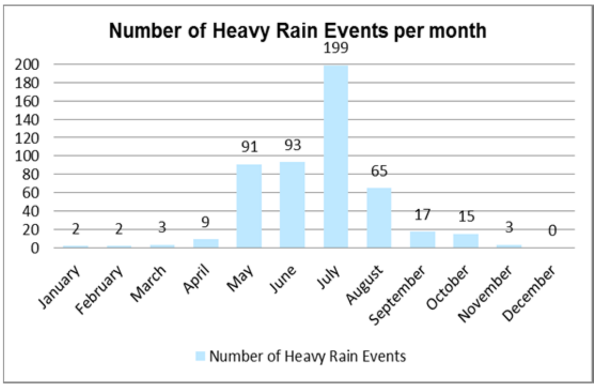


Figure 21: Distribution of heavy precipitation events per month, the winter months October to March contain 25 heavy rain events (compilation according to ESWD)

Table 15: Number of heavy precipitation events 1980 - 2009, no difference between rain/snow (compilation according to European Severe Weather Database)

Year	Number of heavy precip. events	Year	Number of heavy precip. events	Year	Number of heavy precip. events
1980	4	**1990**	0	**2000**	5
1981	3	**1991**	2	**2001**	10
1982	0	**1992**	2	**2002**	30
1983	5	**1993**	5	**2003**	57
1984	2	**1994**	4	**2004**	67
1985	4	**1995**	4	**2005**	115
1986	2	**1996**	2	**2006**	2
1987	3	**1997**	3	**2007**	9
1988	5	**1998**	5	**2008**	64
1989	6	**1999**	6	**2009**	73
			Sum 499		

Concerning heavy precipitation events, the low number in the years 2006 and 2007 with only two and nine reported events is considerable. Even more, before 2001 the number of events per year seems very low. The most heavy precipitation events were measured in 2005 with a total number of 115 events. The number of precipitation events in the winter months (October to March) is relatively small, being only 25 events measured. Here it is clear that most of the heavy precipitation events occur in the summer months between April and September. A monthly distribution can be taken from Figure 21.

Usually, it is mentioned whether hail or severe wind gusts accompanied the precipitation events and how much rain fell within a certain time span. Sometimes the duration of the precipitation event is indicated. Of 499 events, only 184 events were commented upon. The comments on rain heights per time unit are given in Appendix B and remain unremarked upon. The hail events show the following aspects:

Table 16: Number of hail events 1980 - 2009 (compilation according to ESWD)

Year	Number of hail events	Year	Number of hail events	Year	Number of hail events
1980	6	**1990**	1	**2000**	10
1981	2	**1991**	0	**2001**	22
1982	4	**1992**	7	**2002**	60
1983	9	**1993**	8	**2003**	118
1984	15	**1994**	6	**2004**	98
1985	6	**1995**	3	**2005**	166
1986	4	**1996**	2	**2006**	4
1987	8	**1997**	1	**2007**	0
1988	15	**1998**	11	**2008**	95
1989	9	**1999**	15	**2009**	157
			Sum 862		

The following two Figures 22 and 23 show the distribution of hail events on the left per year and on the right per month. In the winter period between October and March a total of 44 events was reported, in the summer months between April and September, a number of 818 hail events occurred.

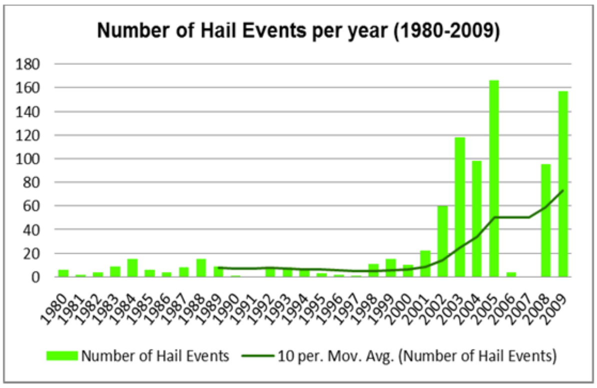


Figure 22: Distribution of large hail events per year in Germany 1980-2009 (compilation according to European Severe Weather Database)

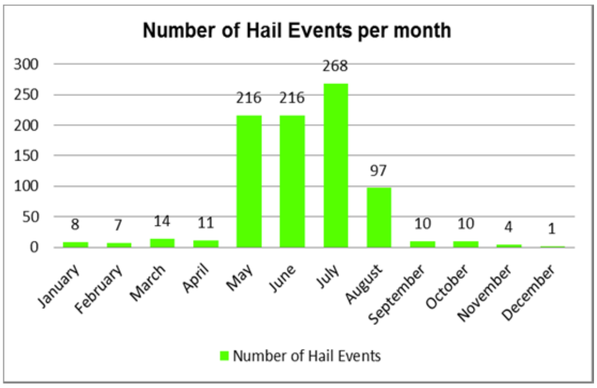


Figure 23: Distribution of large hail events per month in Germany (compilation according to European Severe Weather Database)

Here again, the years 2006 and 2007 show the lowest number of events since 2001. A reason for the gap in the data might be the aspect of observational intensity as mentioned before. Nevertheless, the minimum of hail events per year was recorded in 1991 and 2007 with each zero records, whereas the maximum number of events is listed in 2005 with a total of 166 events.

As with rain, the highest occurrence of large hail events is in the summer months. Precipitation depends, amongst other parameters, on the water content in the atmosphere and the energy, i. e. the air temperature. High air temperatures together with high water content may lead to heavy precipitation events, which is due in summer rather than winter.

A study by Kleinschroth (1999 in DEEPEN 2006) showed the dimensions of hailstorms in Germany. Using hail damage statistics a total of > 1,500 hailstorms in Bavaria were reconstructed and analysed concerning the area of impact. In this study no time frame of occurrence is given. The mean of length of hailstorms was calculated to be 82 km with a deviation of 58 km. The maximum length is 332 km, the minimum 6 km. This shows the high variability of dimensions and therefore the approach of standard dimensions of multi- and supercells is used for the analyses in the work conducted.

3.3.3 Wind-related Events

In this subsection, the wind-related events of storms or severe wind gusts and tornadoes are discussed. Both types of events were taken from the European Severe Weather Database.

Between 1980 and 2009, a total number of 862 severe wind gust events were measured. The following Table 17 shows the distribution per year, as well as Figure 24. Figure 25 thereafter shows the monthly distribution of storms.

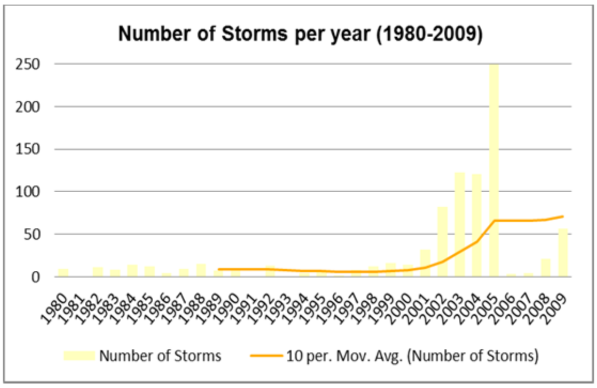


Figure 24: Temporal distribution of severe wind gust/storm between 1980 and 2009 per year (compilation according to ESWD)

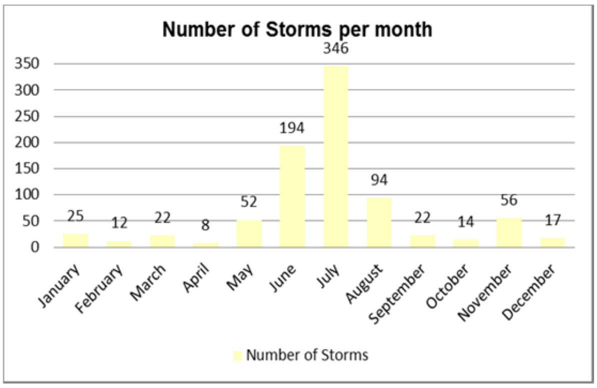


Figure 25: Temporal distribution of severe wind gust/storm events per month of occurrence (compilation according to ESWD)

Table 17: Number of severe wind gust/storm events 1980 - 2009 in Germany (compilation according to ESWD)

Year	Number of storm events	Year	Number of storm events	Year	Number of storm events
1980	9	**1990**	7	**2000**	14
1981	0	**1991**	0	**2001**	32
1982	11	**1992**	13	**2002**	82
1983	8	**1993**	0	**2003**	123
1984	14	**1994**	4	**2004**	121
1985	12	**1995**	5	**2005**	250
1986	4	**1996**	1	**2006**	3
1987	9	**1997**	8	**2007**	4
1988	15	**1998**	12	**2008**	21
1989	7	**1999**	16	**2009**	57
			Sum 862		

In 1981 and 1991 zero severe wind gusts were recorded. In contrast, in 2005 250 severe wind gusts are listed. Again, 2006 and 2007 are poorly documented.

Once more, the summer months seem to be the most active regarding severe wind gusts respectively storm events. This may be due to the high energy content of the atmosphere due to high temperatures as explained in the section of hail events. A maximum of storm events can be found in July, followed by June, whereas the winter months seem to be less active. Nonetheless, the most severe storms in Germany are recorded in winter, e.g. Daria (January), Wiebke (February/March), Lothar and Martin (December) and Kyrill (January).

Tornado events are not as uncommon as thought of. From 1980 to 2009 a total number of 653 tornado events is reported in the European Severe Weather Database in the categories of confirmed or fully verified events. The distribution per year and month can be taken from Table 18 and Figure 26 and Figure 27.

Table 18: Number of tornado events per year (compilation according to European Severe Weather Database)

Year	Number of tornadoes	Year	Number of tornadoes	Year	Number of tornadoes
1980	25	**1990**	9	**2000**	44
1981	6	**1991**	2	**2001**	19
1982	8	**1992**	8	**2002**	36
1983	9	**1993**	9	**2003**	55
1984	13	**1994**	10	**2004**	53
1985	12	**1995**	9	**2005**	55
1986	9	**1996**	8	**2006**	38
1987	11	**1997**	18	**2007**	50
1988	9	**1998**	35	**2008**	28
1989	5	**1999**	29	**2009**	31
			Sum 653		

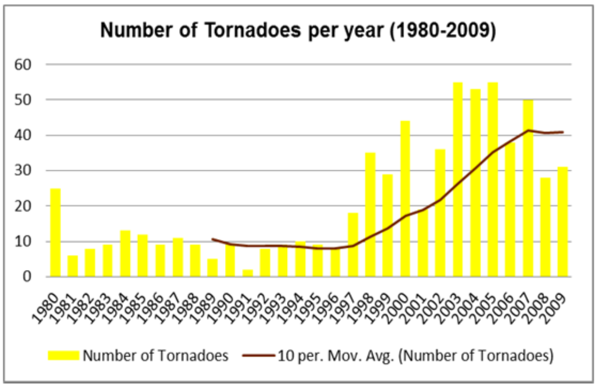


Figure 26: Temporal distribution of tornadoes between 1980 and 2009 per year (compilation according to ESWD)

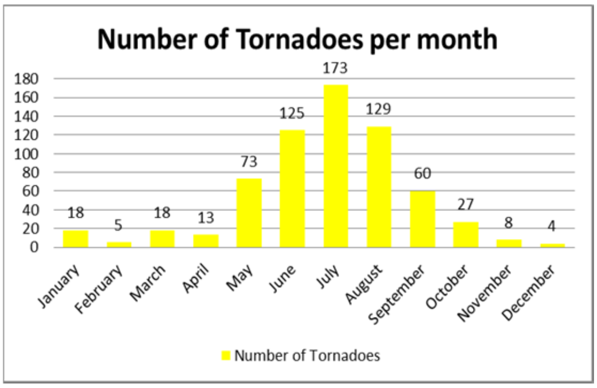


Figure 27: Temporal distribution of tornado events per month of occurrence (compilation according to ESWD)

The number of tornadoes per year has increased since the beginning of the listed period. The maximum number of tornadoes was listed in 2005 with 55 tornadoes, the minimum number was two in 1991.

Tornadoes form usually during summer months, as can be seen in the graph. Most tornadoes occur in July, followed by August and June. Despite this, small numbers of tornado events are been reported in the winter months December (four) and February (five).

3.3.4 Combined Events

3.3.4.1 Thunderstorms and Lightning

The analyses of thunderstorms and lightning storms in Germany between 1980 and 2007 showed the following results: The data is derived from the URBAS project and the ESWD and contains a total number of 93 lightning storms and 257 thunderstorms. The distribution per year and month can be seen in the following Table 19 and Figures 28 and 29. The data series of the URBAS project ends in 2007, while the ESWD provides data until 2009.

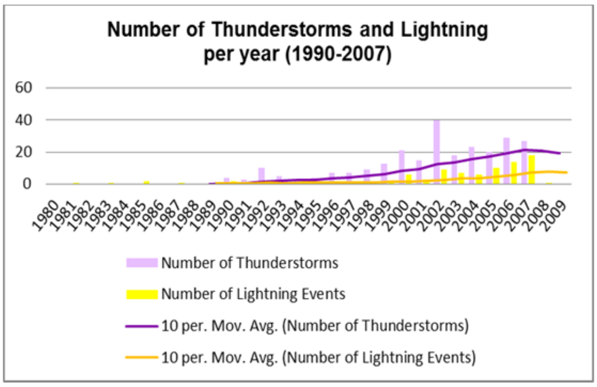


Figure 28: Temporal distribution of lightning and thunderstorm events per year (URBAS project)

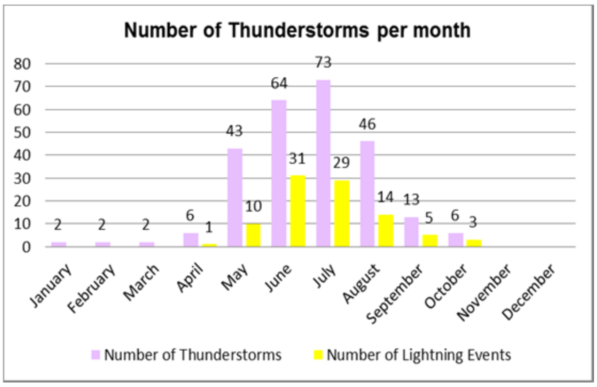


Figure 29: Temporal distribution of lightning and thunderstorm events per month (URBAS project)

Table 19: Number of lightning events and thunderstorms from 1980 - 2009

Year	Number of lightning events	Number of Thunder-storms	Year	Number of lightning events	Number of Thunder-storms	Year	Number of lightning events	Number of Thunder-storms
1980	0	0	**1990**	2	4	**2000**	6	21
1981	1	0	**1991**	0	3	**2001**	3	15
1982	0	0	**1992**	2	10	**2002**	9	40
1983	1	0	**1993**	0	5	**2003**	7	18
1984	0	0	**1994**	3	2	**2004**	6	23
1985	2	0	**1995**	2	4	**2005**	10	20
1986	0	0	**1996**	2	7	**2006**	14	29
1987	1	0	**1997**	1	7	**2007**	18	27
1988	0	0	**1998**	0	9	**2008**	1	/
1989	0	0	**1999**	2	14	**2009**	/	/

Sum 350
Lightning 93 + Thunderstorms 257

In 2002 40 thunderstorms were registered, but zero in the 1980s. Concerning heavy lightning storms, 18 were measured in 2007, along with 27 thunderstorms. The graphs show that lightning storms and thunderstorms do not necessarily occur at the same time. Again, the monthly distribution shows the highest occurrence of extreme events in the summer months (May to August), whereas in November no lightning and only one thunderstorm was registered.

3.3.4.2 Floods and Flash Floods

In this subsection, the data from the URBAS project on floods and flash floods is analysed. Here, the temporal distribution of events is shown in Table 20 and Figure 30 per year as well as Figure 31 on a monthly basis. As in the case of thunderstorms and lightning, the measured data only contains the years 1980 to 2007.

Table 20: Number of flash flood and flood events 1980 - 2007 (URBAS project)

Year	Number of flash floods	Number of floods	Year	Number of flash floods	Number of floods	Year	Number of flash floods	Number of floods
1980	1	0	**1990**	1	1	**2000**	2	10
1981	0	0	**1991**	2	0	**2001**	1	7
1982	0	0	**1992**	2	3	**2002**	9	22
1983	1	0	**1993**	5	3	**2003**	9	9
1984	1	0	**1994**	3	1	**2004**	11	16
1985	1	0	**1995**	3	3	**2005**	4	12
1986	0	0	**1996**	2	1	**2006**	13	4
1987	2	0	**1997**	0	6	**2007**	14	18
1988	0	0	**1998**	5	3	**2008**	/	/
1989	0	0	**1999**	3	9	**2009**	/	/

Sum 223
Flash floods 95 + Floods 128

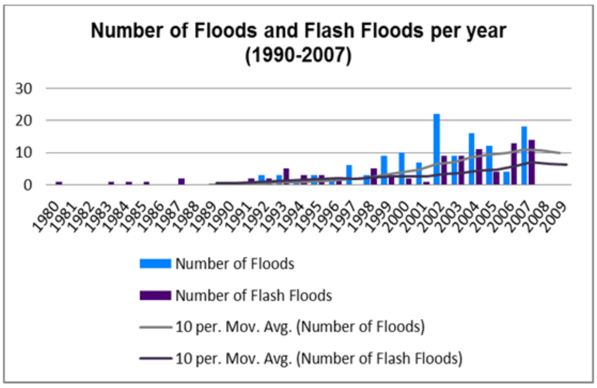


Figure 30: Temporal distribution of flash flood and flood events per year (1980-2007) (URBAS project)

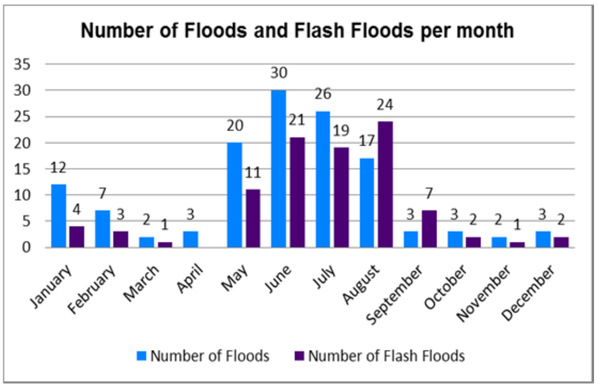


Figure 31: Temporal distribution of flash flood and flood events per month (URBAS project)

The data recorded in the URBAS project seems more consistent than the data from the European Severe Weather Database concerning continuity. In 2007, the highest number of flash floods - 14 - was reported, concerning normal floods, 22 events occurred in 2002. The total number increased throughout the years that were considered in this study.

The monthly distribution of flash floods as well as of floods is more discontinuous than the yearly distribution. A peak seems to be in summer with a maximum of 21 flash floods in August and 30 flood events in June respectively. A second peak seems to be in January and February with four flash flood and 12 flood events in January and three flash flood and seven flood events in February. Prominent examples of winter floods occurred at the coast around Hamburg and Bremen/Bremerhaven due to winterly spring floods and along the Rhine (December 1993 and January 1995). Summer floods on the other hand often occur along rivers with nival/glacial and pluvial regimes, namely the Rhine (May 1994 and May 1999), the Oder (July 1997) and the Elbe (August 2002). Flash floods usually occur after heavy rain events when the soil is saturated with water or the pores are very small due to water deficit. Other possibilities for a reduced absorption may be frozen ground due to freezing temperatures. During flash floods, large amounts of water are discharged supernal rather than draining. This leads to a rapid increase in runoff of small burns which are, consequently, immediately inundated. Thus, it is possible to say that the occurrence of flash floods is directly coupled with heavy rain.

3.4 Synthesis on Statistical Analyses and the Integration of the Data into Concepts

The statistical analysis of air temperatures shows a decrease in icing and frost days as well as an increase in summer and heat days. Precipitation-related events of heavy rain and hail both increased in number of occurrence per year. Also, the wind-related events of storms and tornadoes both show an increase between 1980 and 2009. The same applies for the combined events of thunderstorms and lightning as well as floods and flash floods. The following two graphs show the distribution of all frost, icing, summer and heat days per year in the period 1980 to 2009 (Figure 32) and the distribution of all single events in said period (Figure 33).

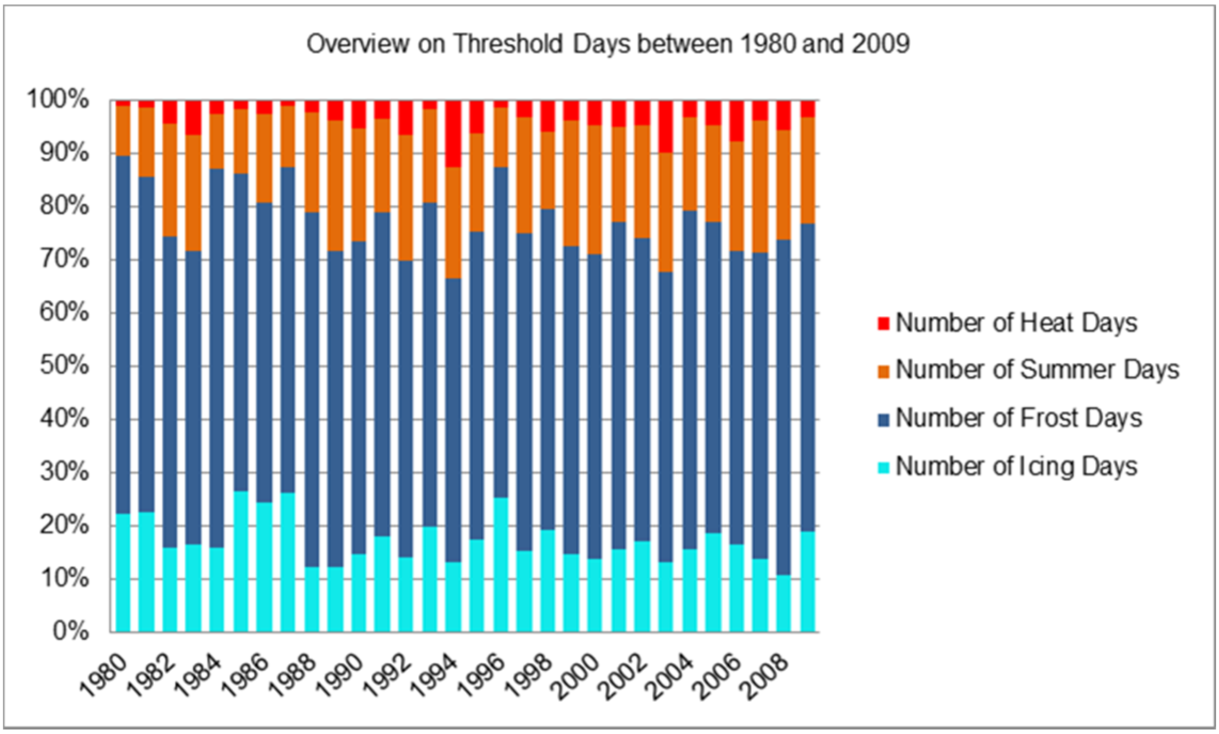


Figure 32: Overview on all threshold days (heat, summer, frost and icing) in the period 1980 to 2009 for all 51 GWS monitoring stations

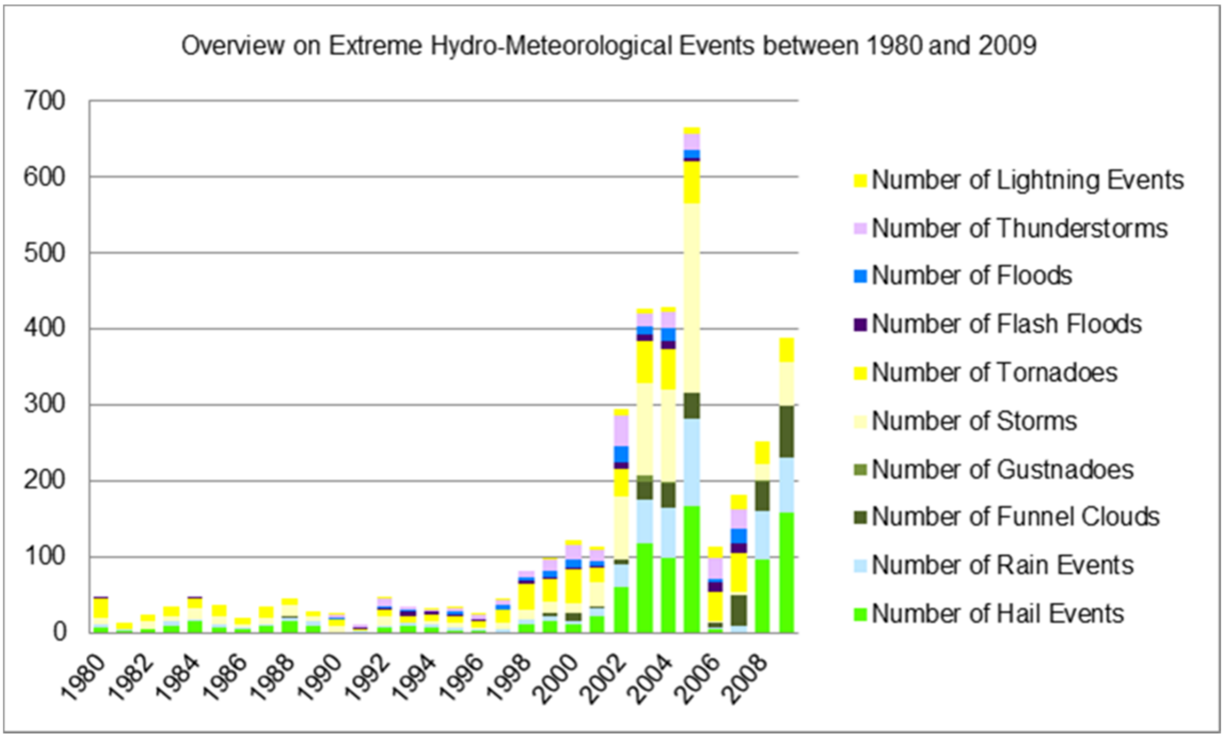


Figure 33; Overview on all single extreme hydro-meteorological events (precipitation- and wind-related events and combined events) in the period 1980 to 2009

In the following sections, this data will be implemented into the GIS-based analysis for the time periods 1990 - 1999 and 2000 - 2009 to indicate the relation between more installed electricity generating units and more extreme events occurring in the 402 districts of Germany. Due to the lack of data regarding extreme weather events and especially installations of PV and wind turbines, the period 1980 - 1989 was not considered in the GIS-based analysis. Within the management cycles, the statistical evaluation of the extreme event data fits into the phases of risk assessment or problem analysis.

Moreover, the statistical evaluation is the basis for the 30 year moving average in temporal distribution. In section 7.6, the 30 year moving average will be used as an indicator for the trend in the coming years. With regard to the German Energy Turnaround this is of use for a prospective planning and adaptation of electricity generating units. The function of FORECAST (Excel 2010®) is used to project this 30 year moving average to the level of possible numbers of events per year in the future. It consists of the existing values and a linear regression based on the averages of years and number of events.

4. Local Planning and Enhanced Climate Mitigation Concepts

In this section, local planning and climate mitigation concepts are introduced. Climate mitigation concepts serve as the basis for the analysis which renewable energies are influenced by extreme hydro-meteorological events and where they are at risk. The case study on ice throw from wind turbines discusses the risk as well as installation distances to critical areas like settlements or streets. These are implemented in land use plans and priority areas for wind turbine installations and can be integrated into the assessment of renewable energy potentials in districts.

4.1 Background Local Planning and Climate Mitigation Concepts

Local planning approaches and Climate Mitigation Concepts in Germany are dedicated to a sustainable future with a reduction of CO_2 equivalent emissions to accomplish the 2 °C climate target and further goals of the German Federal Government. The 2 °C target was set as a political goal first in 1987 by the Advisory Group on Greenhouse Gases (AGGG) as a response to early climate models. Those models predicted a 2 °C increase in global mean temperature caused by a doubling of the CO_2 concentration in the atmosphere (RANDALLS 2010). Underlined by the Second Assessment Report of the IPCC in 1995, in 1996, the 2 °C target was acknowledged in declarations by the EU and the *German Advisory Council on Global Change* (Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen WBGU) (RANDALLS 2010). The IPCC (1995) calculated an increase of 2 °C by 2100 for the mid-range emission scenario. The Third Assessment Report in 2001 contained a graphic[7] which laid emphasis on 2 °C as a threshold to negative impacts on most regions worldwide as well as a large increase in extreme events (SMITH, SCHELLNHUBER & MIRZA 2001). The 2 °C target was reconfirmed in 2009 by Decision2/CP.15 “Copenhagen Accord”, a decision by the Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC 2010).

To reach this target, the German Federal Government proposed several interim goals on energy related climate change adaptation and mitigation. A first step was made in August 2007 with the so-called Meseberg resolution. It contains 29 measures regarding an integrated energy and climate programme of which the most important are:

- By 2020 25 % of the electricity production should be based on combined heat and power (CHP) installations;

[7] later known as the “burning embers” graphic by SMITH ET AL. (2009, p. 4134)

- Increase of share of renewable energies in electricity production to 25 - 30 % by 2020 and subsequent further development;
- Support of clean generation in low emission power plants including Carbon Capture and Storage (CCS);

as well as improved energy management and efficiency programmes (*FEDERAL MINISTRY OF ECONOMICS AND TECHNOLOGY & FEDERAL MINISTRY FOR THE ENVIRONMENT, NATURE CONSERVATION AND NUCLEAR SAFETY* 2007). A complete list of the 29 measures can be found in Appendix E.

The importance of cities and districts in order to realize the measures was emphasized by the *FEDERAL MINISTRY FOR THE ENVIRONMENT, NATURE CONSERVATION AND NUCLEAR SAFETY* together with the *GERMAN FEDERATION OF CITIES AND MUNICIPALITIES* (Deutscher Städte- und Gemeindebund DStGB), the *GERMAN COUNTY ASSOCIATION* AND THE *GERMAN ASSOCIATION OF CITIES AND TOWNS* (2008). Using the motto "think globally – act locally" this cooperation decided that especially cities and districts with their responsibility in local planning and local strategies are major contributors in climate change mitigation and the integration of renewable energies.

Following these agreements, the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety established the *National Climate Protection Initiative* (Nationale Klimaschutzinitiative KSI) in 2007. Shares of the European Emission Trades are used as support for climate mitigation programmes and the preparation of local climate mitigation concepts (KUCHARCZEK ET AL. 2010). Especially in the light of the German Energy Turnaround[8], which was enacted in 2010 and strengthened in 2011 following the tsunami in Japan and the Fukushima accidents, the installation of renewable energies in the German districts is enforced. The White Paper on the German Energy Turnaround contains a phase out of nuclear energy until 2022 as well as an increase in renewable electricity production up to 35 % until 2020. Moreover, electricity demand should be decreasing by 10 % compared to 2010. A major share of electricity should be produced by wind turbines (*FEDERAL MINISTRY FOR THE ENVIRONMENT, NATURE CONSERVATION AND NUCLEAR SAFETY/*Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU) 2011). Therefore, one active measure by the *German Federal Government* together with the Federal States and the districts is a renewal of the distance and height regulations for wind turbines (FEDERAL MINISTRY FOR THE ENVIRONMENT, NATURE CONSERVATION AND NUCLEAR SAFETY 2012).

It becomes clear that an increase in renewable energies is regarded as an important point in climate mitigation processes just as much as a decrease in CO_2 equivalent emissions.

[8] Also called German Energy Transition or German Energiewende

Moreover, the *German Federal Government* and other institutions highlight the role of cities and districts in this process. The above mentioned climate mitigation concepts are a feasible instrument to determine the potential of a region to reach these aims.

Climate mitigation concepts need to be in accordance with the land use planning framework. There are three main land use planning stages on a sub-national level. The planning on the level of the Federal States includes the regional development programme and builds the framework for more detailed local planning. The next level is the regional level including the so-called regional development plan and its realization. The most detailed level is the planning on municipality level of an urban or small area (*BAVARIAN OFFICE FOR THE ENVIRONMENT*/Bayerisches Landesamt für Umwelt 2009). It includes the land use plan and zoning and is the level on which the climate mitigation concepts come into action. Moreover, land use planning is an effective instrument for preventive action against negative impacts of a changing environment (Kanonier 2006) and can therefore be regarded as an adaptation measure.

Within climate mitigation concepts, six main steps need to be taken into account as proposed by the FEDERAL MINISTRY FOR THE ENVIRONMENT, NATURE CONSERVATION AND NUCLEAR SAFETY (2010). These steps are

1. CO_2 and energy balances[9]
2. Assessment of potentials for mitigation[10]
3. Cooperation with responsible parties
4. Catalogue of measures
5. Performance monitoring and
6. Concept for public relations.

A first framework for climate mitigation concepts was established in 1997 by the *GERMAN INSTITUTE FOR URBANISTICS* (Deutsches Institut für Urbanistik gGmbH) (FISCHER & KALLEN 1997). Usually, the CO_2 and energy balances are calculated on the basis of energy consumption data with a territorial or originator basis. Both methods are so-called domestic balances. Within the potential assessment and the scenarios for mitigation the possible implementation of technical potentials for renewable energy installations as well as demand reductions and other mitigation measures are accounted for. The third step of cooperation with responsible parties includes early discussions, e.g. in workshops and meetings, for the

[9] CO_2 and energy balances are calculated for all sectors, including private households, industry, trades and services, waste/waste water, traffic and especially the municipality owned properties as role model. In each sector, the share of renewable and conventional energy carriers is stated and each energy carrier and type is accounted for by using different factors for CO_2 emission per kWh.

[10] and adaptation. Adaptation is not explicitly referred to in the documents by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Nevertheless, adaptation activities are highly welcome and should be integrated into the assessment.

preparation of the climate mitigation concept. Technically and economically feasible mitigation options are part of the catalogue of measures. Regarding sustainable electricity supply, the installation of renewable energies, the renewal of street lighting and incentives for the public to reduce their heat and electricity demand are highlighted. Steps 5 and 6, the performance monitoring and public relations are future concepts including repeated balance calculations to verify the goals and information spreading.

The steps (1) CO_2 and energy balances, (2) assessment of potentials and (4) catalogue of measures refer to installation of renewable energies. Within the assessment of potentials for mitigation, not only the reduction of the emissions of greenhouse gases like carbon dioxide and methane plays a major role but also the increase of renewable energies to energy supply.

This highlights the importance of cities in local planning and the responsibilities regarding

- Energy supply (heat and electricity);
- Urban (land-use) planning;
- Community and business energy management as well as
- Renovation of building stock and mobility (KREFT, SINNING & STEIL 2010).

By comparing six integrated climate mitigation concepts (four in cities, two in districts) on the following pages, similarities and discrepancies are shown.

Portrait "Climate mitigation concept for the City of Karlsruhe" (CITY OF KARLSRUHE 2009)		
Base year	2007 **tCO_2/year*person** 10.7	
Approach	Final energy **Type** Territorial	
Electricity mix	National mix	
Percentage sectors final energy	Industry	44
	Households	29
	Trade and services	24
	Traffic	Not included
Percentage sectors CO_2 emissions	Industry	48
	Households	26
	Trade and services	23
	Traffic	Not included
Catalogue of measures	General	11
	City planning	3
	Energy efficiency	17
	Renewable energies	16
	Traffic	9
	Information, support and participation	24
Remarks	The steam power plant (Rheinhafen-Dampfkraftwerk) and the refinery (MiRO) need special consideration in the CO_2 and energy balance	

Portrait "Energy and climate mitigation concept for the City of Frankfurt am Main" (DUSCHA ET AL. 2008)		
Base year	2005 **tCO_2/year*person** 12.8	
Approach	Final energy **Type** Territorial	
Electricity mix	National mix with consideration of CHP	
Percentage sectors final energy	Industry	34
	Households	22
	Trade and services	21
	Traffic	23
Percentage sectors CO_2 emissions	Industry	35
	Households	20
	Trade and services	25
	Traffic	20
Catalogue of measures	Electricity saving offensive	8
	Renovation of households	18
	Energy efficiency in non-residential buildings	17
	Associations and churches	12
	Public property	10
	Sustainable energy supply	12
	Climate protection pact for the city	6
Remarks	Some measures show overlapping	

Portrait "Integrated Climate Mitigation Concept for the City of Esslingen am Neckar" (HERTLE ET AL. 2010)		
Base year	2007 **tCO_2/year*person** 11.9	
Approach	Final energy **Type** Territorial	
Electricity mix	National mix	
Percentage sectors final energy	Industry	43
	Households	26
	Trade and services	12
	Traffic	13
Percentage sectors CO_2 emissions	Industry	50
	Households	233
	Trade and services	12
	Traffic	13
Catalogue of measures	General	7
	Households	8
	Trade and services	4
	City administration	5
	Multiplier (cooperation and 50/50 projects)	4
	Energy supply	5
	Traffic	10
Remarks	none	

Portrait "Climate Mitigation Concept for the City of Münster" (DUSCHA ET AL. 2009)		
Base year	2006 **tCO_2/year*person** 8.2	
Approach	Final energy **Type** Territorial	
Electricity mix	local mix (combined cycle plant)	
Percentage sectors final energy	Industry	8
	Households	33
	Trade and services	33
	Traffic	26
Percentage sectors CO_2 emissions	Industry	10
	Households	33
	Trade and services	34
	Traffic	24
Catalogue of measures	General	9
	Construction and residence	10
	Trade and services	7
	Energy conversion and renewable energies	9
	Traffic	12
Remarks	Revised balances according to new standard Special consideration of the combined cycle plant on the territory under investigation	

Portrait "Integrated Climate Mitigation Concept District of Hameln-Pyrmont" (FRAUENHOLZ ET AL. 2010)		
Base year	2007 **tCO_2/year*person** 8.9	
Approach	n/a **Type** n/a	
Electricity mix	n/a	
Percentage sectors final energy	Economy (incl. industry and trade and services)	n/a
	Households	n/a
	Traffic	n/a
Percentage sectors CO_2 emissions	Economy (incl. industry and trade and services)	25.8
	Households	42.7
	Traffic	31.5
Catalogue of measures	Households	30
	Community facilities	19
	Economy	12
	Traffic	21
Remarks		

Portrait "Integrated Climate Mitigation Concepts District of Friesland" (WINTER ET AL. 2010)		
Base year	2009 **tCO_2/year*person** n/a	
Approach	n/a **Type** n/a	
Electricity mix	n/a	
Percentage sectors final energy	State	12
	Electricity	9
	Mobility	17
	Heat	33
	Food supply	5
	Consumption	24
Percentage sectors CO_2 emissions	State	8
	Electricity	18
	Mobility	18
	Heat	25
	Food supply	12
	Consumption	19
Catalogue of measures	Electricity	3
	Heat	4
	Mobility	6
	Renewable energies	7
	Residence	10
	Companies	4
	Tourism	2
	Education	4

It can be observed that similarities occur especially for the approach and type of balance used for the climate mitigation concepts. Mostly the approach is final energy based and on a territorial basis which means that all emissions on the specified area are accounted for. In some cases (Frankfurt, Münster and Karlsruhe) this means that special regard is paid to either a local electricity mix or other factors to reduce negative impacts by power plants or refineries. However, there are also noticeable differences. The city of Karlsruhe did not include traffic as one of the main contributors to emissions. Usually, the main sectors are industry, households, trade and services and traffic. Nevertheless, the district of Friesland chose a different approach. With regard to the catalogue of measures, most concepts included a point especially on energy conversion, renewable energies or energy supply in general. Still, the measures are either different or the focus is shifted to the necessary topics identified in the areas with the best potential for change.

4.2 GIS-Analyses on Renewable Energies

The identification of influences of extreme weather events on power plant structures leads to the mapping analysis of the hazards. Thus, the extreme weather data and the data of renewable energies were mapped in the Geographical Information System ArcGIS® by ESRI Inc. According to Table 3, where the influences of extreme weather events on the electricity generating units were identified, each type of power plant is spatially joined with the extreme weather data. As pointed out in Sections 2.4 and 4.1, this kind of hazard maps can be used as a planning instrument and decision support once affected districts and renewable energy infrastructures are identified. In the following sections, each map cluster is described in detail. The important aspects are:

- The type of event,
- a temporal resolution of two time slides ranging from 1990 to 1999 and 2000 to 2009
- the distribution of events in Germany based on administrative districts.

The events of tornadoes, severe wind gusts, heavy rain, hail, floods, thunderstorms and lightning are displayed as single point events. That means the exact coordinates of the events in the Gauß-Krüger-system are the basis. For the analysis of thunderstorms a buffer diameter of 25 km was chosen according to the classification of a supercell where typical diameters range between 15 and 50 km. The pictograms for the extreme events are directed at the symbols used by SCHÖNWIESE (1994) in accordance with the classification by the World Meteorological Organisation. The following tables give an overview on the most common symbols. Table 21 shows the pictograms for the single events according to SCHÖNWIESE (1994), Table 22 lists all pictograms for floods, flash floods and tornadoes as derived from the ESRI symbol database and Table 23 contains all other symbols.

Table 21: Pictograms for extreme weather events rain, snow, hail and thunderstorm according to SCHÖNWIESE (1994)

Weather event	Pictogram
Rain	●
Snow	*
Hail	▲
Thunderstorm	

The pictograms for lightning, floods, flash floods and tornadoes were taken from the ESRI symbols database and are displayed in Table 22:

Table 22: Pictograms for extreme events floods, flash floods and tornadoes (ESRI database)

Weather event	Pictogram
Flood	 light blue
Flash flood	 dark blue
Tornado	
	Yellow: years 1990 - 1999 Red: years 2000 - 2009

Table 23: Other pictograms and icons used in the mapping

Item	Pictogram or icon
Hydropower plants	light blue 1990s, dark blue 2000s
Wind turbines	light green 1990s, dark green 2000s
PV installations	□ filled yellow 1990s, filled orange 2000s
Frost	Point: octagon dark blue Surface: IDW-classes in shades of dark blue
Icing	Point: octagon light blue Surface: IDW-classes in shades of light blue
Summer	Point: octagon orange Surface: IDW-classes in shades of orange
Heat	Point: octagon red Surface: IDW-classes in shades of red
Severe wind gusts / storms	yellow background 1990s, orange background 2000s

The temperature measurements as derived from the *German Weather Service* are pieces of single point information at the gauging station. After this, temperatures were interpolated with the Inverse Distance Weighting Method (IDW). The IDW is a geospatial interpolation which puts pieces of single point information into relationship. Thus, the highest and lowest values mark the range for the average. The relation between two points is assumed to decline the further the distance of the points. The output of the space between is continuous raster information with values between the highest and the lowest input temperatures in this study. The procedure for calculating the IDW in ArcGIS® is to take the temperature point information as input and then choose the z-value of the temperatures measured. The output cell size is then set to 3000 (default was set on ~2200, so the next highest cell size [m] was set). The next step contains the power of the distance with most reasonable values between 0.5 and 3. Here the default of 2 is acceptable. The higher the power, the less influence the single points have on each other. The other optional functions were left as default.

To take the changes in frequency of extreme events into account, the hazard maps are split into the time slides 1990 - 1999 and 2000 - 2009, each encompassing a total of ten years. The time slide maps 1990 - 1999 include all extreme events in said period in combination with renewable energies built until 1999. In comparison, the time slide maps 2000 - 2009 include all extreme events in said period in combination with all renewable energies built until 2009 along with the power plants built in the earlier time frame.

4.2.1 Hydro Power Plants

4.2.1.1 Air Temperatures

During the identification of influences, no references were found for effects of air temperatures on hydropower plants. Thus, this section has been cut and no maps were created.

4.2.1.2 Precipitation-related Events

Hydropower plants depend largely on the amount of runoff and the slope. For this reason, the plants are mostly sited in southern Germany where the slope is large enough to have adequate potential energy to be converted to mechanical energy. As hydropower plants are subject to continuous runoff, they can be used as base load power plants.

The distribution of heavy rain events shows that the plants are well suited for their setting, as they are within regions of high precipitation and therefore in a situation where runoff is assured. Hydropower plants are less affected by the precipitation event itself but more by the resulting flood or drought events, depending on the supply of water in form of rain. Nonetheless, weathering of building structure takes place as in case of every other building structure. The zip code areas were differentiated by shades of blue in Map 1 regarding the number of power plants possibly affected.

Between 1990 and 1999, 143 of 8.271 zip code areas (ZCA) with 1 to 13 hydro power plants were possibly affected by heavy rain events. The following Table 24 shows the distribution by category of hydro power plants possibly affected:

Table 24: Hydro power plants in the period 1990 - 1999 possibly affected by heavy rain events

Number of hydropower plants per ZCA	Number of ZCAs possibly affected by heavy rain
1	67
2 - 5	52
6 - 10	20
> 10	4

The zip code areas with > 10 possibly affected hydro power plants are in Rottweil, Beratzhausen, Deggendorf and Oppenau, two in Baden-Wuerttemberg and two in Bavaria. By heavy rain events possibly affected hydro power plants can be found in every area state[11] but not in the city states[12]. Between 2000 and 2009, 142 zip code areas with 1 to 11 hydro power plants were possibly affected by heavy rain events. Table 25 shows the distribution according to the categories used in the maps:

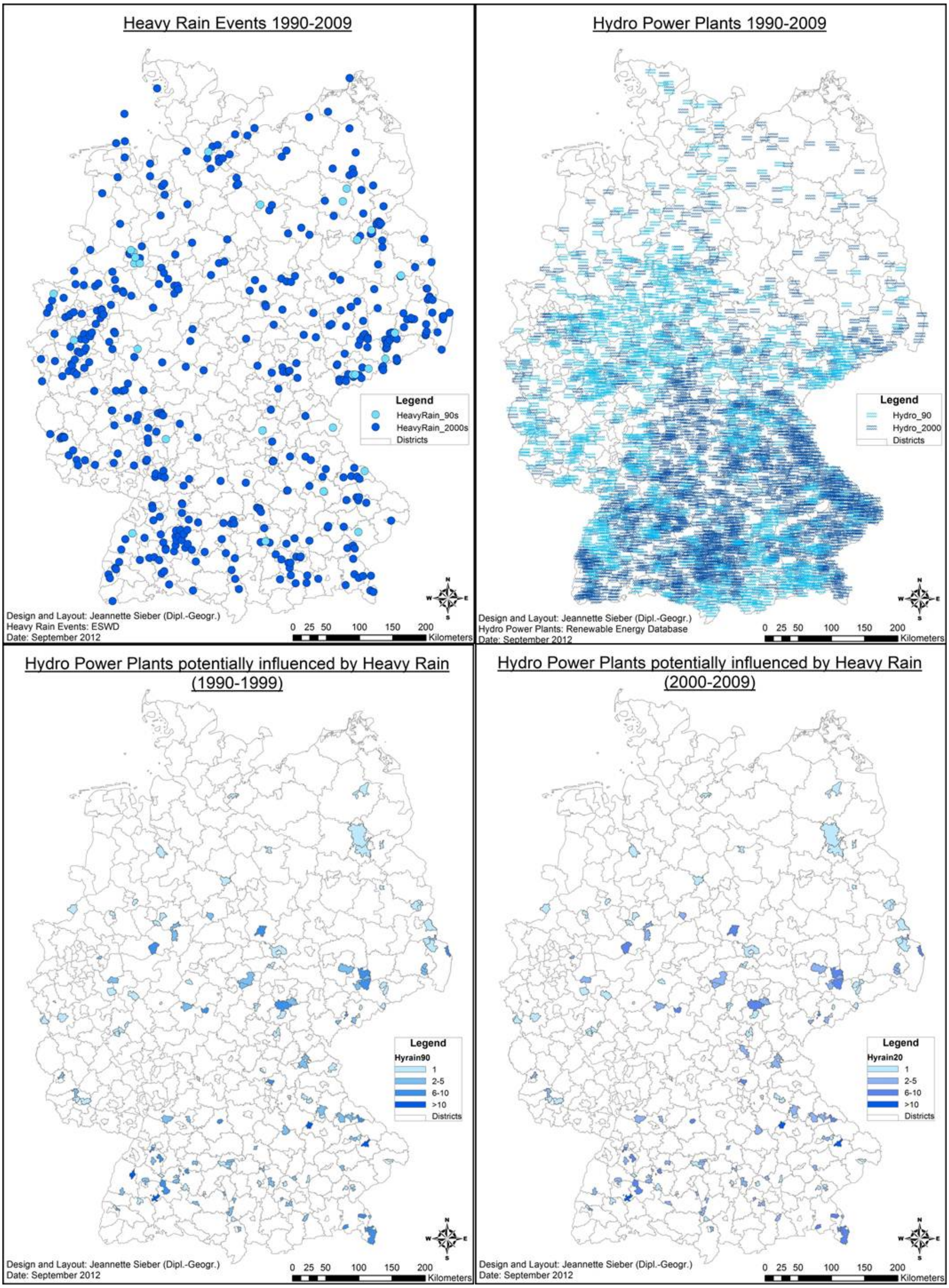
Table 25: Hydro power plants in the period 2000 - 2009 possibly affected by heavy rain events

Number of hydropower plants per ZCA	Number of ZCAs possibly affected by heavy rain
1	66
2 - 5	53
6 - 10	20
> 10	3

The ZCA with >10 possibly affected hydro power plants were Rottweil, Beratzhausen and Deggendorf, one in Baden-Wuerttemberg and two in Bavaria. Again, possibly affected hydro power plants can be found in every area state.

[11] Area state is used for the States: Baden-Wuerttemberg, Bavaria, Brandenburg, Hesse, Mecklenburg-West Pomerania, Lower Saxony, North Rhine-Westphalia, Rhineland-Palatinate, Saarland, Saxony, Saxony-Anhalt, Schleswig-Holstein and Thuringia

[12] City state is used for the States: Berlin, Bremen and Hamburg



Map 1: Hydropower plants and rain events

Winter rain events in combination with icing or frosty conditions may indicate snow fall. If precipitation falls as snow, the runoff is not directly available for hydro-electricity production. Moreover, icing conditions can lead to an ice layer on the water body which consequently might block the water inlet structures of hydropower plants. Most plants are protected by a mechanical grill to avoid a blockage of the turbines by branches, litter or other deposits. Thus it is clear that winter rain events might have an impact on hydropower plants more on the electricity production than on the structure itself.

4.2.1.3 Wind-related Events

As tornadoes might be relatively destructive on any kind of structure, in Map 2 the tornado events are mapped together with hydropower plants. In the period 1990 - 1999, a total number of ZCAs of 16 were subject to possible impacts of tornadoes on hydro power plants. With six possibly affected hydro power plants, Oberkirch in Baden-Wuerttemberg stands out. Table 26 gives an overview on the categories of ZCAs:

Table 26: Hydro power plants in the period 1990 - 1999 possibly affected by tornadoes

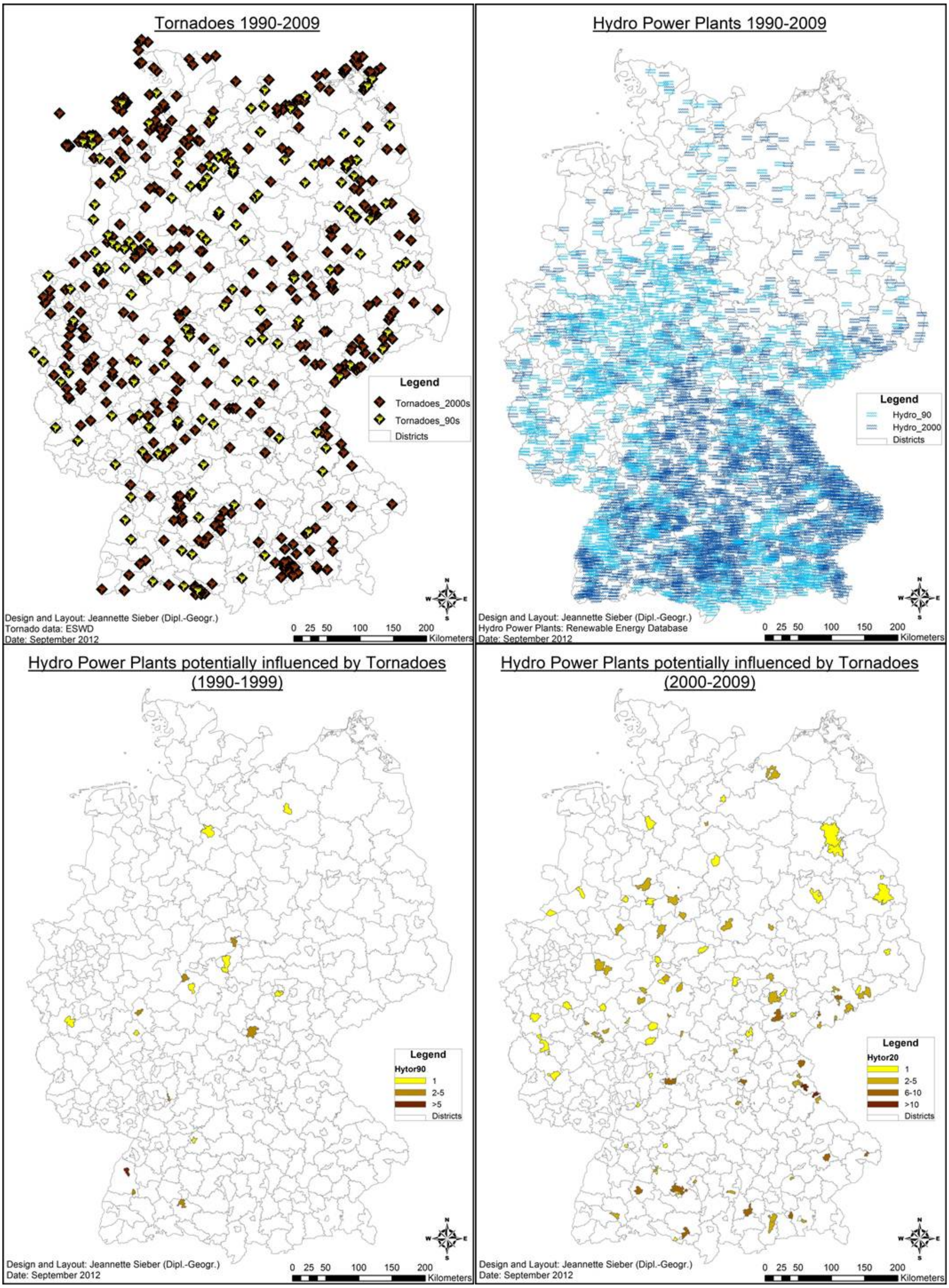
Number of hydropower plants per ZCA	Number of ZCAs possibly affected by tornadoes
1	8
2 - 5	7
6 - 10	1
> 10	/

Affected zip codes areas can be found in the States Baden-Wuerttemberg, Hesse, Thuringia, North Rhine-Westphalia, Lower Saxony and Mecklenburg-West Pomerania.

Comparing the period 2000 - 2009 with the earlier time slide, the number of ZCAs with possibly affected hydro power plants increased considerably. Now, 96 ZCAs were involved, at the same time, the number of tornadoes increased from 138 in the 1990s to 409 in the 2000s. Table 27 gives an overview according to the categories:

Table 27: Hydro power plants in the period 2000 - 2009 possibly affected by tornadoes

Number of hydropower plants per ZCA	Number of ZCAs possibly affected by tornadoes
1	38
2 - 5	43
6 - 10	13
> 10	2



Map 2: Hydro power plants and tornado events

In this period, the ZCAs Schönsee and Vohenstrau (both Bavaria) stand out with 14 resp. 15 possibly affected hydro power plants. In every area state except Saarland and Schleswig-Holstein encountered possible effects of tornadoes on hydro power plants.

4.2.1.4 Combined Events

Hydropower plants hold a special position during flooding events. First, the efficiency increases as long as the capacity of the turbine is not yet reached. The installed capacity mostly depends on runoff and slope as well as on the type of turbine. The highest capacity is reached when the difference between head and tail water is highest, i.e. the penstock is at a maximum point.

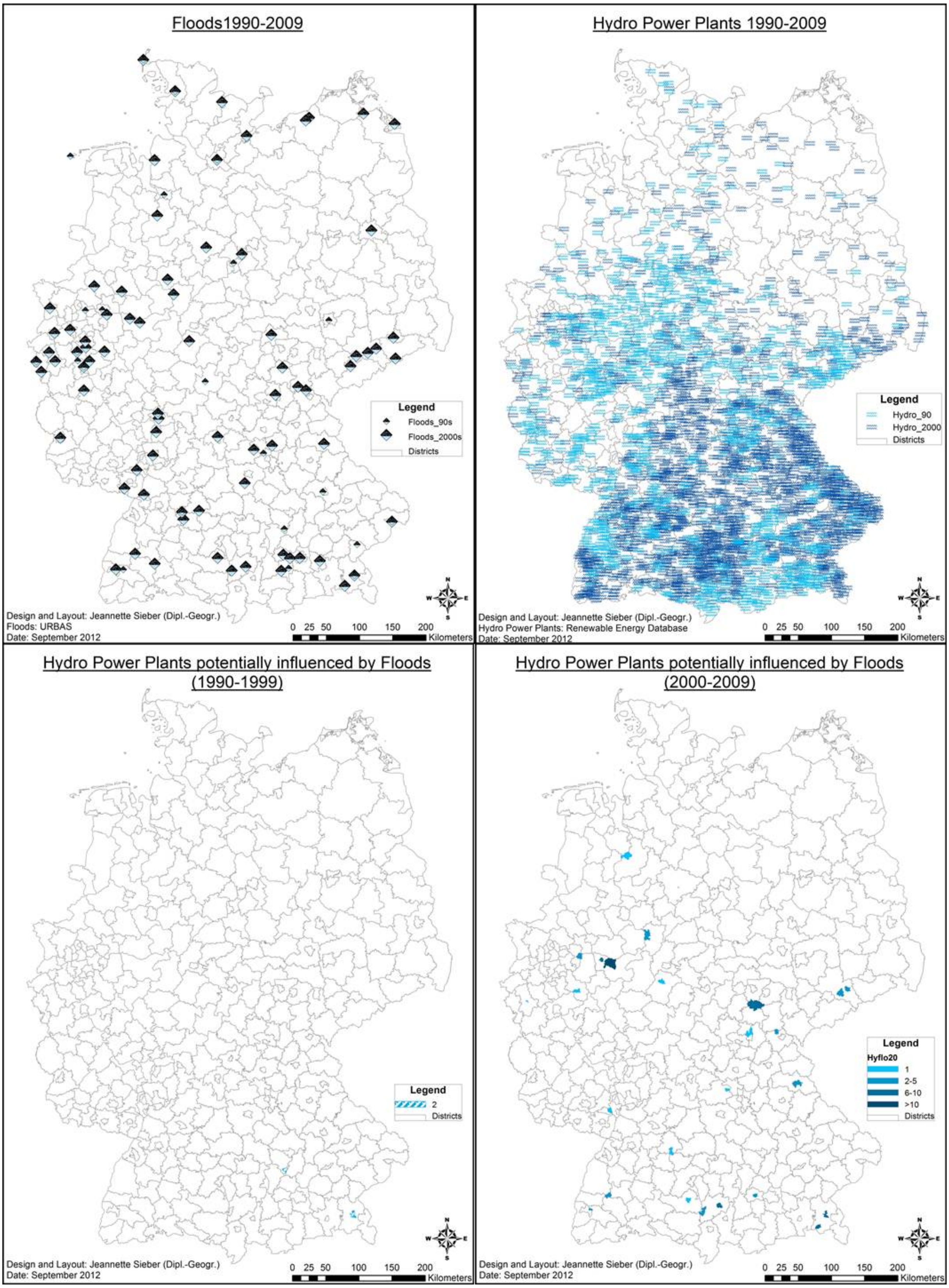
The analyses showed that only two zip code areas with hydropower plants encountered floods in the period 1990 - 1999; these were Aresing and Traunstein, both in Bavaria and both with two possibly affected power plants each (Map 3).

In the period 2000 - 2009, already 28 zip code areas with possible effects of floods on hydropower plants are counted. Table 28 gives the corresponding overview:

Table 28: Hydro power plants in the period 2000 - 2009 possibly affected by floods

Number of hydropower plants per ZCA	Number of ZCAs possibly affected by floods
1	12
2 - 5	10
6 - 10	5
> 10	1

Meschede in North Rhine-Westphalia counts 18 hydropower plants possibly affected. Other possibly affected hydropower plants can be found in the States Schleswig-Holstein, Lower Saxony, North Rhine-Westphalia, Hesse, Thuringia, Saxony, Rhineland-Palatinate, Bavaria and Baden-Wuerttemberg.



Map 3: Hydro power plants and flood events

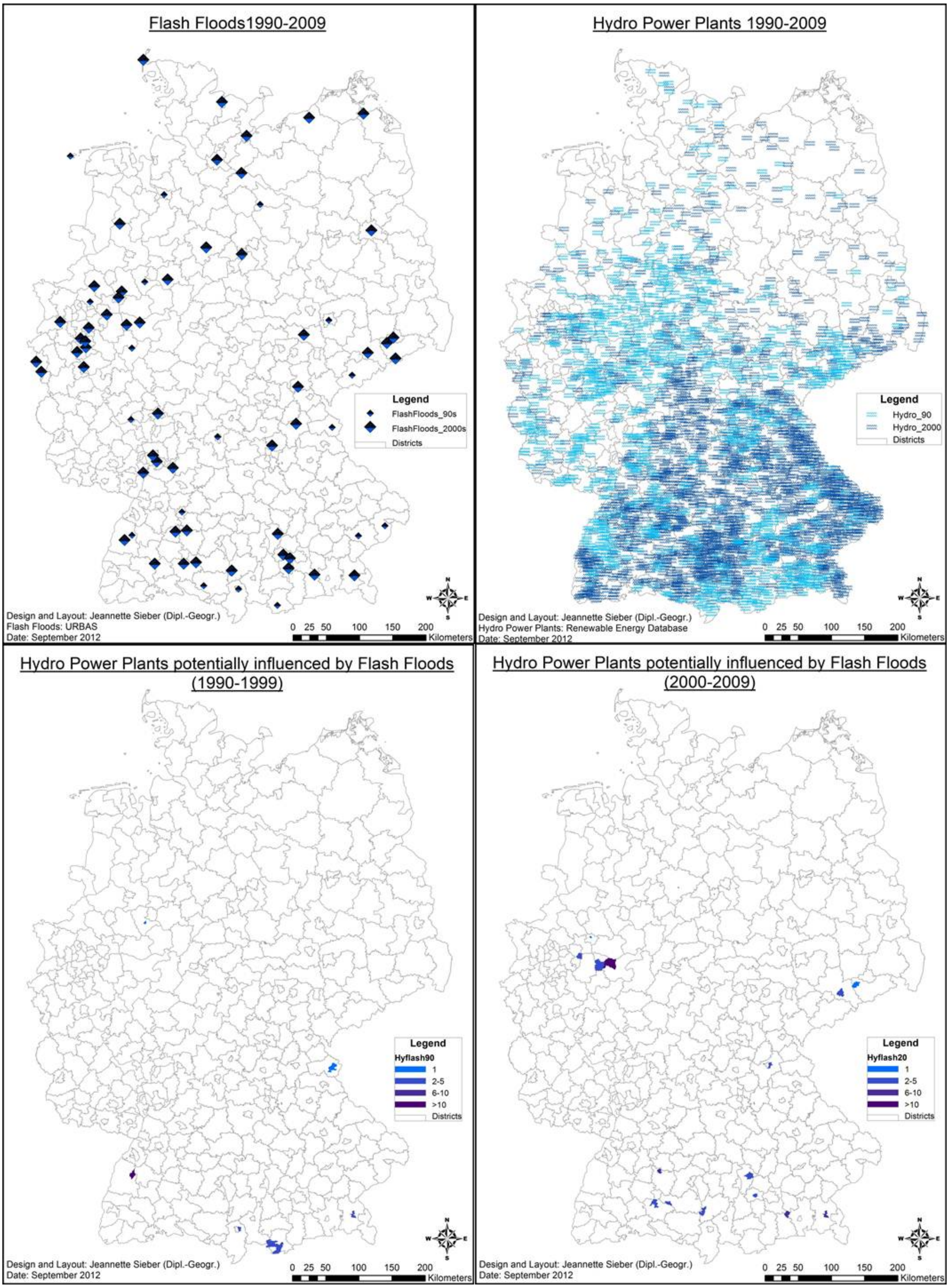
In the period 1990 - 1999 a total number of six zip code areas was counted for having hydro power plants possibly affected by flash floods. Oppenau (Baden-Wuerttemberg) with 13 power plants stands out. In the three States Baden-Wuerttemberg, Bavaria and North Rhine-Westphalia flash floods with possible impacts on hydro power plants occurred in said period.

Between 2000 and 2009, 18 zip code areas were affected altogether. Again, Meschede with 18 possibly affected hydro power plants stands out. Moreover, the States Baden-Wuerttemberg, Bavaria, Saxony and North Rhine-Westphalia accounted for possibly affected hydro power plants due to flash flood occurrence. Table 29 gives an overview on the categories of possibly affected power plants, Map 4 illustrates these findings:

Table 29: Hydro power plants in the period 2000 - 2009 possibly affected by flash floods

Number of hydropower plants per ZCA	Number of ZCAs possibly affected by flash floods
1	5
2 - 5	9
6 - 10	3
> 10	1

When the capacity is exceeded, most hydropower plants are used as dams in order to regulate the runoff. During that time, no electricity can be generated. Here again, due to their exposed location along or in rivers, hydropower plants are prone to floods and flash floods. Due to the installed protection measures, the insensitivity and helpful installations like the mechanical grills hydropower plants are mostly affected by secondary effects like the cut-off of electricity generation and the isolation from the network rather than by direct damages due to flooding.



Map 4: Hydro Power Plants and Flash Floods

4.2.2 Wind Turbines

4.2.2.1 Air Temperatures

Concerning wind turbines and air temperatures, no direct effects were found. Instead, wind turbines are highly affected by the combination of the effects of precipitation and cold temperatures, as in the case of ice accretion and freezing. Since there is no standard procedure on how to evaluate such cases, the analyses are shown in the subsection of precipitation events (Map 6 and Map 7).

4.2.2.2 Precipitation-related Events

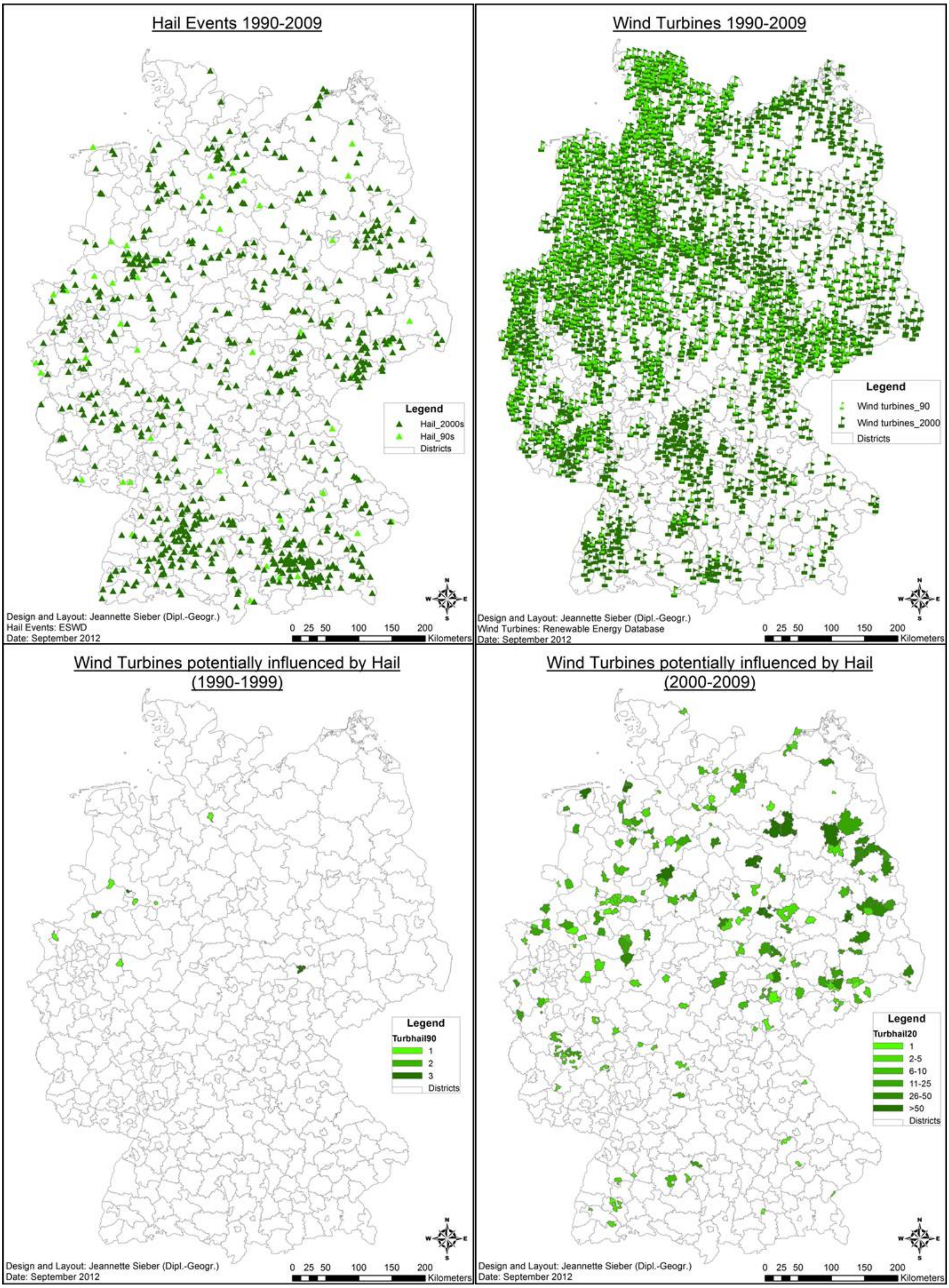
The GIS-analyses show that in the period 1990 - 1999 nine zip code areas contained possibly affected wind turbines due to hail. These can be found in Lower Saxony, North Rhine-Westphalia and Saxony-Anhalt. The most possibly affected wind turbines are situated in Freyburg/Unstrut (Saxony-Anhalt) and Osnabrück (North Rhine-Westphalia) (Map 5).

Between 2000 and 2009 already 188 zip code areas are listed. The number of hail events increased from 54 (1990 - 1999) to 730 (2000 - 2009), as well did the number of installed wind turbines from 5,266 (overall installed 1990 - 1999) to 19,772 (overall installed 2000 - 2009). In a zip code area of Pritzwalk, a total number of 120 wind turbines might have encountered hail events in said period. The following Table 30 gives an overview on the possibly affected number of zip code areas related to the category of wind turbines:

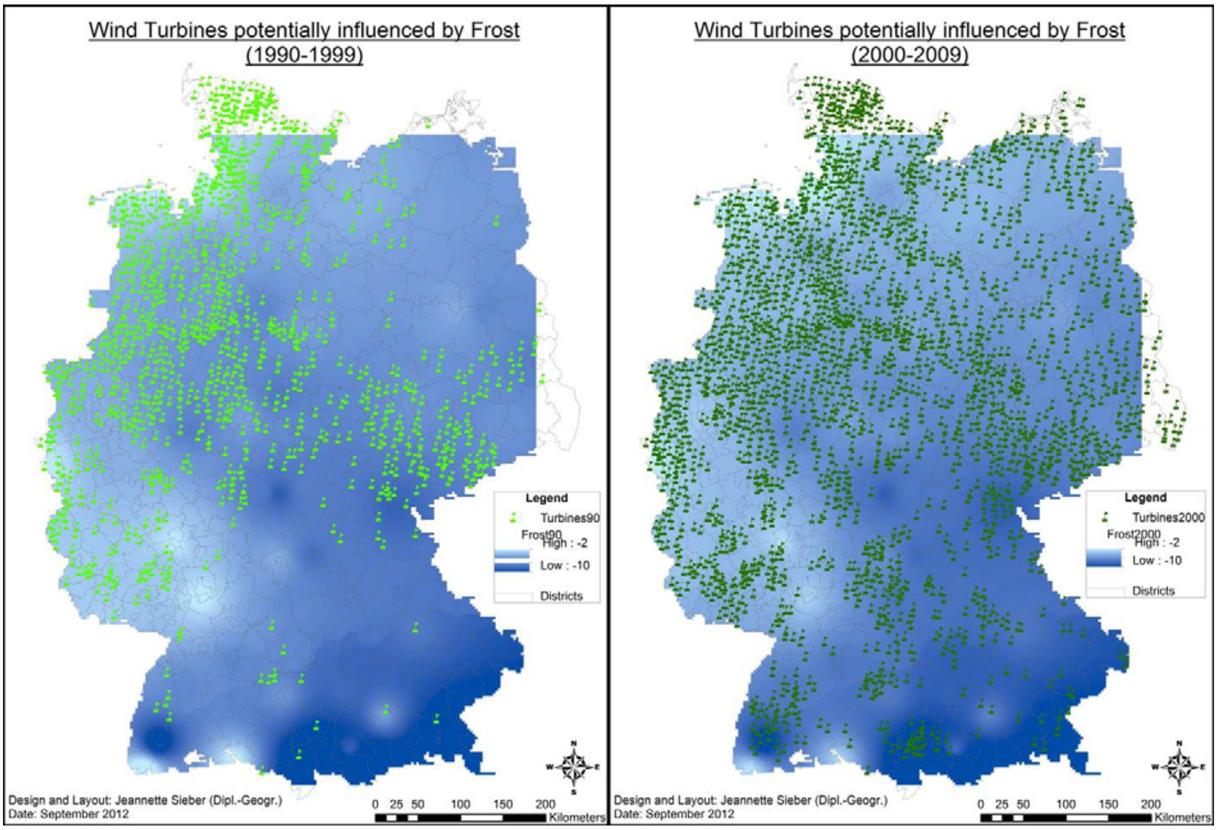
Table 30: Wind turbines between 2000 and 2009 possibly affected by hail

Number of wind turbines per ZCA	Number of ZCAs possibly affected by hail
1	28
2 - 5	60
6 - 10	33
11 - 25	40
26 - 50	16
> 50	11

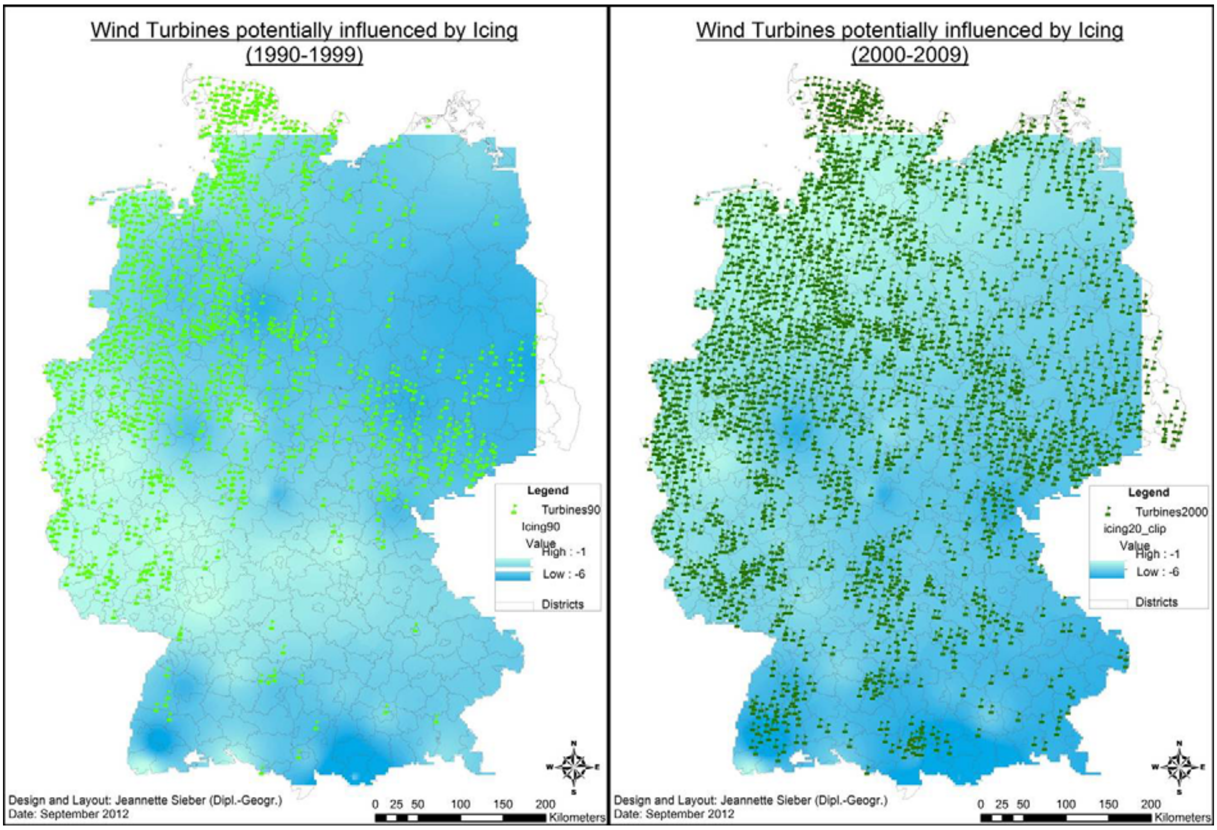
ZCAs with possibly affected wind turbines in said period can be found in every area state, but also in Hamburg and Bremen. So with the exception of Berlin, all States encountered hail events with possible impacts on wind turbines.



Map 5: Wind turbines and hail



Map 6: Wind turbines and frost conditions



Map 7: Wind turbines and icing conditions

Influences on wind turbines due to winter rain events under icing and frosty conditions might be freezing of, and ice accretion on, rotor blades. The distribution of cold temperatures and winter rain events shows that especially wind turbines in the northern part of Germany are subject to extreme conditions as well as wind turbines on heavily exposed sites (e.g. the Black Forest).

Two different approaches are common for securing electricity generation: de-icing and anti-freeze. De-icing describes the processes that lead to removal of ice accretion, whereas anti-freeze relates to coatings and products that prevent ice accretion from the beginning. The options are described in Section 2.3.2.

Unfortunately, wind turbine accidents in Germany are poorly documented. A compilation by the operators of the Caithness Windfarm Information Forum includes reports from Germany as well as other international accidents. Accidents involving ice throw from ice accretion on wind turbines are listed in the following Table 31:

Table 31: Date and site of wind turbine ice throw accidents (compilation according to CAITHNESS WINDFARM INFORMATION FORUM, update 06/04/2011, source online)

Date	Site/area	Date	Site/area
1996	Borgholzhausen, Sauerland	**08/12/2002**	Muensingen, Reutlingen, Wuerttemberg
29/10/1996	Krummendeich/ Lower Saxony	**26/02/2004**	Lankern bei Dingden, near Hamminkeln Kreis Wesel, Westphalia
08/11/1996	Werdum/Buttforde, Wittmund/ Lower Saxony	**14/11/2004**	Carzig, Märkisch Oderland / Brandenburg
10/01/1997	Selbitz-Sellanger, Hof/Bavaria	**12/12/2004**	Rhede, Kreis Borken, Westphalia
21/01/1997	Stein-Neukirch, Westerwald /Rhineland-Palatinate	**12/12/2004**	Lankern near Dingden, Wesel,Westphalia
29/11/1997	Willmandinger Alb, Himmelbjerg/Baden-Wuerttemberg	**30/01/2005**	Bölling bei Dahl, Hagen/Westphalia
05/01/1999	Gebrannten Rücken, Bromskirchen, Frankenberg/Hesse	**01/02/2005**	Schlüchtern-Hohenzell, Main-Kinzig-Kreis / Hesse
27/04/1999	Grebenhain, Lauterbach	**17/12/2005**	Lankern bei Dingen, Wesel, Westphalia
27/04/1999	Engelrod Helpersheim with Grebenhain, Vogelsbergkreis/Hesse	**08/01/2006**	Filsumer Wind Park, Filsum near Leer/Lower Saxony
26/02/2002	Sefferweich near Bitburg / Rhineland-Palatinate	**28/12/2006**	Schauenburg-Martinhagen, Kassel/Hesse

From this compilation, 20 incidents of ice throw can be identified, which are all caused by frost.

DURSTEWITZ (2003) analysed the wind turbine accidents of the 250 MW wind-programme. Therein, 880 icing events from 1990 to 2003 were reported and a total downtime of 64,200 hours resulted. Most of the events took place between October (three events) and May (four events in the Alps, altitude > 2,000 m asl), the absolute highest number is 336 events in December. In about 90 % of all cases, the turbines needed to be stopped due to ice accretion. Other impacts listed were, for example increased noise (2 %), increased vibration of blades (5 %) and reduced power output (13 %).

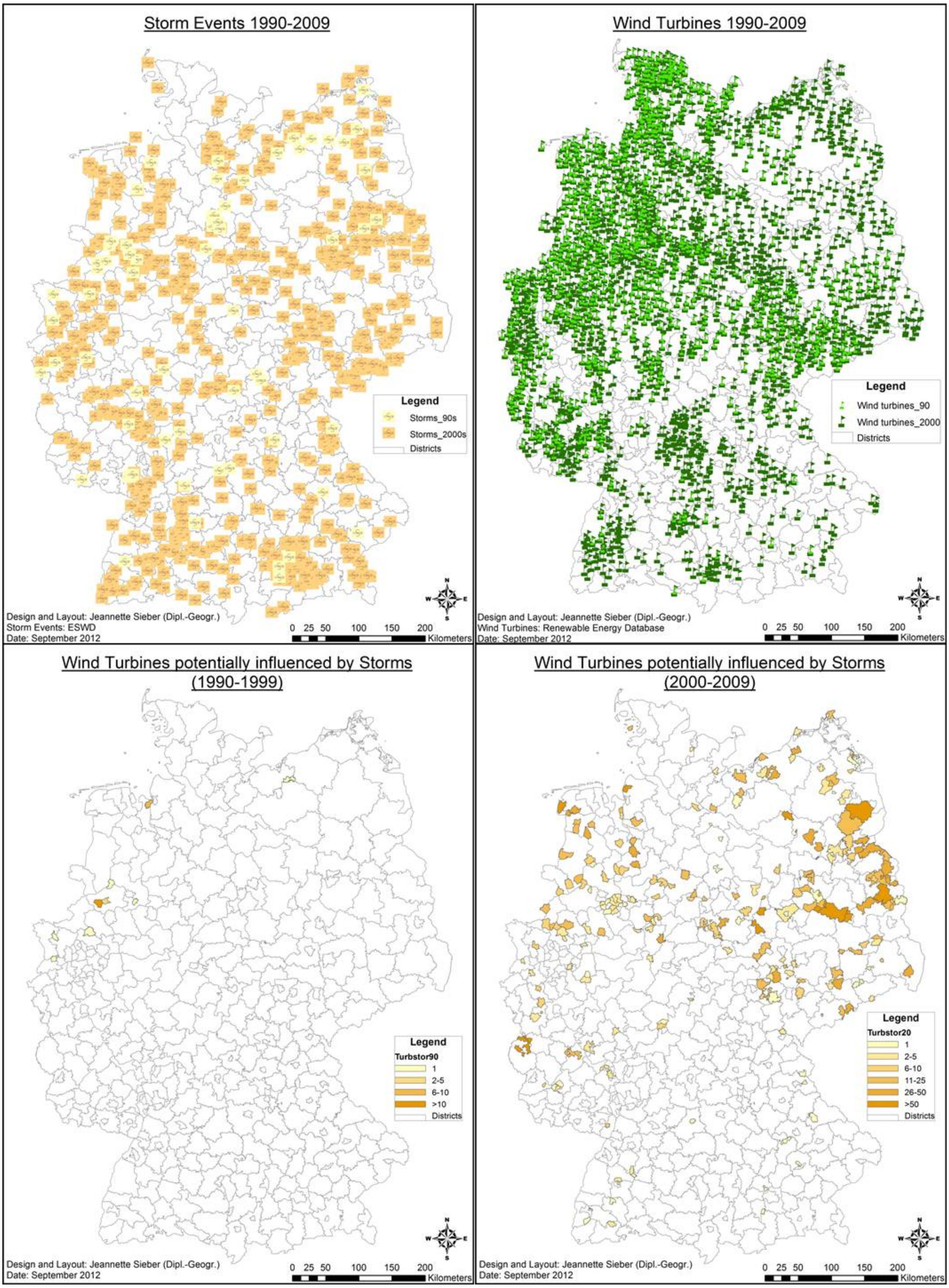
4.2.2.3 Wind-related Events

Usually, wind turbines should be planned and installed in corridors of high wind speeds in order to maximise the electricity output. Still, the turbines are usually only constructed to withstand wind velocities of about 150 km/h. Strong wind gusts, e.g. during winter storm Kyrill in 2007 reached maximum wind speeds of more than 210 km/h. Wind fall areas in forests are now under discussion for the installation of new wind turbines due to the strongly requested German Energy Turnaround and the extension in renewable energies (GOEBELS 2010).

The following map cluster shows the possible impacts of storms on wind turbines on a zip code area level (Map 8). In the period 1990 - 1999, nine ZCAs are listed for possibly having encountered storm impacts on wind turbines. Steinfurt (North Rhine-Westphalia) had the most possibly affected wind turbines counting eleven turbines in one zip code area. Only the northern parts of Germany were influenced, namely the States of Lower Saxony, North Rhine-Westphalia and Mecklenburg-West Pomerania.

On the contrary, the period 2000 - 2009 identifies 200 ZCAs. Not only has the number of storms in Germany increased (1990s: 66, 2000s: 707) but also the number of wind turbines per ZCA (see Table 32 for overview). Jüterbog (Brandenburg) with 188 possibly influenced wind turbines and Prenzlau (also Brandenburg) with 253 head the table.

In said time frame in every area state except Saarland possible effects were recorded. Also Bremen and Hamburg as two city states are on the list.



Map 8: Wind turbines and storm events

Table 32: Wind turbines in the period 2000 - 2009 possibly affected by storms

Number of wind turbines per ZCA	Number of ZCAs possibly affected by storms
1	33
2 - 5	56
6 - 10	37
11 - 25	44
26 - 50	20
> 50	10

According to DIN 1055-4 (*German Institute for Standards*/Deutsches Institut für Normung e.V. 2005a) Germany is divided into four regions of so-called wind zones. Wind zone 1 covers the Central Uplands, zone 2 works mostly for the Alpine Foreland and the Northern and North Eastern parts of Germany, including Thuringia, Saxony, Saxony-Anhalt, Brandenburg, Berlin, Mecklenburg-West Pomerania and Lower Saxony. Wind zone 3 covers the coastal part of Mecklenburg-West Pomerania, most of Schleswig-Holstein and parts of Lower Saxony and Bremen. Wind zone 4 ranges over the coastal areas towards the North Sea and the North Sea itself as well as a small part around Holstein and Fehmarn. The time-averaged wind speeds for the regions are as follows: Zone 1 = 22.5 m/s, zone 2 = 25.0 m/s, zone 3 = 27.5 m/s and zone 4 = 30.0 m/s. Those wind speed are valid for 10 min wind gusts in a height of 10 m above ground and an occurrence probability of 0.02, i.e. a 50-year wind gust.

Within the years 1980 to 2009, a total number of 862 severe wind gusts has been measured and most of the events seem to overlap with the installed wind turbines. The analyses of the Caithness Windfarm Information Forum data show that 25 of the 99 accidents are due to storms, mostly structural or blade failures. A table in Appendix D contains the identified failure data.

Regarding the possible impacts of tornadoes on wind turbines in Germany, the GIS-based analyses showed that between 1990 and 1999 33 zip code areas were affected (Map 9). In most of the ZCAs less than ten wind turbines might have been under the influence of tornadoes. Nevertheless, Norden (Lower Saxony, district of East Frisia) counts 60 possibly affected turbines. Most of the ZCAs lie in the northern part of Germany, but also some ZCAs in the Saarland, Hesse, Thuringia and Saxony are on the list.

Between 2000 and 2009 122 zip code areas can be counted were tornadoes might have had an impact on wind turbines. The following Table 33 shows the distribution per category:

Table 33: Wind turbines between 2000 and 2009 possibly affected by tornaodes

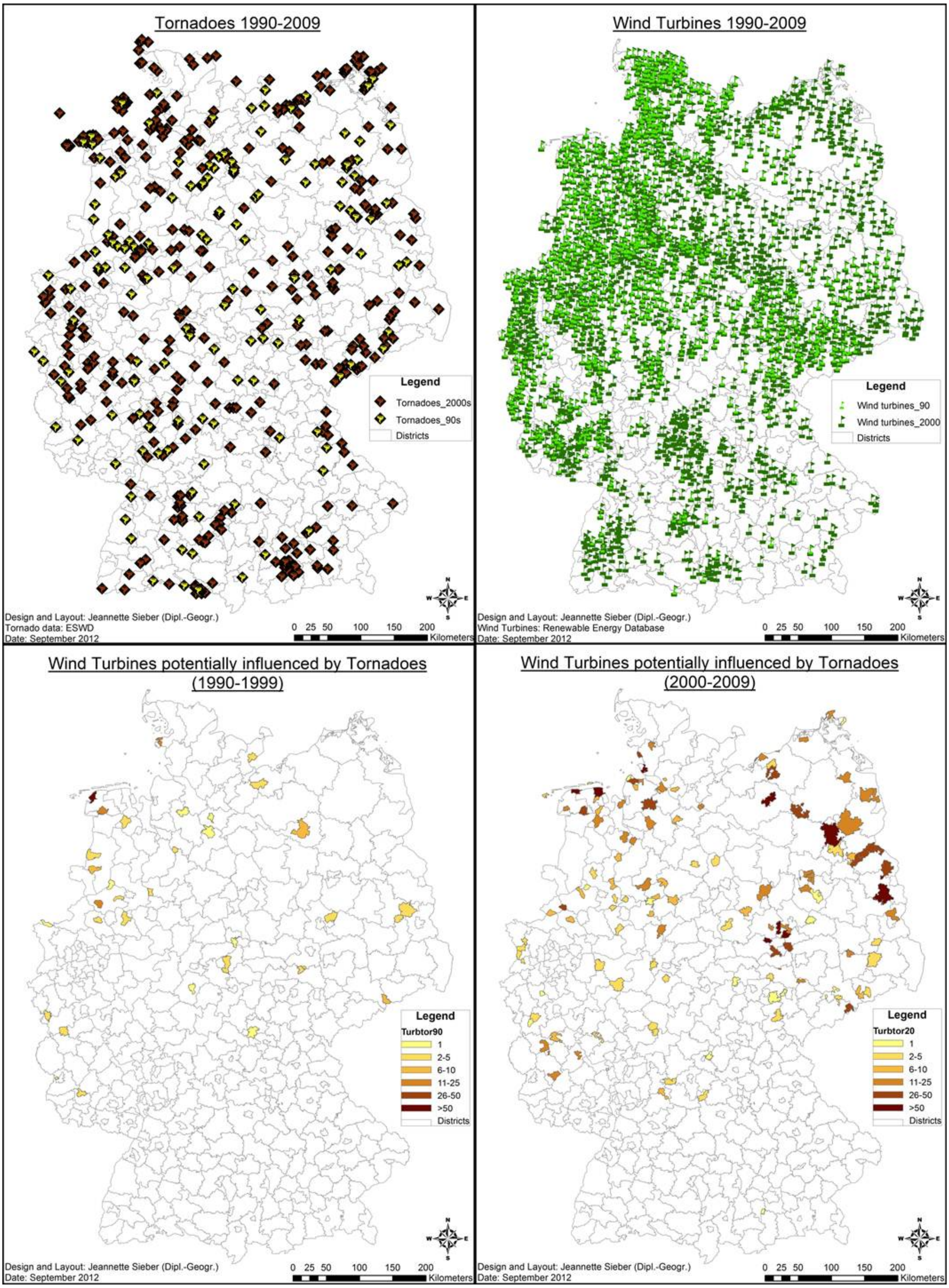
Number of wind turbines per ZCA	Number of ZCAs possibly affected by tornadoes
1	18
2 - 5	32
6 - 10	22
11 - 25	29
26 - 50	13
> 50	8

The spatial analysis shows the most affected zip code areas with simultaneously the most possibly affected wind turbines in the states Brandenburg, Mecklenburg-West Pomerania, Lower Saxony and Saxony-Anhalt. Further states with possible impacts are Schleswig-Holstein, Saxony, Thuringia, Hesse, North Rhine-Westphalia, Rhineland-Palatinate, Bavaria and Baden-Wuerttemberg. Also Hamburg, as the only city state, encountered possible influences.

In the CWIF database one accident due to tornadoes was reported:

Table 34: Blade failure accident due to tornado occurrence (CWIF 2011)

Accident type	Cause	Date	Site/area	Details
Blade failure	tornado	23.06.2003	district Dithmarschen / Schleswig-Holstein	Damage reported to windpark following local tornado



Map 9: Wind turbines and tornado events

4.2.2.4 Combined Events

Lightning strikes as well as thunderstorms may lead to damages of blades and the structures. An analysis of the reported events shows that 24 accidents are based on lightning impact. 27 more accidents (fires) are reported with unknown causes. In some of these cases lightning might have been the trigger.

In the period 1990 - 1999 only one zip code area showed a parallel occurrence of a thunderstorm and a wind turbine. Buchholz in der Nordheide (Lower Saxony) had one installed wind turbine and one thunderstorm in said period (Map 10).

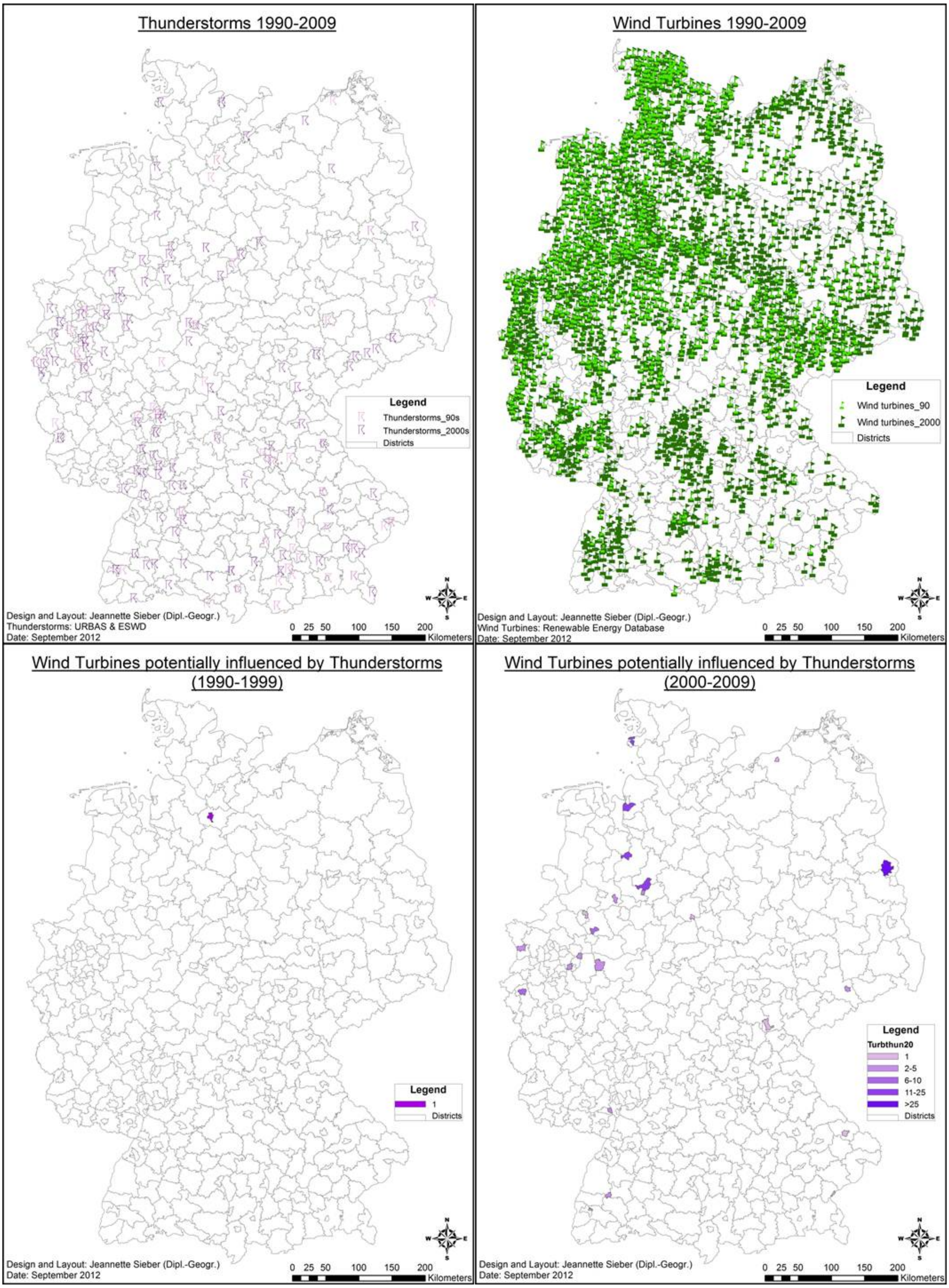
Even in the period 2000 - 2009 only 24 zip code areas could be identified. The most wind turbines were installed in Seelow (41 in total) which could have experienced a thunderstorm. Most affected ZCAs list less than ten wind turbines (see Table 35).

Table 35: Wind turbines between 2000 and 2009 possibly affected by thunderstorms

Number of wind turbines per ZCA	Number of ZCAs possibly affected by thunderstorms
1	7
2 - 5	10
6 - 10	2
11 - 25	4
26 - 50	1
> 50	/

Between 2000 and 2009 a total number of 193 thunderstorms was registered. At the same time, about 19,772 wind turbines were installed. In this analysis, only the directly affected zip code areas were considered even though thunderstorms might stretch over a 50 km diameter. This needs to be regarded as a limiting factor in the analyses. Another limiting factor could also be the short term appearance of thunderstorms over a small area. This shows how difficult thunderstorms are at display, they can be either multicells with > 10 km diameter or very much localized vice versa.

Nevertheless, all area states except Saarland, Hesse and Saxony-Anhalt suffered from possible impacts. Using a 25 km buffer around the thunderstorm events, all area states experienced at least one thunderstorm between 2000 and 2009 and had wind turbines installed at the same time.



Map 10: Wind turbines, lightning strikes and thunderstorms

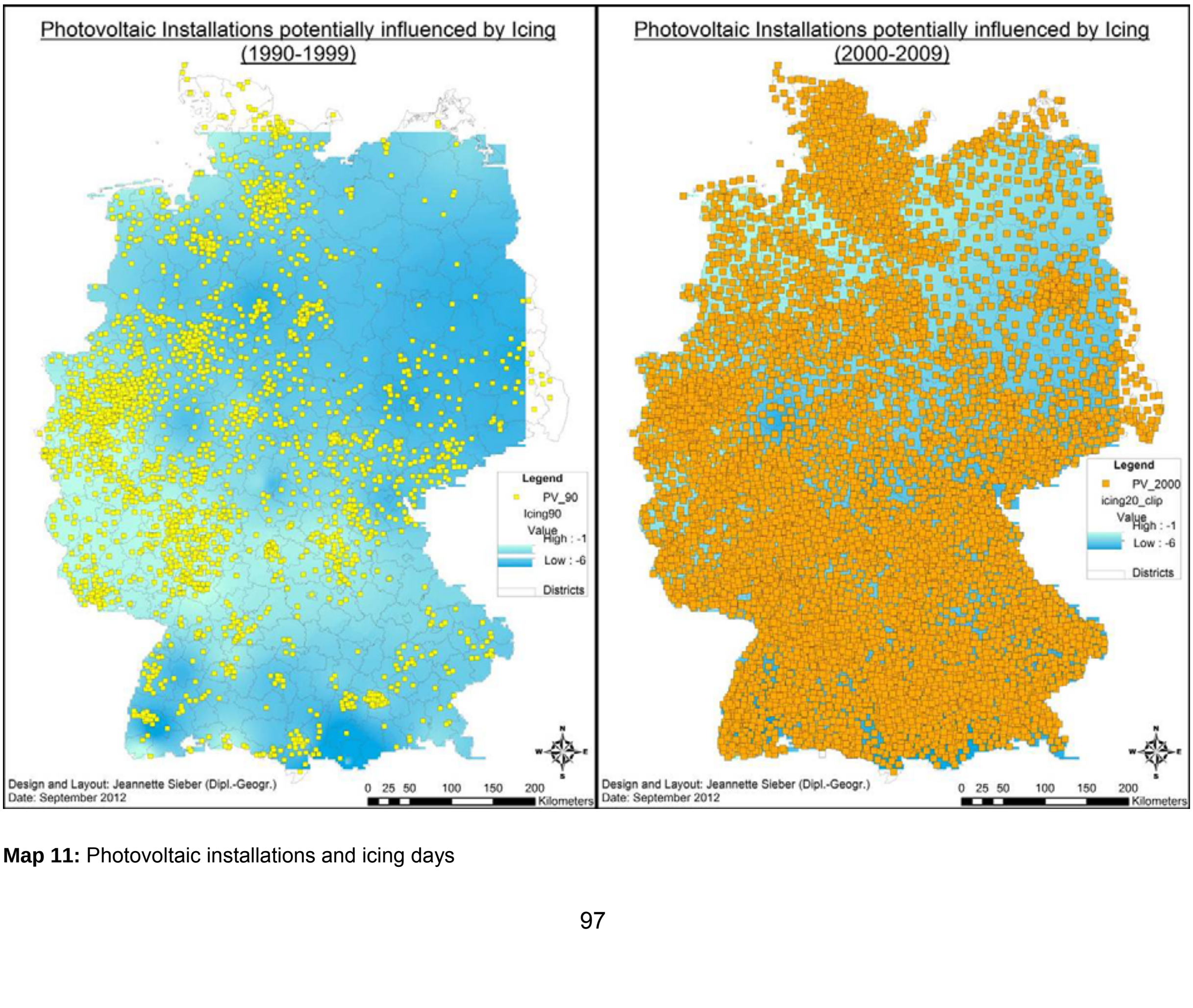
Within the GIS, the zip code accurate wind turbines are clipped with thunderstorms with a buffer of 25 km in diameter for the time slide 2000 - 2009. 4,682 wind turbines are identified within the buffers, which may be subject to thunderstorms. That means that about 24 % of all wind turbines have very likely been influenced by a thunderstorm in said period.

4.2.3 Photovoltaic Installations

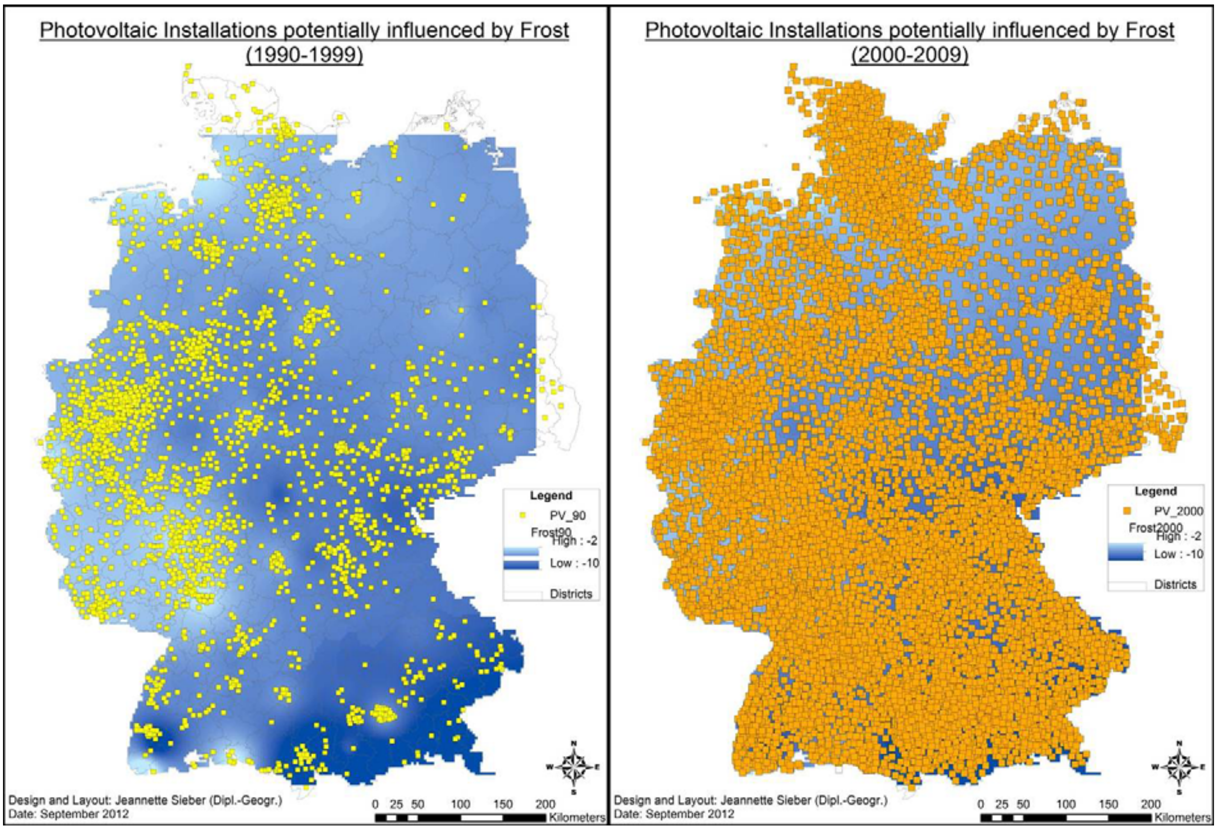
In 2008 about 4,200 PV installations were damaged due to fire, storm, snow load and overvoltages (PHOTOVOLTAIK-MAGAZIN ONLINE 2010). This list shows that influences of extreme weather events are common in Germany. This section deals with the influences of air temperatures, heavy precipitation (also winter precipitation and low temperatures) as well as with storms and tornadoes and thunderstorm/lightning events on PV installations.

4.2.3.1 Air Temperatures

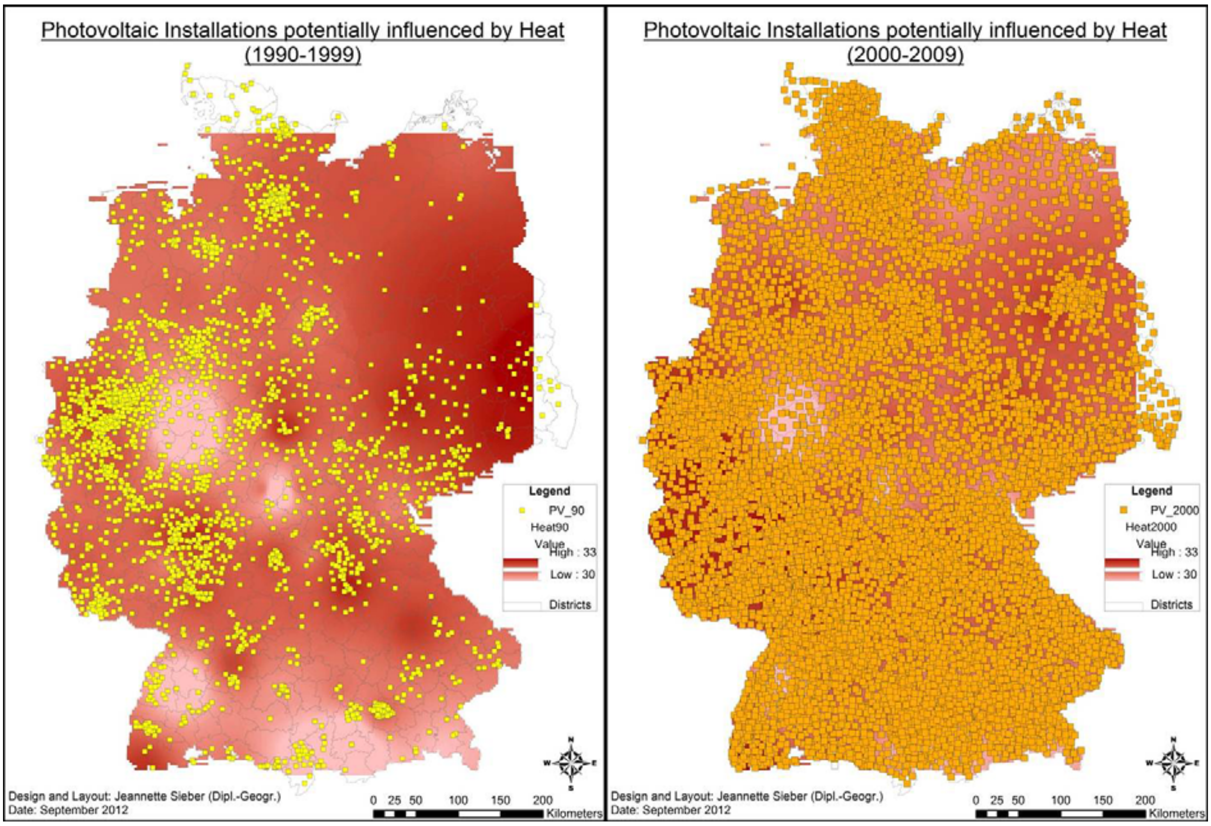
As described in section 2.1.1 PV installations are vulnerable to temperature stresses which leads to increased or decreased efficiency. For a complete overview, the following Maps 11 to 13 show the distribution of PV installations under icing, frosty and heat conditions. Nevertheless, due to a lack of precise data, no calculations or comparison are made.



Map 11: Photovoltaic installations and icing days



Map 12: PV and frost days



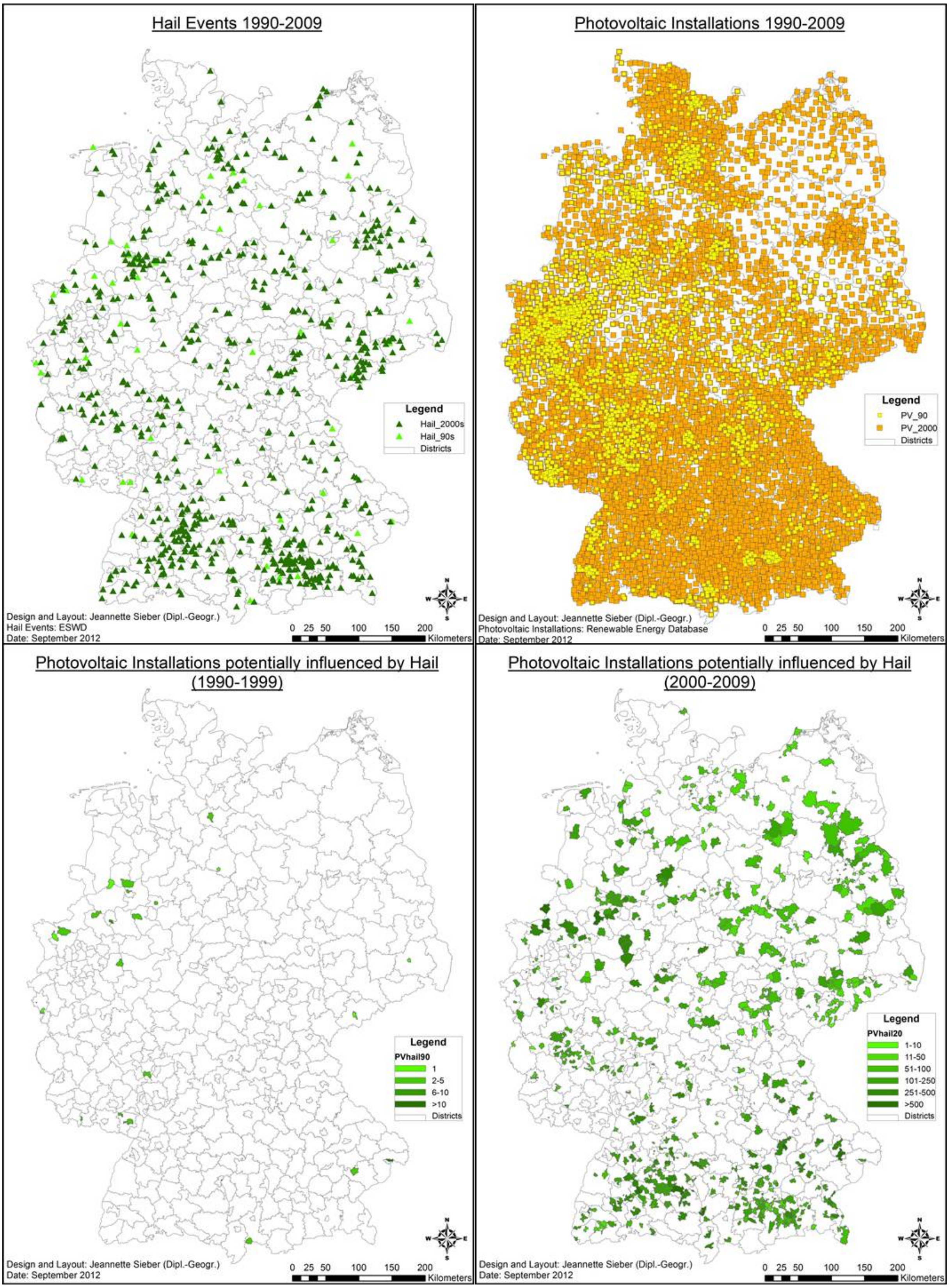
Map 13: PV and heat days

4.2.3.2 Precipitation-related Events

Hail events are very common in Germany and are well distributed. Only small parts of Schleswig-Holstein and Mecklenburg-West Pomerania seem free of hail events – which, even then, may be due to a lack of monitoring stations.

The analyses of the period 1990 - 1999 showed 23 zip code areas with possible impacts of hail on PV installations. In said period, a total number of 7,793 PV installations is registered. In the same time slide, about 54 hail events are listed. So about half of the hail events in said period occurred in ZCAs with installed photovoltaic panels. However, in all ZCAs the number of possibly affected PV installations was under 15.

In contrast, the period 2000 to 2009 showed 595 affected ZCAs. Now the highest number of possibly influenced PV installations is 713 in Osterhofen (Bavaria). Table 36 and Map 14 give an overview on the categories on PV installations possibly under the influence of hail.



Map 14: PV and hail

Table 36: PV installations between 2000 and 2009 possibly affected by hail events

Number of PV installations per ZCA	Number of ZCAs possibly affected by hail
1 - 10	40
11 - 50	167
50 - 100	157
101 - 250	160
251 - 500	63
> 500	8

Between 2000 and 2009 in every state (area and city) PV installations were under the possible impact of hail events. In the earlier period only the states Lower Saxony, North Rhine-Westphalia, Rhineland-Palatinate, Saarland and Bavaria were affected. Not even Berlin, Bremen and Hamburg recorded possible impacts by hail even though cities usually have more PV installations than rural areas.

Rain only has a small impact on PV installations. Nevertheless, rain may indicate reduced insolation and therefore a reduction in efficiency. The following map shows the distribution of heavy precipitation events and PV installations in Germany.

Icing and frosty conditions in combination with winter precipitation events may indicate snowfall and therefore reduced efficiency due to snow cover on the PV panels. Usually, the distribution of PV installations is denser in cities as PV panels are often installed by private operators on the roof of their privately owned buildings. Moreover, the southern Black Forest shows an occurrence of many PV installations, low temperatures and winter precipitation events. So to conclude, especially highly equipped urban areas in the western part of Germany are subject to snow events and consequently to reduced efficiency of PV installations during the winter season where insolation is reduced all over Germany.

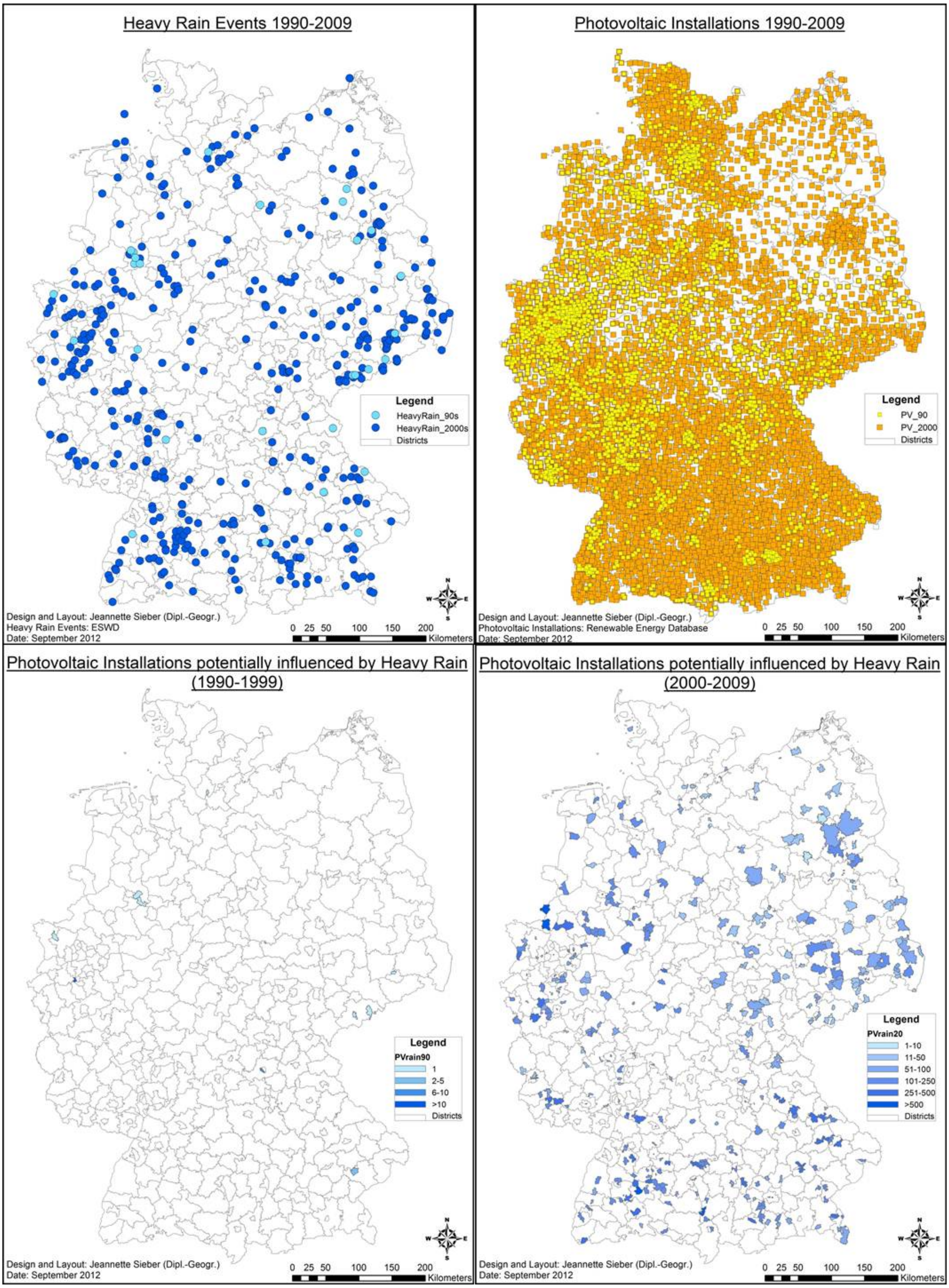
Between 1990 and 1999 only ten zip code areas show simultaneous occurrence of rain events and installed PV panels. Monheim am Rhein (North Rhine-Westphalia) counted 24 PV installations affected by heavy rain. The map interpretation shows influenced ZCAs with PV installations in Lower Saxony, North Rhine-Westphalia, Saxony and Bavaria as well as Schleswig-Holstein.

On the other hand, between 2000 and 2009 370 zip code areas were affected. Borken (North Rhine-Westphalia) accounted for 703 PV installations possibly influence by heavy rain (see Table 37 for overview).

Table 37: PV installations between 2000 and 2009 possibly affected by heavy rain events

Number of PV installations per ZCA	Number of ZCAs possibly affected by heavy rain
1 - 10	31
11 - 50	114
50 - 100	89
101 - 250	100
251 - 500	32
> 500	4

The local analysis reveals possible influences of heavy rain on PV installation in every area state and also in every city state. Nevertheless, most affected seem North Rhine-Westphalia, Saxony and Saxony-Anhalt which did not exclusively show also the most heavy rain events (Map 15).



Map 15: PV and heavy rain events

4.2.3.3 Wind-related Events

Severe wind gusts or storms will only impact PV installations in case of inaccurately mounted constructions. Nevertheless, the following maps show the distribution of PV installations and storms as well as tornadoes.

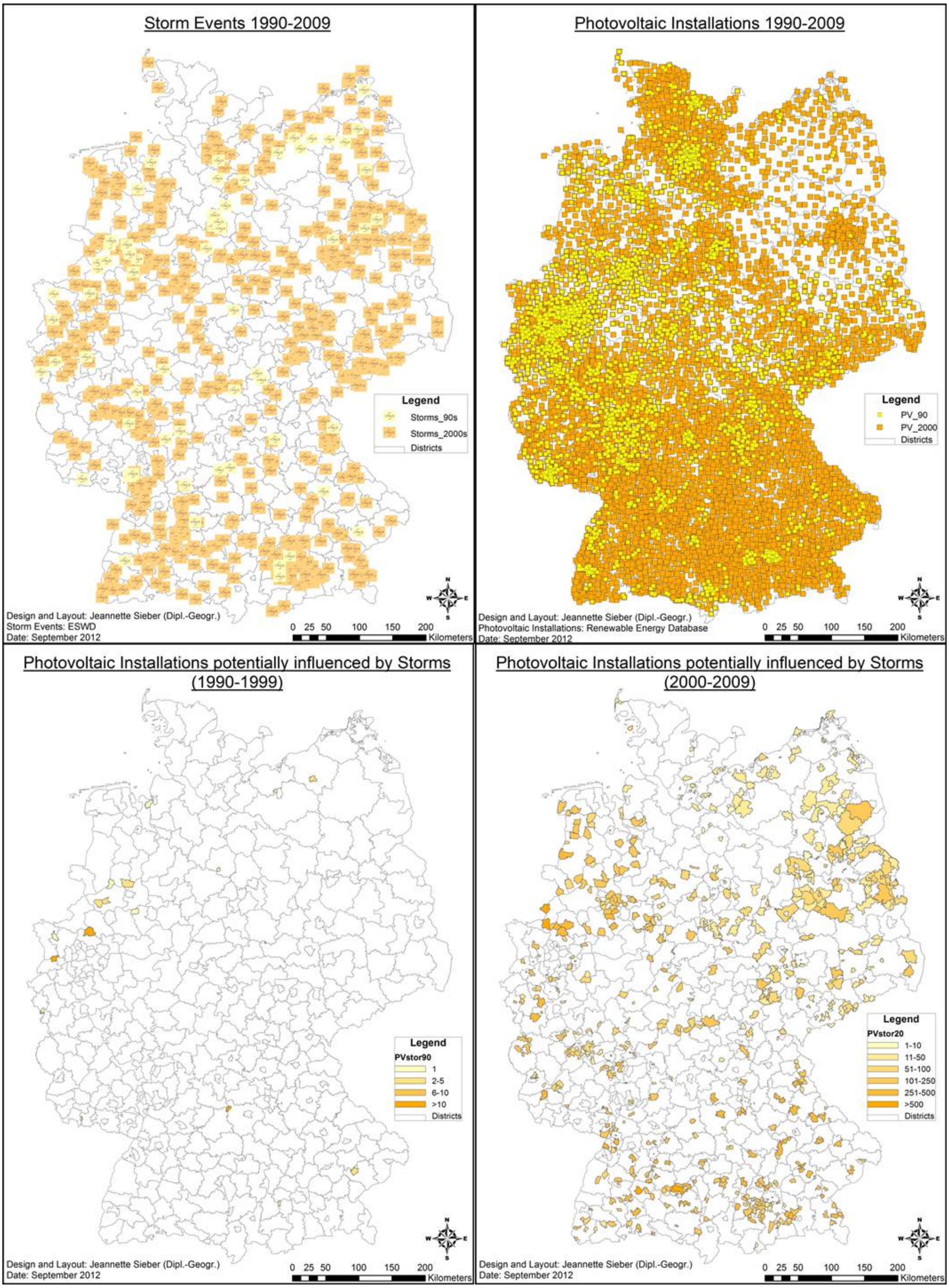
The statistical analysis lists 18 zip code areas with possible influences of storms on PV installations in the period 1990 - 1999 in the states Mecklenburg-West Pomerania, Lower Saxony, North Rhine-Westphalia, Saarland, Baden-Wuerttemberg and Bavaria. The most installed PV panels could be found in Haltern (North Rhine-Westphalia).

For the period 2000 - 2009 there is another great leap in installed capacity and therefore in possibly affected installations due to storms. In total, 552 zip code areas are listed with Borken (North Rhine-Westphalia) holding the most PV installations possibly under influence. Table 38 shows again the overview of the categories.

Table 38: PV installations between 2000 and 2009 under possible influence of storms

Number of PV installations per ZCA	Number of ZCAs possibly affected by storms
1 - 10	44
11 - 50	169
50 - 100	141
101 - 250	143
251 - 500	51
> 500	4

In said time slide it becomes clear again, that PV installations are under influence in every area state and also in every city state. PV installations are, as described in chapter 2.2, subject to the influence of every kind of extreme hydro-meteorological single event and very exposed due to the mounting on roofs and also as free-standing PV panels. This becomes clear considering the GIS-based analyses (Map 16).



Map 16: PV and storms

In Map 16 it is illustrated that PV installations as well as storms seem to accumulate in urban areas. Moreover, the storms can be seen as a triangle reaching from Berlin to the Rhine-Ruhr region, down along the Rhine valley to the Danube valley and up north to Berlin again. In those areas, PV installation density is high. Storms are described as the third most cause of PV installation failure in Germany (SIEG 2010).

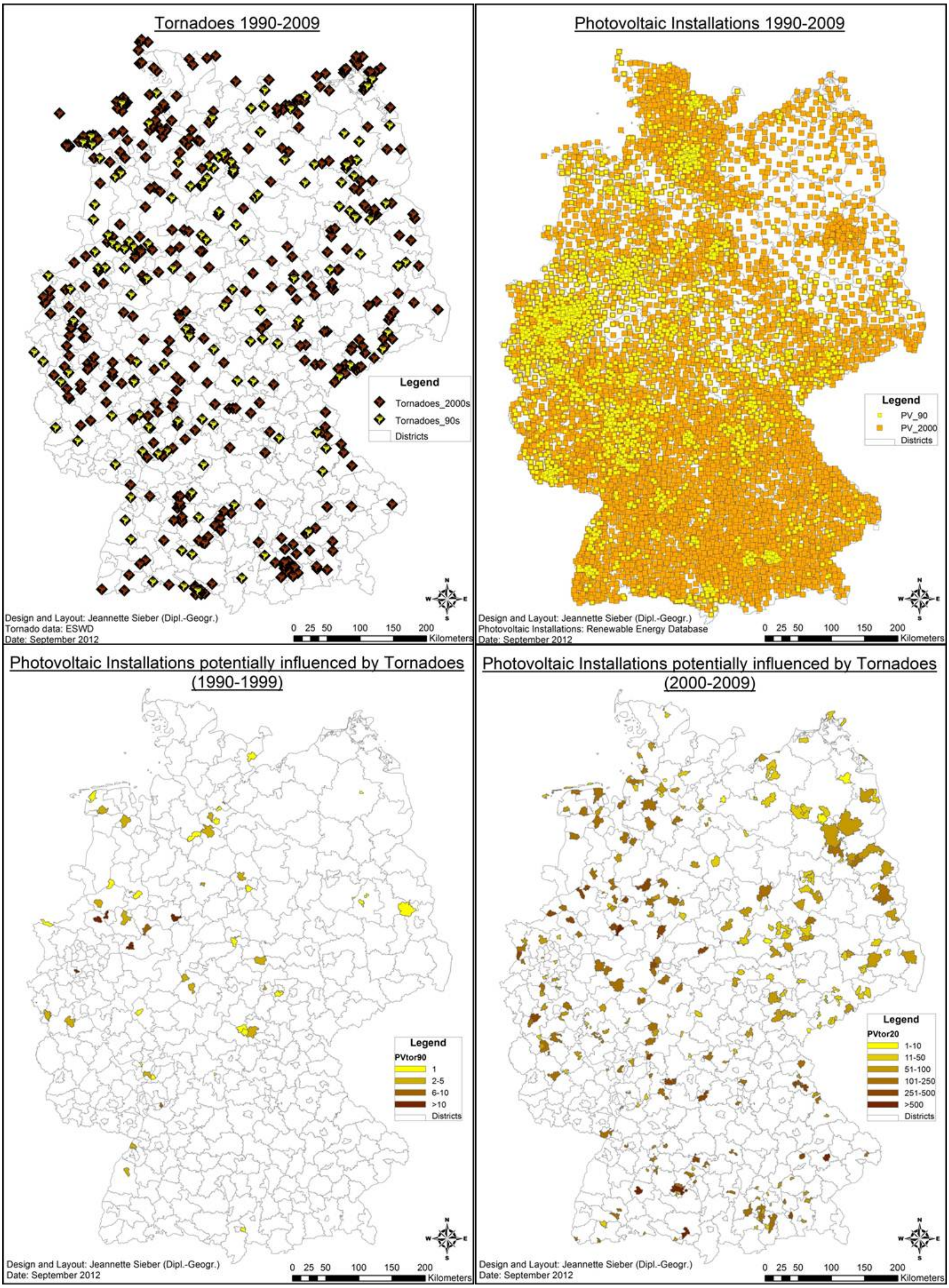
The analyses of possible impacts of tornadoes on PV installation showed that between 1990 and 1999 a total number of 48 zip code areas might have encountered said difficulties. Soest (North Rhine-Westphalia) had the most installed capacity probably under influence. Using the GIS-based results, tornadoes possibly influencing PV installations occurred in every area state except Rhineland-Palatinate, Saarland and Saxony-Anhalt and also in Hamburg.

During the period 2000 to 2009 291 zip code areas suffered from possible impacts of tornadoes on PV installations. Here, Landau a. d. Isar (Bavaria) stands out with 853 possibly affected PV installations. Table 39 shows the distribution in the categories.

Table 39: PV installations between 2000 and 2009 possibly affected by tornadoes

Number of PV installations per ZCA	Number of ZCAs possibly affected by tornadoes
1 - 10	18
11 - 50	86
51 - 100	84
101 - 250	78
251 - 500	20
> 500	5

Possible impacts of tornadoes on PV installations are well distributed over Germany; every area state except Saarland notes them but also the city states Hamburg and Bremen (Map 17).



Map 17: PV and tornadoes

4.2.3.4 Combined Events

Concerning combined events only thunderstorm and lightning strikes are a threat for PV installations. Lightning impact on PV installations may lead to fire and overvoltages, both often resulting in complete destruction of the installation. At the very least, control devices need to be exchanged after a lightning strike, due to complete burn out.

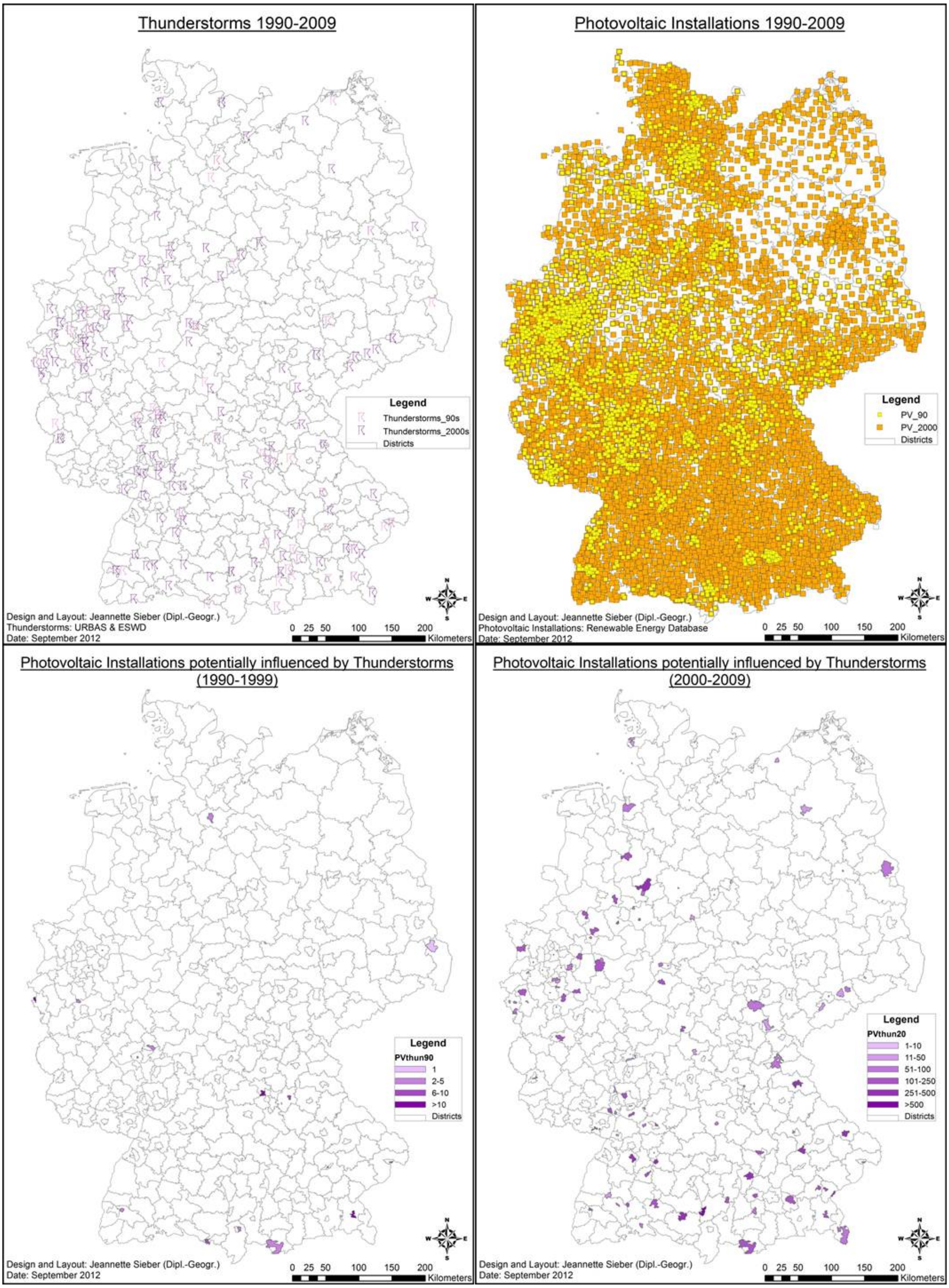
In the period 1990 - 1999 17 zip code areas show possible impacts of thunderstorms on PV installations. With 27 possibly influences plants, Aachen (North Rhine-Westphalia) stand out. The distribution in Germany shows possible influences in Lower Saxony, Saxony, North Rhine-Westphalia, Hesse, Baden-Wuerttemberg and Bavaria. None of the city states is in the results.

Between 2000 and 2009 113 zip code states are registered. Memmingen (Bavaria) accounts for 587 possibly affected PV installations during that time. Again, Table 40 and Map 18 show the distribution:

Table 40: PV installations between 2000 and 2009 possibly affected by thunderstorms

Number of PV installations per ZCA	Number of ZCAs possibly affected by thunderstorms
1 - 10	18
11 - 50	30
51 - 100	25
101 - 250	30
251 - 500	9
> 500	1

Possible influences of thunderstorms on PV installations can be found in every area state except Saxony-Anhalt and Saarland. Also Hamburg and Berlin show overlappings between thunderstorms and installed capacity during said period. When a buffer of 25 km around the exact location of thunderstorms is applied, a total number of 341,000 possibly affected PV installations in the period 2000 - 2009 results. This means that about 55 % of all installed PV panels have possibly been under the influence of a thunderstorm. Moreover, now all area states show possible influences only by location.



Map 18: PV, lightning strikes and thunderstorms

4.3 Case Study – Ice Throw from Wind Turbines in Germany

Wind turbines are widely and critically discussed in Germany. Their advantages are regularly listed as the CO_2-neutral generation of electricity, the distributed generation of electricity, that wind energy is renewable and the resource is for free (not necessary to import resources). However, there are many citizen initiatives arguing against the installation of further wind turbines because wind turbines are visible over a long distances and influence scenery; they are loud, wind emergence is not regular and is insecure and wind energy plants have a strong effect on nature in general (e.g. death of birds, shading). Nevertheless, extreme weather events like cold conditions and high humidity may lead to ice accretion on wind turbines, especially on the blades. The following graph shows the development of installed capacity as well as the number of installed wind turbines in Germany between 1992 and 2010 (BUNDESVERBAND WINDENERGIE E.V. 2011, Figure 34).

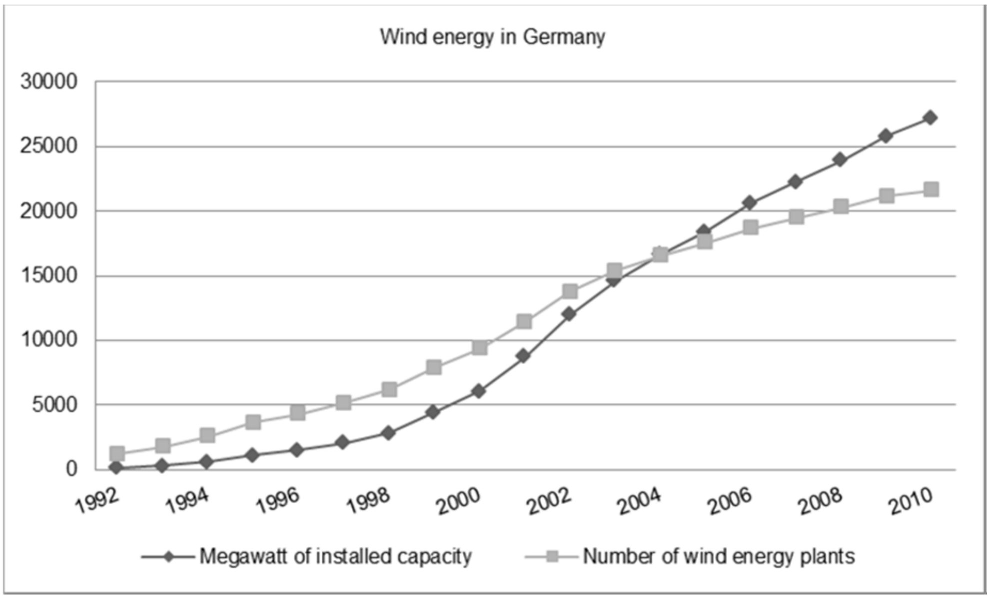


Figure 34: Wind energy in Germany. Displayed are Megawatts of installed capacity (dark grey with rhombi) and number of wind turbines (light grey with squares) for the years 1992 to 2010 in yearly time steps (data according to *GERMAN WIND ENERGY ASSOCIATION*/Bundesverband WindEnergie e.V. 2011)

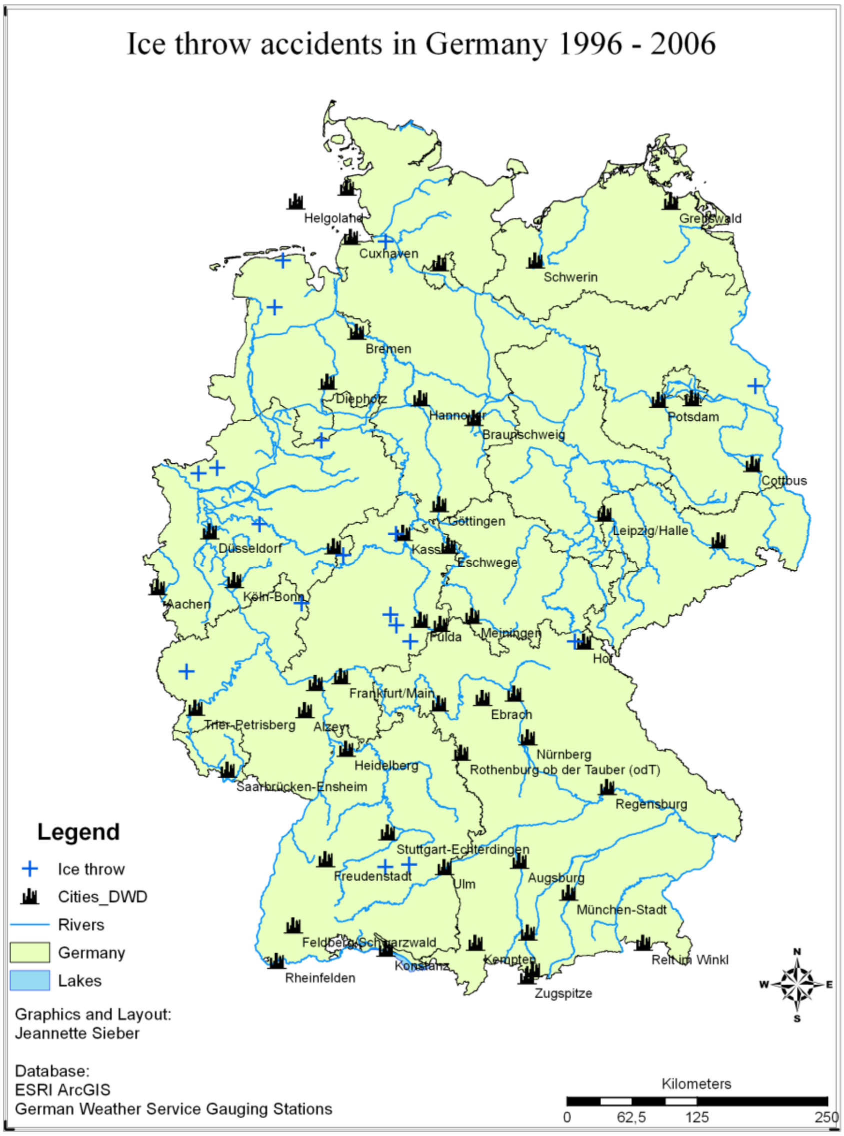
In section 4.2.2.2, the analyses of the data by CWIF (2011) and DURSTEWITZ (2003) indicated 20 reported ice throw accidents and 884 icing events listed in the "250 MW Wind"-Programme. One of the problems of ice throw accidents is that the event itself is not measured automatically but that eyewitnesses, who found thrown ice lumps, are needed.

In general, wind turbines icing may result in several potential risks: turbine malfunction, a decrease in performance and a threat to people and the built environment. A summary of the consequences includes:

- decreases in electricity generation due to (involuntary) shutdown;

- risk of blade failures induced by additional load and vibrations during rotation with ice accretion;
- malfunctions of lightning protection systems, anemometer and control systems due to freezing;
- mechanical failure due to frozen lubricants;
- falling pieces of ice and ice throw with subsequent damages to buildings and cars as well as injuries.

For a better overview on where icing conditions and ice throw were reported, the following Map 19 is generated.



Map 19: Ice throw accidents in Germany between 1996 and 2006 (according to CWIF 2011), blue crosses indicate ice throw sites

The map shows, that ice throw accidents have not only been reported at high elevations, like the Swabian Alb and the Vogelsberg, but also in the Northern German Lowlands. Ice throw accidents are well distributed over Germany. DURSTEWITZ (2003) found that even along the coast up to 20 % of all icing events were recorded, 13 % happened in the Northern Lowlands and 67 % of icing events are listed in the mountainous regions.

A coarse display of possible ice throw accidents in Germany was made by CHOLLEY (2007). Therein, the examples of Carzig (Brandenburg) and a site in North Rhine-Westphalia show radii of 100 m and 150 m for possible ice throw. The radii were taken according to the maximum reported ice throw at Guetsch, an alpine test project site where wind turbine performance under harsh conditions is monitored and analysed, and the maximum reported ice throw in Germany based on located ice fragments.

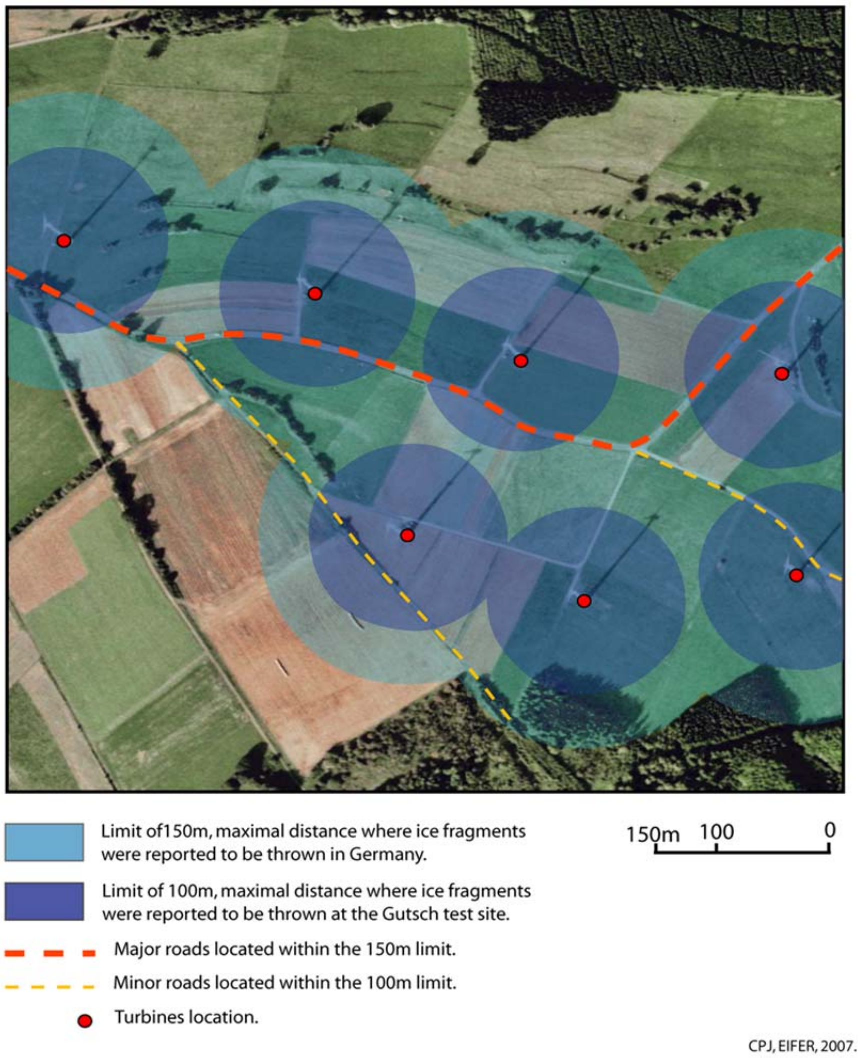


Figure 35: Spatial analysis of ice throw at the site in North Rhine-Westphalia (CHOLLEY 2007). Dark blue areas show a diameter of 100 m, light blue areas show a diameter of 150 m around each wind turbine

The first example shows that major and minor roads (respectively dashed red and yellow lines) might be affected by ice throw (Figure 35). Moreover, in the southern part of the wind energy park, forest areas might be impacted by thrown ice fragments.

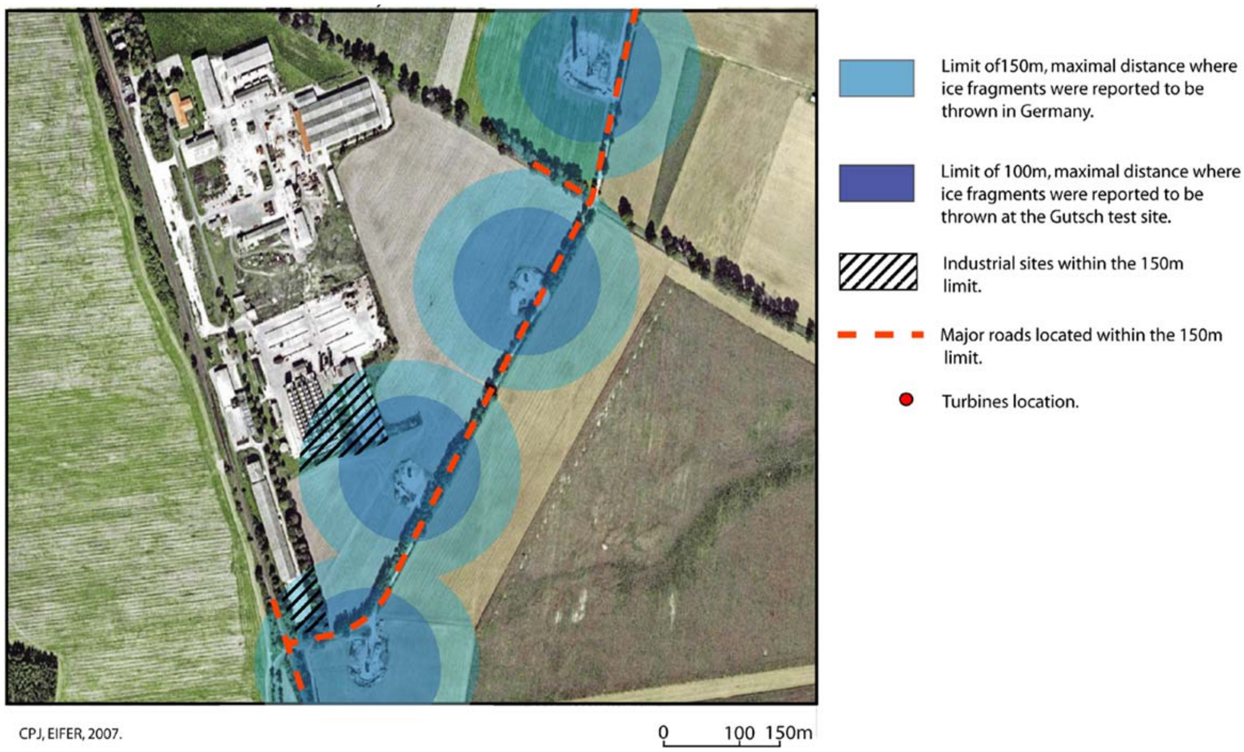


Figure 36: Spatial analysis of ice throw at the site of Carzig (Brandenburg) (CHOLLEY 2007). Dark blue areas show a diameter of 100 m, light blue areas show a diameter of 150 m around each wind turbine

The second example shows that even the inner buffer of 100 m reaches over major roads (highlighted in a red dashed line) and the outer, as well as the inner, buffer affects an industrial site nearby (hatched area) (Figure 36).

To avoid similar impacts, requirements for installing distances between wind turbines and structures should be followed. Nonetheless, there are no nationally consistent guidelines for distances to wind turbines. Only North Rhine-Westphalia and Baden-Wuerttemberg have a set of standards according to the “order for wind energy” (*Policy for planning and permission of wind turbines*/Grundsätze für Planung und Genehmigung von Windkraftanlagen 21.10.2005 STATE MINISTRY FOR BUILDING AND TRANSPORT NORTH RHINE-WESTPHALIA ET AL. 1995/2005 and MINISTRY OF THE ENVIRONMENT, CLIMATE PROTECTION AND THE ENERGY SECTOR (BADEN-WUERTTEMBERG), ET AL. 2011). Therein, the following distances to other structures are clarified (seeTable 41). As both examples show, these recommendations were not adhered to.

Table 41: Distances between wind turbines and other structures (according to the policy by the STATE MINISTRY FOR BUILDING AND TRANSPORT NORTH RHINE-WESTPHALIA ET AL. 1995/2005)

Structure and use	**Distances to wind turbines with a total height of < 100 m**	**Distances to wind turbines with a total height of > 100 m**
Single housing and settlements of up to 4 houses	300 m	3.5 * height
Rural settlements	500 m	5 * height
Urban settlements, settlements of summer cottages, camping grounds	1,000 m	10 * height
Freeways, highly frequented major roads and railways	100 m	1 * height
Major roads, country roads	50 m	1 * height
Overhead wires	50 m	1 * height
National parks, nature protection reserves and other protection areas (birds, water, dunes)	≥ 200 m, max. 500 m	4 * height minus 200 m
Forest	200 m	200 m
Water bodies (first order)	≥ 50 m	1 * height minus 50 m
Dams	≥ 300 m	≥ 300 m

A decision by the HIGHER ADMINISTRATIVE COURT OF RHINELAND-PALATINATE (2006) states that wind turbines are forbidden as soon as they pose a risk to human safety. The owner of a tree nursery went to law against a wind turbine operator because of the possibility of ice throw onto her property where employees were at risk from thrown ice fragments.

In order to avoid ice accretion and subsequent ice throw, measures like heating wires along the blades, inflatable pillows along the rim of blades and blade coating are common practice. These measures can be distinguished between de-icing methods and anti-icing methods. De-icing means the removal of ice after accretion, whereas anti-icing means the avoidance or reduction of ice accretion from the beginning (see Section 2.3.2).

A study by CATTIN (2008) lists heating inside the blades, as well as heating wires at the rim of the blades, as feasible solutions. Heating inside the blade works as follows: as soon as ice accretion is detected, the rotor is stopped. After that, warm air is blown into the blade in order to heat the whole surface. When the ice has melted, electricity generation can re-start again. The limitations of this method are that the tips of the blades might not be reached by warm air and do not heat up adequately. Moreover, warm air cannot exceed certain temperatures in order not to damage the material of the blades (mostly glass fibres). In addition, this method is rather expensive.

On the other hand, heating wires can be installed along the complete rim, which means that the blade is warmed evenly. Additional heating wires, and other heating options like sheeting, could also be installed in the blade. In doing so, resistance and flow patterns are changed, which might not always be beneficial. Both de-icing systems seem to create reductions in efficiency and are not feasible solutions.

Anti-icing measures range from simple actions like painting blades black (to absorb more heat from the atmosphere), using hydrophobic coatings (adhesion of water is reduced) and nano-coatings (including proteins against frost which reduce crystallisation of ice). Several enterprises like BASF Coatings GmbH and Clariant International Ltd. support research on anti-icing/anti-freeze coatings for wind turbines. Nevertheless, these coatings might be impacted by particles and, due to rotation and high blade speeds, might lose their effect. Long-term studies on this topic are not yet available. It should be kept in mind that such systems often do not lead to suitable results for completely ice free blades of wind turbines and should be installed in combination with other measures.

4.4. Synthesis

Section 4 highlighted the importance of renewable energies in climate mitigation concepts to reach the long-term perspective goals of maximum 2 °C global warming, 1 t/CO_2-equiv. emissions per person and year and how they integrate into the German Energy Turnaround.

The mentioned climate mitigation concepts consist of six steps where the integration of renewable energies is set in the potential analysis and in the catalogue of measures. Renewable energy planning on a regional to local level takes place through land use plans and the support of zoning and priority areas for e.g. wind turbines. At this point, the combination of adaptation and mitigation measures in enhanced climate mitigation concepts is prepared.

In the further analyses, the assessment in Geographical Information Systems shows the diversity of the impacts as well as the spatial and temporal distribution of extreme hydro-meteorological events over Germany with regard to the renewable energies of wind turbines, hydropower plants and PV installations. These distributions are not consistent but the increase of installed capacity as well as the increase in number of extreme events leads to more affected zip code areas in the period 2000 - 2009 compared to 1990 - 1999.

The case study shows that regulations on installation distances reduce the risk for other infrastructure e.g. due to the influence of ice throw. Ice throw can occur almost anywhere in Germany (which is attributed to frost and icing and heavy rain distribution). Taking into account the heavy rain events for ice throw conditions illustrates the case of two extreme events whereas already light rain might be enough for freezing on blades and the accumulation of ice depending on the site-specific situation.

Local planning therefore needs to consider standardised installation distances to protect other infrastructure. Operators of wind parks and manufacturers of larger installations need to be aware of the adaptation options like ice proof coatings, heating wires or other measure to reduce the risk of ice throw itself.

In Section 6.3, attention is paid to two examples where classical climate mitigation concepts were set up but the possible impacts by extreme hydro-meteorological events were not included for climate change adaptation. These two comparative studies reveal the gaps in the overall concepts for climate mitigation and the concentration to the reduction of emissions.

5. Corporate Risk Management and Climate Adaptation Options

Section 5 deals with corporate risk management and climate adaptation options for industrial installations and thermal power plants. Therefore, an introduction is given to corporate risk management approaches and regulations like the ISO 31 000. The case study focuses on flood risk at an exemplary thermal power plant site and the implementation of adaptation options as well as a management cycle including GIS-based analysis into emergency planning.

5.1 Background on Corporate Risk Management and Implemented Environmental Management Information Systems

Risk management for enterprises usually focuses on financial and market risks for companies. It mostly consists of risk realisation, assessment and regulation. However, legal requirements do not include the necessity for environmental or social risk implementation (LOEW, CLAUSEN & ROHDE 2011). Using the ISO 31 000 Risk Management – Guidelines for Principles risk management process as a basis, the whole approach involves the points communication and consultation, context identification including subject identification and goals, risk assessment, risk identification, risk analysis, risk evaluation, risk handling as well as monitoring and review.

A study by the sustainability rating agency imug in 2009 showed that climate change implementation in enterprise risk management is still insufficient, especially in relation to DAX-30[13] enterprises (LOEW, CLAUSEN & ROHDE 2011). In 1998, the *Corporate Sector Supervision and Transparency Act* (Gesetz zur Kontrolle und Transparenz im Unternehmensbereich KonTraG, A.U. 1998) has been legislated for stock companies as well as for limited liability companies. The Act includes the obligation on implementing a risk management system, though the term risk is not clearly defined. FIEGE (2006) addresses burglary and environmental risk as to be included according to the Act. In this study, risk management consists of the same aspects as described in LOEW, CLAUSEN & ROHDE. On the contrary, it is referred to a strictly legal point of view, which only includes early warning measures as sufficient risk management. The FEDERAL MINISTRY FOR THE ENVIRONMENT, NATURE CONSERVATION AND NUCLEAR SAFETY (2011) concludes that regulatory frameworks for risk management, for example the ISO 31 000, do not involve external risks like climate

[13] DAX is the German stock index, listing the 30 largest companies in terms of order book volume and market capitalization

change or shortage in resources to full extent. Therefore, risk management regulations need to be completed and extended by further guidelines, regulations and management systems.

Environmental management and industrial environmental management information systems concentrate on the impacts a company or site may have on the environment. In order to avoid any negative impacts on environment, companies underlie the guidelines of Directive 96/82/EC[14] (A.U. 1996) after the chemical spill in Seveso, Italy in 1976 and establish voluntary environmental management systems according to the Eco-Management and Audit Scheme (EMAS) or ISO 14001, the standard for the use of the environmental management systems. The SEVESO-II guideline names the necessity to implement measures that "*aim at preserving and protecting the quality of the environment, and protecting human health, through preventive action*" (paragraph 2). Central part of the guideline is the description of the companies under consideration as well as a detailed procedure for the safety report. Therein, the following points are addressed (SEVESO-II guideline Annex II):

- The location of the site including geographical, meteorological, geological, hydrographic and further aspects;
- The characterization of the installation, i.e. the activities, resources and products;
- The analysis of possible impacts and risks, as well as preventive actions and measures; and
- The analysis of protection measures to be installed in order to avoid future accidents.

The approach of the SEVESO-II guideline is put into practice by the 12. *Federal Immission Control Ordinance* (12. Bundes-Immissionsschutzverordnung BImSchV, A.U. 2000), the so-called *Hazardous Incident Ordinance*.

Voluntary actions are characterized by the establishment of environmental management systems according to the EMAS (*GERMAN EMAS ADVISORY BOARD*/Umweltgutachterausschuss UGA 2011) or ISO 14000 standards series[15]. The ISO 14000 standards are internationally accepted and prevalent, whereas the EMAS is named as a European alternative to the ISO 14000 standards. Integral part of ISO 14000 as well as EMAS is the preparation of an emergency plan. In this emergency plan, the avoidance of negative impacts by the site or installation on the environment is addressed. A detailed description of the use of EMAS and ISO 14001 can be found in FÖRTSCH & MEINHOLZ (2011).

[14] Council Directive 96/82/EC of 9 December 1996 on the control of major-accident hazards involving dangerous substances (SEVESO-II guidelines/Richtlinie)
[15] The series includes ten separate standards, for example on user guidelines, on definition of terms and on Life Cycle Assessment.

All of these environmental management systems have in common, that the impacts of the company, the site or the installation on the environment are addressed, whereas the impacts of the environment, namely climate change impacts or impacts of extreme weather events, are not mentioned. These impacts are considered to be unavoidable and that they need to be handled ex post. Only the SEVESO-II guidelines and associated documents address the need for preventive action. Nevertheless, these systems provide a general management cycle that allows for the implementation of preventive measures.

Industrial Environmental Information Systems (Industrial EIS) use several tools for the assessment and management of environmental information at a company site. Therein, interviews, checklists, several analyses and decision-making and display tools are implemented for an integrated approach. Such Industrial EIS should be able to determine, to regulate, to assess and to display all relevant environmental data (SOMMER 2010). Nevertheless, Geographical Information Systems are only used as an additional tool for map-making instead of using its strengths as a holistic tool in environmental management. In 2009, TEUTEBERG & STRAßENBURG conducted a literature review on Industrial EIS. They found Industrial EIS to be poorly noticed in scientific research and literature due to a considerable lack of information.

All of these approaches have several aspects in common. Usually, risk management is divided into three or four stages: (1) risk identification; (2) risk analysis; and (3) risk response (MILLS 2001, see also Sections 2.4 and 3.1). Moreover, risk management related to companies is seen as a cyclic procedure with the goal of improving the company's performance. Risk management affects every part and entity of a company so that measures and approaches must be found, which protect every level of the company (COMMITTEE OF SPONSORING ORGANIZATIONS OF THE TREADWAY COMMISSION COSO 2004). And all of these approaches combine local site information, weather parameter data and proposals for making the company more (climate) resilient, regardless of the name, for example environmental risk management, climate change risk-uncertainty-decision-making or industrial information management.

The following description of the method and data used in the work conducted here makes clear, that environmental (information) management systems for industrial activities is the basis for further research. Here, the additional benefit of using Geographical Information Systems for a complete decision-making is addressed as well as the necessity for implementing local weather and climate information in continuous measure planning.

5.2 Results of the GIS-Analyses of Thermal Power Plants

The GIS-based analyses of the influences of extreme weather events on thermal power plants follows the same structure and rules as the analyses on renewable energies as described in section 4.2.

Thus, the extreme weather data and the data of thermal power plants (oil-, gas- and coal-fired as well as nuclear facilities) were mapped in the Geographical Information System ArcGIS® by ESRI Inc. According to Table 2, where the influences of extreme weather events on the electricity generating option were identified, each type of power plant is spatially joined with the extreme weather data. Additional pictograms for these analyses are listed in the following Table 42.

Table 42: Other pictograms and icons used in the mapping

Item	Pictogram or icon
Thermal power plants	 building stock brown
Nuclear power plants	

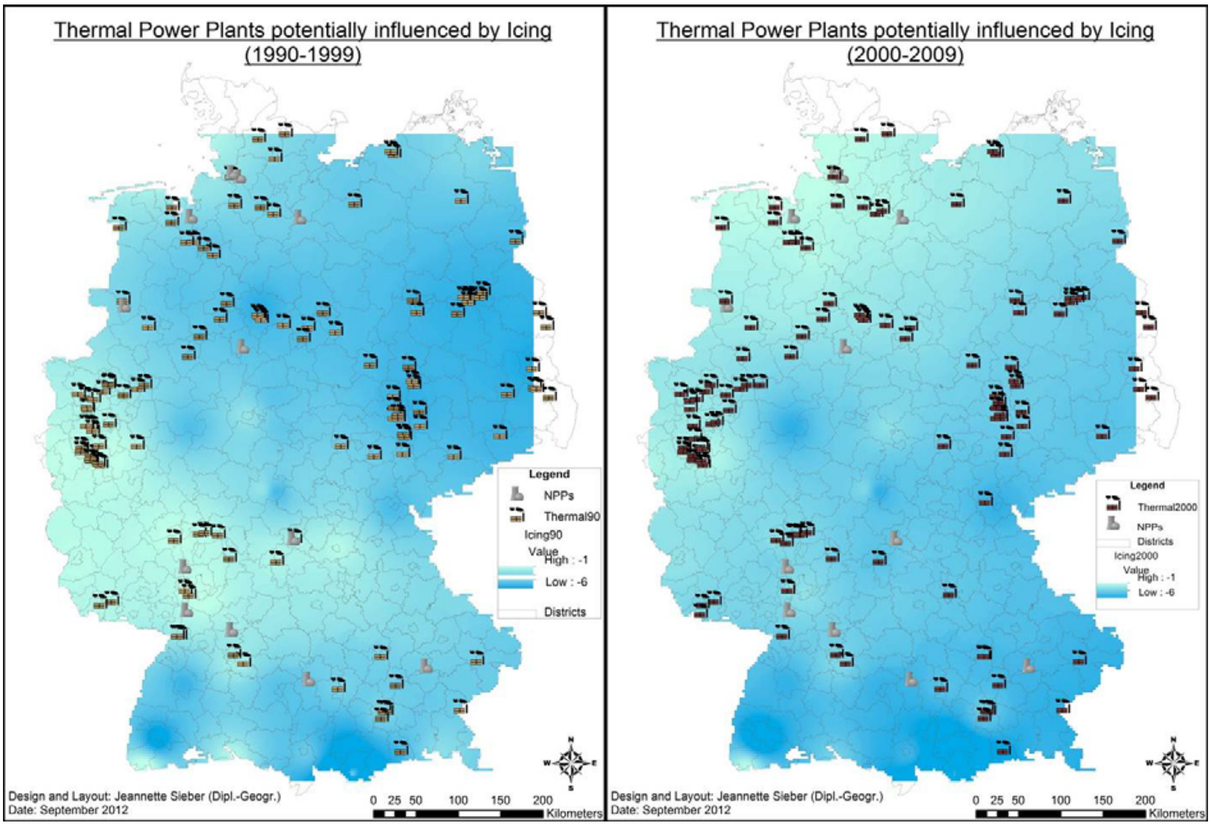
For thermal power plants no difference was made in time slides as only few power plants were affected by extreme events.

5.2.1. Air Temperatures

Air temperatures have an overall effect on thermal power plants (e.g. reduction of Carnot efficiency, weathering of building structure). As thermal power plants all over Germany are affected by high or low air temperatures, only few differentiations can be made concerning spatial distribution. The influences of high or low air temperatures are reflected in daily or even hourly feed-in of electricity. However, changing air temperatures affect thermal power plants often indirectly, that means the influence of changing water temperatures has a bigger effect than air temperature alone. In this section, the icing, frost and heat days are displayed together with the interpolation results of the IDW.

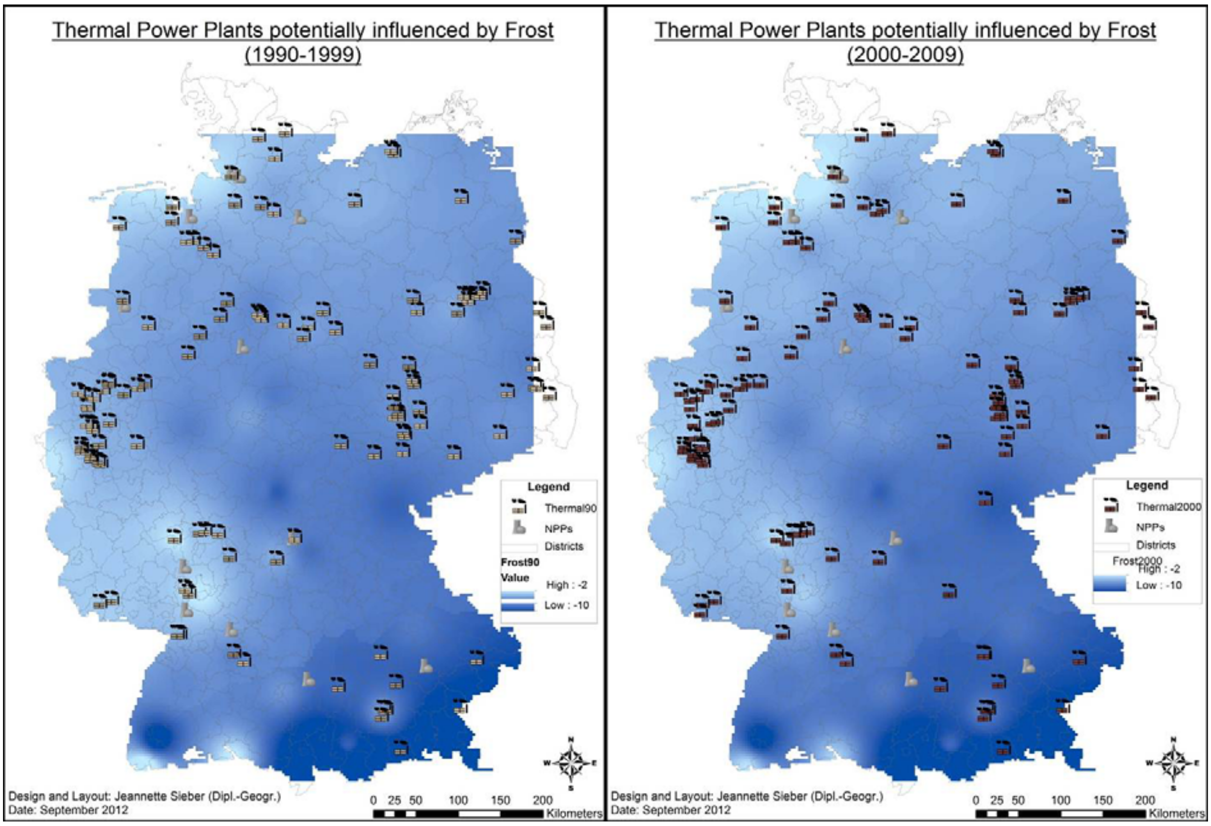
Map 20 shows the icing conditions in the years 1980 to 2009 interpolated with the IDW in Germany and their possible impacts on thermal power plants due to spatial overlapping. Every monitoring station has experienced icing days in the chosen time span. Measured temperatures for icing conditions range between -28.9 to 0 °C. The IDW for the time frame 1990 - 1999 shows a temperature range between -1.76 and -5.57 °C. Extreme cold conditions only occur in a few regions of Germany, for example in the Leine valley, around Potsdam, Berlin and Leipzig as well as around some Central Uplands such as the stations

Kahler Asten, Feldberg/Black Forest and Wasserkuppe. Also the districts Upper Allgäu and Garmisch-Partenkirchen show a high density of icing days between 1990 and 1999. Relatively warm regions, on the contrary, are between Cologne and Aachen, the Rhine-Main area and the Main valley. Also Munich and most parts of Rhineland-Westphalia seem warmer in this period. In the time slide 2000 - 2009, the IDW shows a temperature range between -1.15 and -5.96 °C. The regions with the most icing days are again the Central Uplands of Kahler Asten, Wasserkuppe and Schwarzwald. Now there is a clear grade in temperatures from the colder southern Germany to the warmer northern Germany. Cities such as Stuttgart, Munich and Cologne still are warmer than the surrounding rural areas. The most affected would be coal-fired power plants with coal stockpiles where freezing can occur.



Map 20: Thermal power plants (TPPs) and icing conditions

The frost day distribution shows temperatures between -2 and -10 °C in the time span 1990 - 1999. The coldest regions are southern Bavaria and the Central Uplands of Kahler Asten, Wasserkuppe and Feldberg/Black Forest. The warmest regions are around Lake Constance, Heidelberg, Mainz, Aachen and the regions of East Frisia and the North Sea Coast. In the time frame 2000-2009, temperature range has changed to -2.39 and -8.56 °C. However, the distribution in Germany is almost the same, except that the district Hof stands out as another cold region (Map 21).

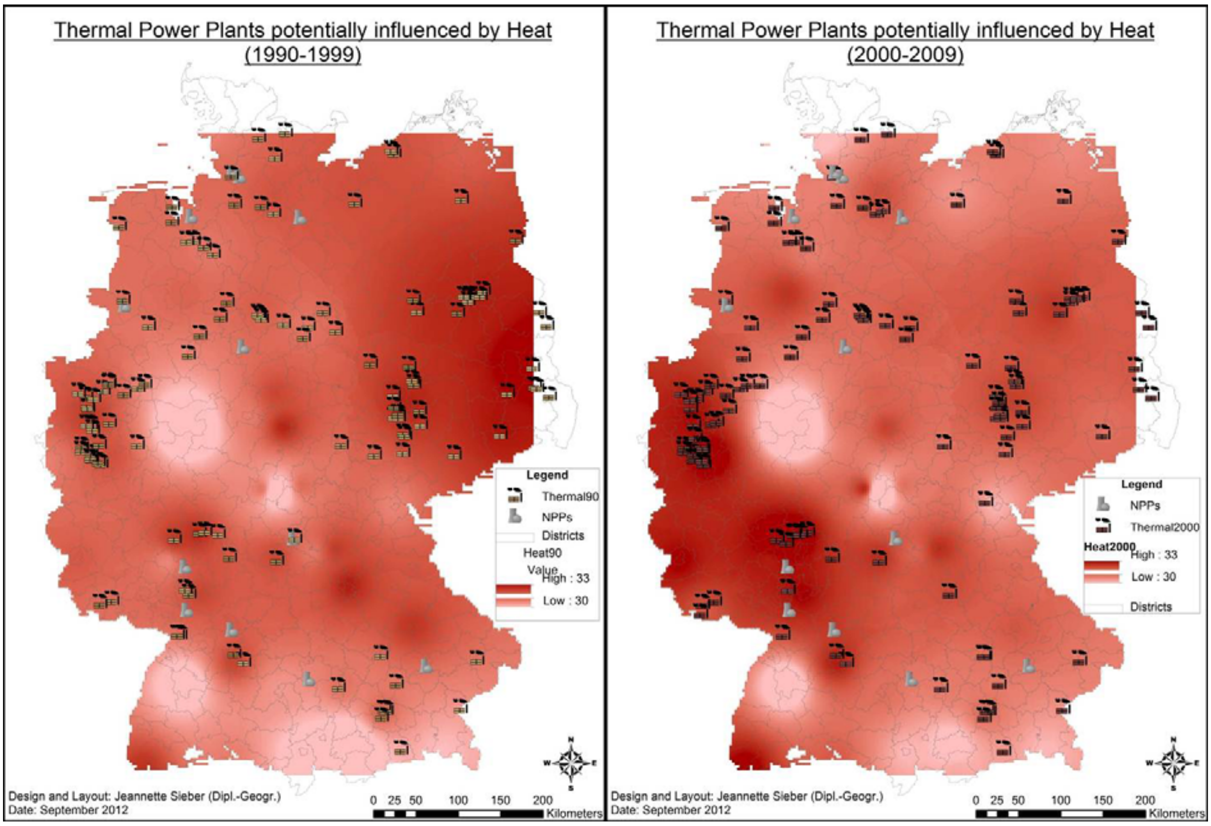


Map 21: TPPs and frost conditions

Even though summer days are not used for further analyses, the distributions in the time slides 1990 - 1999 and 2000 - 2009 are described here.

In the time span 1990 - 1999, temperatures ranged between 25.00 and 27.3 °C. The relatively coldest regions were the Central uplands of Feldberg/Black Forest, Wasserkuppe, Kahler Asten and in the regions Kempten, Hof, Western Pomerania and along the North Sea Coast. Warmest regions, on the contrary, are on an axis between Aachen, Frankfurt and Regensburg along the rivers Rhine, Main and Danube, as well as around Berlin and Potsdam and around Schwerin. Also the Lake Constance region was warmer than the surrounding regions.

Regarding the period 2000 - 2009, temperatures ranged between 25.47 and 27.32 °C – slightly warmer than the time frame 1990 - 1999. The coldest regions again were the Central Uplands of Feldberg/Black Forest, Wasserkuppe and Kahler Asten. Also the districts Aurich, Frisia and Wittmund appear rather cold. In contrast, the Main and Danube valley were relatively warm, also a triangle between Leipzig, Dresden and Cottbus. Another warm spot on the map is again Schwerin. The following Map 22 contains the illustration of heat day distribution.



Map 22: TPPs and heat conditions

The time slide 1990 - 1999 shows the hottest days in Brandenburg followed by Nuremberg, Eschwege, Frankfurt and Regensburg. In contrast, the relatively coldest regions are in the southern part of Germany, especially in the Allgäu and the districts Freudenstadt and Ortenaukreis. Other cold regions in Germany can be found around the Central Uplands Kahler Asten and Wasserkuppe. Temperatures ranged according to the IDW interpolation between 30.25 and 32.40 °C. Taking a closer look at the time slide 2000 - 2009, temperatures ranged between 30.6 and 32.42 °C in the IDW interpolation. The hottest regions shifted to the western part of Germany, namely Rhineland-Westphalia, Saarland and parts of Northrhine-Westphalia alone the Rhine valley. Also some of the hottest regions were the districts Breisgau and Lörrach. Those are followed by Brandenburg and Saxony-Anhalt. Again, in contrast, the coldest regions were around the Central Uplands of Kahler Asten and Wasserkuppe, around Freudenstadt and in the northern part of Germany, in the district of Dithmarschen.

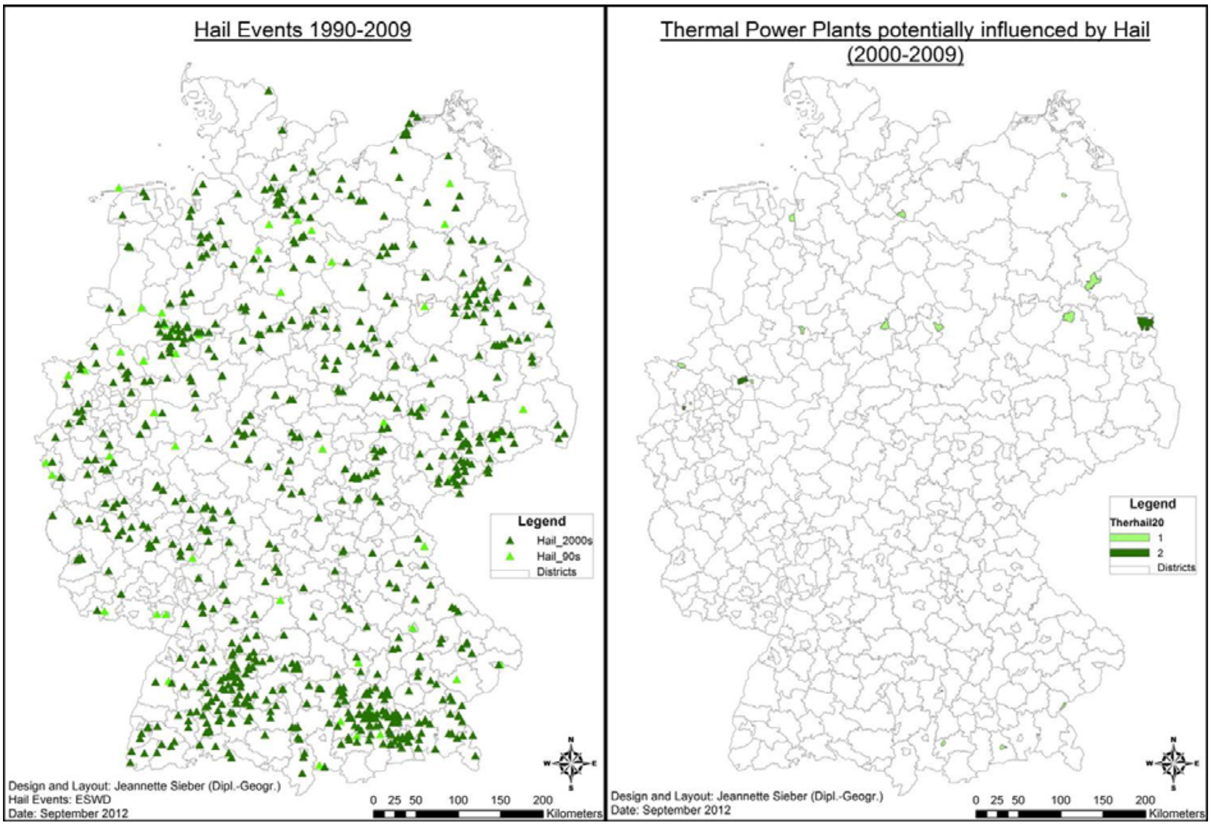
Heat days or even heat periods may have greater impact on power plant performance than summer days, mostly due to rising water temperatures and loss of cooling power. During heat days, the maximum air temperatures exceeds 30 °C, projected on water temperatures, even the thresholds for cyprinid (max. 28 °C, temperature rise max. 3 K) and salmonid (max. 21.5 °C, temperature rise max. 1.5 K) water bodies may be exceeded. Moreover, high air temperatures may lead to spontaneous combustion in coal stockpiles and even lead to a complete burn down of the coal reserves.

5.2.2 Precipitation-related Events

Thermal power plants are affected by hail and heavy precipitation. In this context, heavy precipitation can mean heavy rain as well as heavy snow, depending on the air temperatures. Therefore, two map clusters are shown: the first one contains hail events (Map 23). The second map cluster contains all heavy precipitation events measured, regardless of the air temperature (Map 24).

In the whole period between 1990 and 2009, hail events seem to occur all over Germany, so every thermal power plant might be subject to hail stone impact. In this case the analysis was conducted only for the period 2000 - 2009 and the hail events as well as the thermal power plants in said period. During the analysed time frame either one or two power plants were possibly influenced per zip code area. Affected power plants can be found in Schleswig-Holstein, Mecklenburg-West Pomerania, Brandenburg, Lower Saxony, North Rhine-Westphalia and Bavaria.

Hail usually leads to damages on the building structures, which counts as weathering and not as the impact of extreme weather in this context. Nevertheless, weathering has an influence on building covers and investments may be necessary for a more stable building cover to avoid damages by extreme weather events.

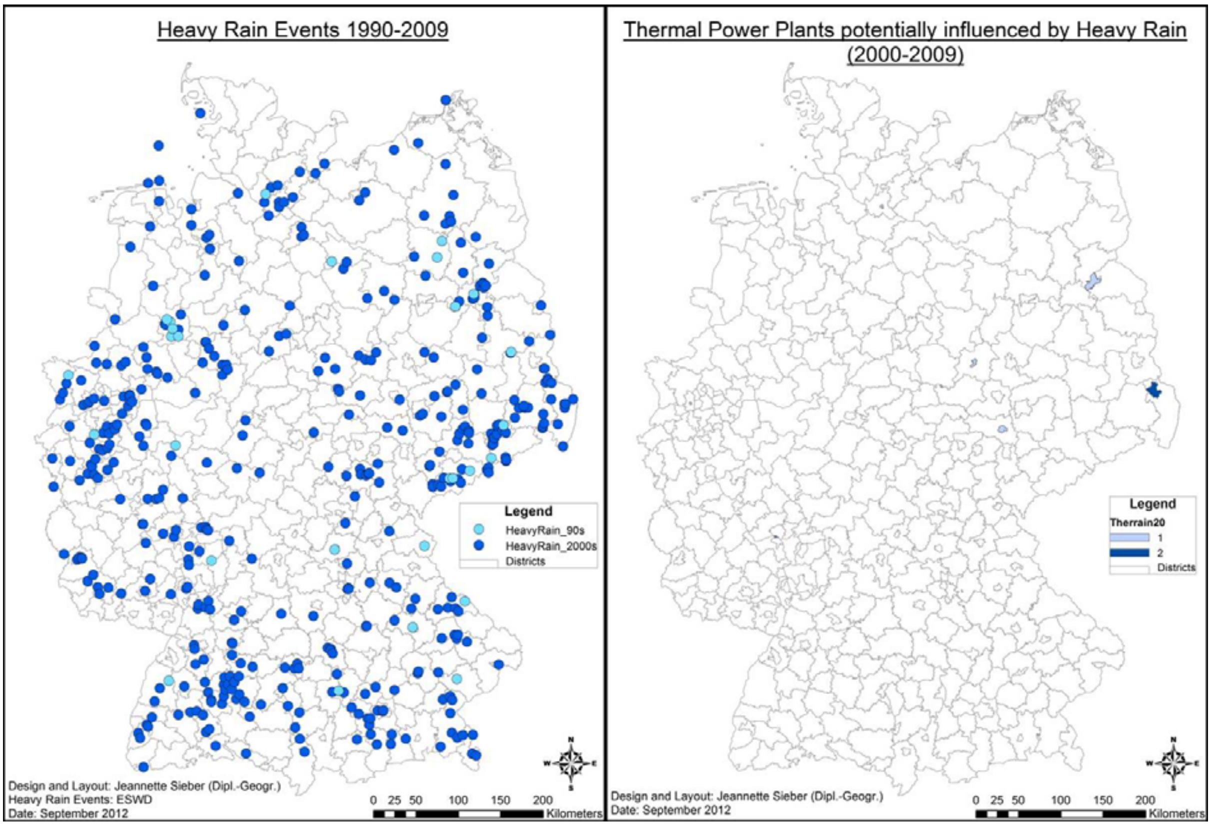


Map 23: TPPs and hail events

Just like hail events, heavy rain events are distributed rather evenly over Germany. Nevertheless, power plants in Hamburg, North Rhine-Westphalia, Saxony-Anhalt, Saxony, Brandenburg and Rhineland-Palatinate were possibly most affected in the period 2000 - 2009.

Extreme precipitation events were measured especially in highly populated urban areas, like the Rhine-Ruhr area, Munich, Rhine-Main area and Hamburg respectively in highly equipped areas like Leipzig-Halle agglomeration. A reason for this might be a high density of the monitoring network and the interest of infrastructure protection, which leads to an increased attentiveness of the population.

Snow events might influence the accessibility of the power plant site so that shift work is hindered or the on-site security is impaired. Moreover, snow and freezing temperatures can lead to a blockage in the water intake of the cooling system for thermal power plants. Even worse might be ice jam on the water body, blocking the cooling water intake completely. Besides direct damages, snow events are likely to have an impact on the operation and the efficiency of the power plant. Freezing temperatures in concurrence with rain can lead to freezing of coal stockpiles and therefore limited practicability of the resource.



Map 24: TPPs and rain

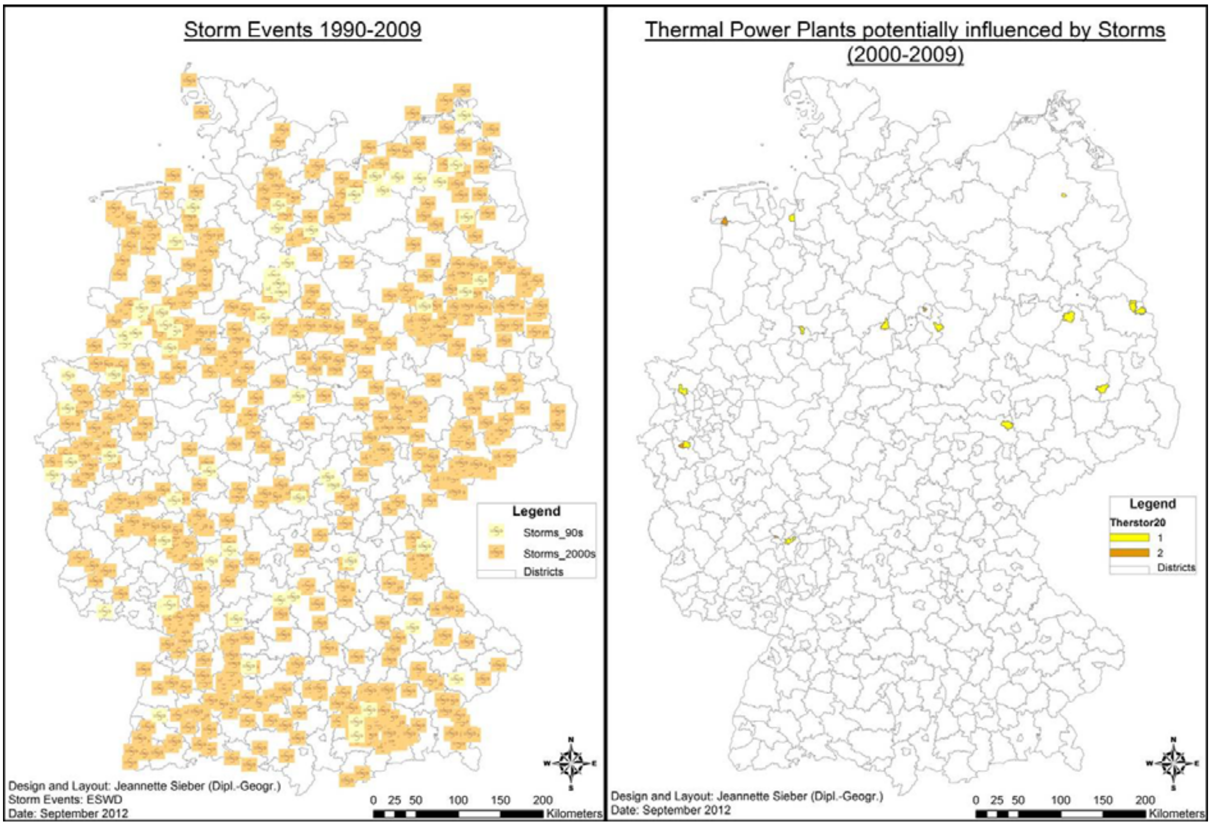
Events of extreme precipitation may lead to damages of the building structures, to flooding due to an overloaded drainage system of power plant sites and especially in the case of coal-fired sites, to an increased erosion of particles from coal stockpiles.

5.2.3 Wind-related Events

In this section, the events of severe wind gusts and tornadoes and their spatial influence on thermal power plants is shown. Map 25 therefore contains thermal power plants and severe wind gusts in the range of storms.

In the period 2000 - 2009 18 zip code areas with thermal power plants located have possibly been under the influence of storms. Again, one or two thermal plants were simultaneously affected. Thermal power plants most exposed to the influence of storms are situated in the states of Lower Saxony, Mecklenburg-West Pomerania, Brandenburg, North Rhine-Westphalia, Hesse, Rhineland-Palatinate and Saxony-Anhalt but also in the city state Berlin.

Severe wind gusts can lead to damages on the building stock, overhead wires as well as towers (insulation) and cooling towers. Moreover, storage tanks and coal stockpiles can be negatively influenced. Damages at thermal power plants are due to affected overhead wires, erosion of coal stockpiles and effects on building structure.

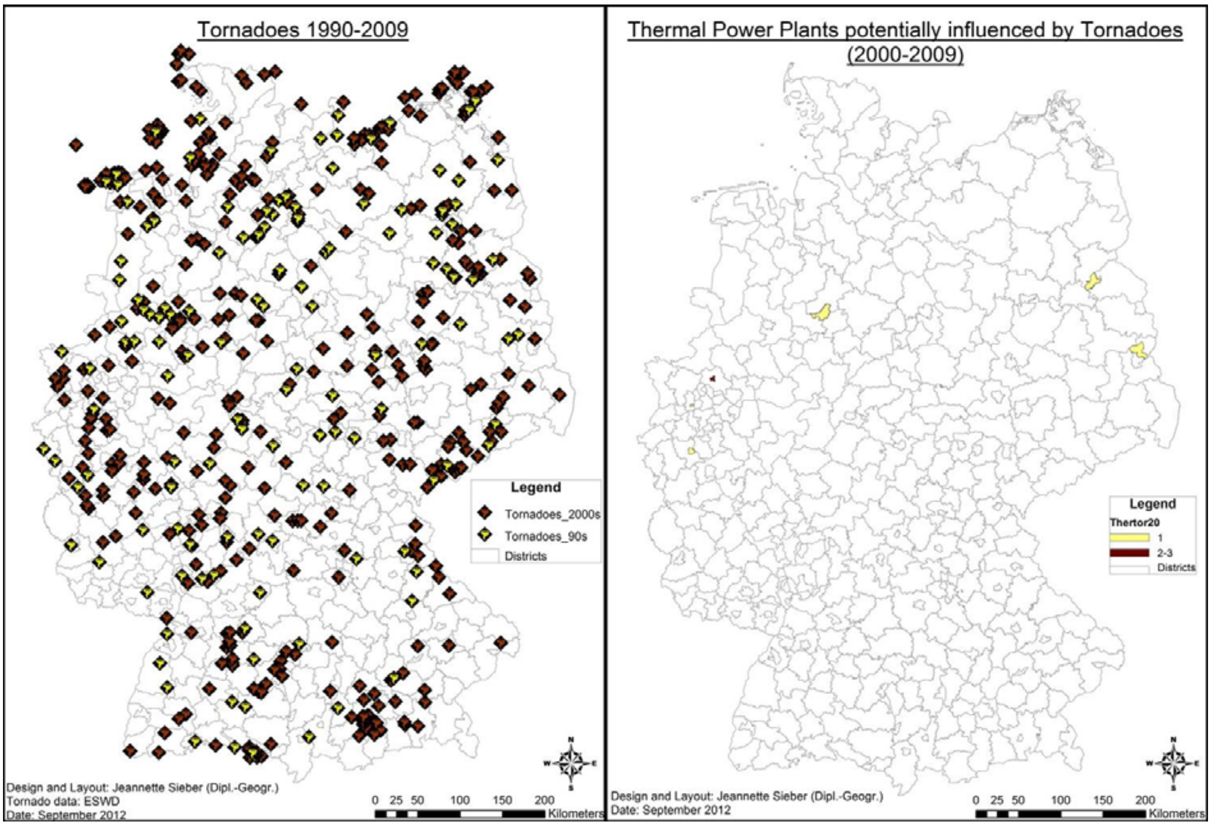


Map 25: TPPs and severe wind gusts

Map 26 on the other hand contains tornado events. They may have the same impacts on the structures but are nonetheless more destructive than severe wind gusts as they have higher wind speeds starting at 17 m/s (F0 on the Fujita-scale) going up to more than 142 m/s. Moreover, the temporal distribution of tornadoes is shown in two divisions of 1990s events (yellow) and 2000s events (orange) to gain an overview on the temporal changes of the number of events.

The number of tornado events rose in the periods 1990 - 1999 (yellow) and 2000 - 2009 (orange) from 137 to 409 events per decade. Nevertheless, the occurrence stayed well distributed all over Germany. Usually tornadoes develop in the warm summer season when significant differences in the air temperature occur. At the same time, demand for electricity is high due to cooling needs so an impact of tornadoes on thermal power plants might lead to reduced feed-in in the electricity network.

In the period 2000 - 2009 seven zip code areas were affected. This time, one or three thermal power plants were under influence at the same time. Marl (North Rhine-Westphalia) counts three possibly affected thermal units. Moreover, Lower Saxony, North Rhine-Westphalia and Brandenburg encountered effects of tornadoes on thermal power plants.



Map 26: TPPs and tornadoes

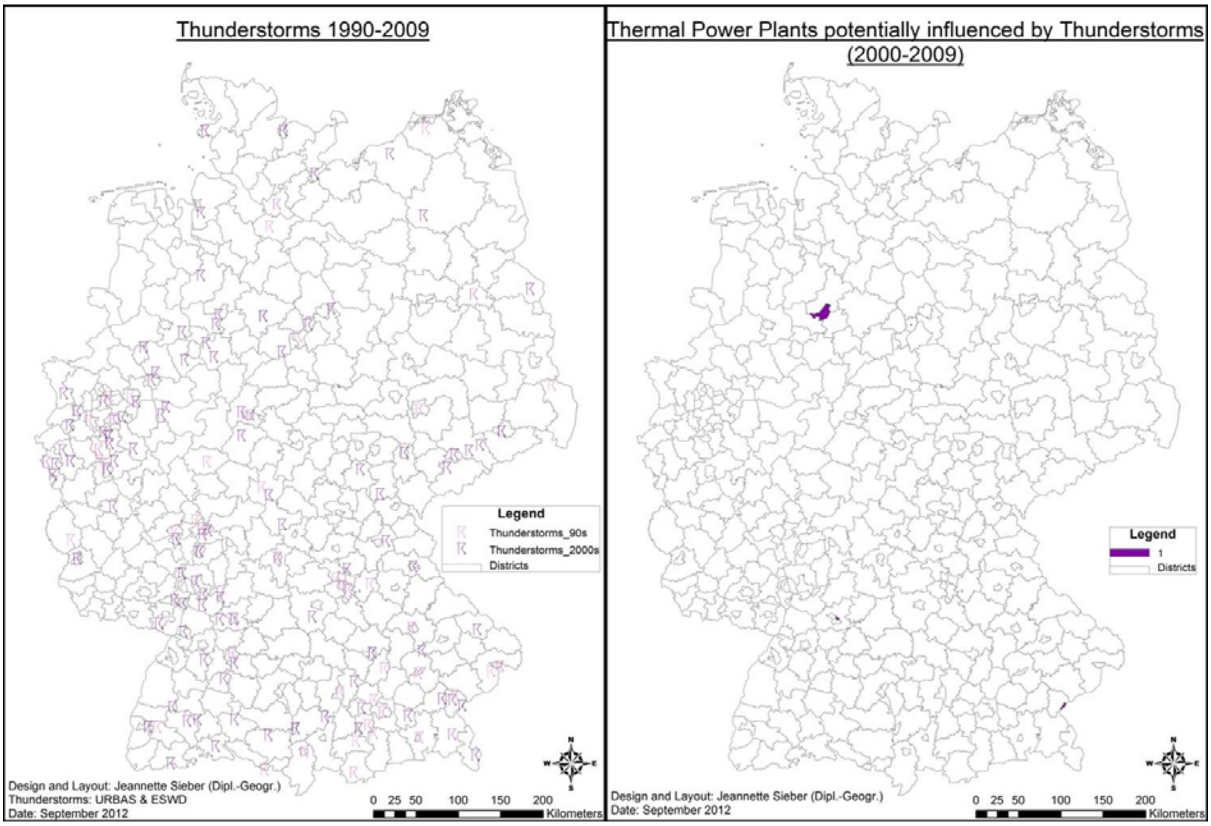
5.2.4 Combined Events

For the period 2000 - 2009 four thermal power plants have been under the influence of thunderstorms related to zip code areas. Possibly affected thermal power plants can be found in Lower Saxony, North Rhine-Westphalia and Baden-Wuerttemberg.

Extending the effects of thunderstorms to a diameter of 25 km, the number of possibly affected thermal power plants increases to 122 power plant sites with a total of 153 units. These affected power plants are situated in the area state Lower Saxony, Brandenburg, North Rhine-Westphalia, Saxony-Anhalt, Saxony, Hesse, Thuringia, Baden-Wuerttemberg, Bavaria and Rhineland-Palatinate. But also, in the city states Hamburg and Berlin influenced units are displayed.

The thunderstorm and lightning map for thermal power plants shows that not all conventional thermal or nuclear power plants experienced those extreme weather events (Map 27). Nevertheless, events could have occurred but were not registered or events might have had effects on the network structures and therefore influenced those power plants by secondary effects. On the other hand, lightning events seem more common in urban and highly equipped areas, e.g. the Rhine-Ruhr region, the Rhine-Main region, Berlin and Munich.

Concerning floods and flash floods, the single point information is kept as such. Unfortunately, the URBAS database contains information on the cities of occurrence of extreme events but neither coordinates nor the gauging station for flood measurement. Therefore, the spatial information was transformed into coordinates, and even then, not always in accordance with river information. The flood and flash flood information has not been commented upon, and only the tables for the occurrence are given as additional information.



Map 27: TPPs, lightning and thunderstorm events

In the period under investigation, two districts suffered from the impact of flood events on thermal power plants. These are Rostock (Mecklenburg-West Pomerania) and Braunschweig (Lower Saxony). Moreover, the same districts were most possibly affected by flash floods in the period 2000 - 2009.

For conventional thermal power plants no thresholds concerning flood protection level are obligatory but most operators base their protection level according to the VDI-guideline No. 6004-1 "Protection of Building Services – Flood – Buildings, installations, equipment" (ASSOCIATION OF GERMAN ENGINEERS 2006) . Here, it is suggested that installations should be constructed at least +0.5 m above the design flood level. The design flood level is described as the flood level which is to be expected in case of construction dependent on the type of construction work. That means, a nuclear power plants needs to withstand a 10,000-year flood[16] (KTA 2207 GERMAN NUCLEAR SAFETY STANDARDS COMMISSION 2004) whereas other installations only need to withstand a 100-year flood (e.g. conventional thermal power plants). Dams in Germany also underlie a design water level of 10,000-years.

5.3 Case study - Flooding of Thermal Power Plants in Germany as an Example for Corporate Risk Management

Most thermal power plants are built along rivers due to their need of large amounts of water for cooling purposes. This can turn into a disadvantage during high water levels or floods. Power plants are critical infrastructures because telecommunication and many other industries and infrastructures depend on electricity. Thermal power plants located alongside rivers as well as coastal sites may be at risk of flooding due to high water levels and, at the same time, high wind speeds (e.g. cyclones or monsoons). Moreover, an increase in sea levels in relation to climate change can be hazardous to electricity generation (Stern in FEENSTRA ET AL. 1998). Efficiency and the physical infrastructure are affected by flooding as well as by increased sea levels (PARKPOOM, HARRISON & BIALEK 2004). According to RADEMAEKERS ET AL. (2011) about 55 % of Europe's electricity production is derived from the burning of fossil fuels. This indicates the vulnerability of electricity production to the influence of flooding.

Flooding can occur after heavy rainfall when water drainage is overloaded. Usually, rainfall is considered during the planning phase only up to the probable maximum precipitation (PMP) in which a tempo-spatial relationship of rainfall in a set timeframe is exceeded. This worst precipitation event at, or near, a site is referenced in drainage design (YEN 1988).

In this example, flooding is due to high river water levels. As previously described, the protection level for conventional thermal power plants is a 100-year event as recommended by the VDI-standard 6004-1. Nuclear power plants, on the other hand, should be protected against a 10,000-year flood event (KTA 2207 GERMAN NUCLEAR SAFETY STANDARDS COMMISSION 2004). The threshold for conventional thermal power plants can easily be exceeded.

The 2002 and 2006 floods along the River Elbe, the 1997 floods along the River Oder and the 1993, 1995 and 1999 flooding of the River Rhine demonstrated the need for power plants to adapt to flood situations in general. Due to the changing climate, air temperatures and precipitation are expected to increase in Germany, the latter especially in winter

[16] 10,000-year floods are also called a once-in-10,000-years event, the probability of occurrence is one event in 10,000 years

(FEDERAL ENVIRONMENTAL AGENCY/UBA 2007). Due to the direct influence of increasing precipitation on river runoff, higher and more frequent flooding is expected (MOSER 2006). The German research group KLIWA (climate change and consequences for water management) initiated a research project on 158 gauging stations in Bavaria and Baden-Wuerttemberg. There was no observed change in average runoff, but more frequent floods have occurred during the winter season over the last decades. One explanation could be a seasonal shift in heavy precipitation from summer to winter months (RESEARCH GROUP KLIWA 2002). Based on climate projections and the resulting change in runoff, the co-operation project "climate change and consequences for water management." The research group KLIWA decided to put on a climate change factor which describes a climate-induced extra amount for planning tasks. In order to plan flood protection measures, a so-called design water level or design flood is calculated. It is the highest water level to be expected for certain regions and over a specific return period. For example, the design water level for the River Rhine for a 100-year flood needs to be multiplied by 1.15 which means that the new design water level would be 4.6 m instead of 4 m. This climate change factor is specific to different regions in Southern Germany (RESEARCH GROUP KLIWA 2006). Ratings for existing, as well as planned power plants, need to take the climate change factor into account in order to adapt for future flooding. This means that design specifications for flood protection need to be revised. Since precipitation will increase in winter, the hazard of flood situations will increase on average as well. When applying the climate change factor to design floods, the amounts of runoff associated with certain return periods, or recurrence intervals, will also rise (RESEARCH GROUP KLIWA 2006; Table 43).

Table 43: Overview of the climate change factor for runoff changes in Baden-Wuerttemberg. The most relevant return periods of HQ_{100} and HQ_{1000} are highlighted light grey (according to LfU 2005 in RESEARCH GROUP KLIWA 2006). The factor separation into five groups represents different regions with similar characteristics. There is no specific region code for the Upper Rhine valley, but the surrounding areas equal region code 2

T [years]	**Climate change factors**				
	1	2	3	4	5
2	1.25	1.5	1.75	1.5	1.75
5	1.24	1.45	1.65	1.45	1.67
10	1.23	1.4	1.55	1.43	1.6
50	1.18	1.23	1.25	1.31	1.35
100	1.15	1.15	1.15	1.25	1.25
500	1.06	1.03	1.0	1.08	1.05
1000	1.00	1.00	1.00	1.00	1.00
For annualities > 1,000 years the factor will stay 1.00					

Protection against flooding can never be standardised because thermal power plants are built on different terrain levels and each individual site, whether conventional thermal or nuclear, has different requirements. Therefore, the calculation of flood protection measures must take the return period into account, or estimated interval between floods, at a specific site. For example, the height of a dike is calculated using the design flood and the so-called freeboard, the vertical difference between design flood level and dike top (DIN 19 712 GERMAN INSTITUTE FOR STANDARDS/Deutsches Institut für Normung e.V. DIN 1997). The application of this method to site-specific risk management is described in the following Sections 5.3.1 and 5.3.2.

5.3.1 Site-related Approach

The first step in the site-related approach to flood protection is to identify the problem itself (“Do”). This identification encompasses the direct and indirect influences of high water levels on the power plant structures listed in Table 44 and Table 45.

As soon as a power plant operator recognises the possible exposure to a hazard, in this case to floods, the initial steps in the planning process should be to take a critical inventory of all existing, as well as missing, protection measures and plans. If the identification reveals gaps in protection, the following step is research, compiling a comparison of risks, an estimate of risks as well as an evaluation of perception (“check”). These perceptions are part of developing an emergency management system as well as supplying temporary protection measures (“Act”). The subsequent step contains the equipment acquisition, the training of staff and the implementation of the emergency plan (“Plan”).

Table 44: Overview on elements of thermal power plants, direct and indirect influences of flood water. Specific influences on conventional thermal power plants

Structure	Direct influence	Indirect influence
Conventional thermal specific		
Coal transport/storage and distribution	Stockpiles flooded, erosion of particles	Accumulation of hazardous substances in coal, coal particles in water may accumulate and contaminate areas downstream
Chimneys	Erosion of shell, damages to substance	Collapse of tower/chimney due to pressure
Facilities for waste and by-product treatment	Intrusion of water, damages to substance	Contamination of areas downstream when eroded, wetting of hazardous substances in case of wrong storage

Table 45: Overview on general elements of thermal power plants, direct and indirect influences of flood water

Structure	Direct influence	Indirect influence
General elements of thermal power plants		
Buildings (offices, recreation)	Intrusion of water Damages to substance Damages to interior	Contamination due to mud as well as hazardous substances
Access roads	Overflowing	No access to power plant Difficult to evacuate
Cooling tower	Flooding of cooling tower pond to avoid its floating	Contamination due to hazardous substances
Reactor/Boiler	Intrusion of water	Contamination due to mud as well as hazardous substances
Storage rooms	Intrusion of water	Wet protection measures Wetting of hazardous substances in case of wrong storage
Security places	Intrusion of water	Difficult to evacuate Contamination due to mud as well as hazardous substances
Cooling water intake and discharge structures	Overflowing Damages to structures due to collision with objects	Blockage with objects
Switchyard	Intrusion of water	Underground cables damaged

5.3.2 GIS-based Approach

The GIS-based approach as described in Section 3.1 starts with planning a general structure for the management process, data requests and background research ("Plan"). A GIS-structure consists mostly of the original data, tables, processed data and the output. Within this structure, the layers for a GIS are prepared, the data sources are combined and compared and afterwards – if necessary –uncertainties are calculated ("Do"). Therefore, all available data from the Digital Elevation Model and site-specific data, constructions and other buildings, necessary to calculated design water levels are collected. To calculate the actual state and the target, the design water levels are displayed within the GIS, first by simply creating a layer of one polygon with the specified height of the water level over the terrain. Through an overlay of the Digital Elevation Model, site-specific data and the "water layer" a simple overview of dry and flooded areas is produced. In a second step, real water depths can be calculated within the GIS. To complete an analysis, different water levels that result in adaptation measures at the site and are defined in the operation manual, are displayed and analysed with regard to possible consequences to and damages of constructions and the operating process ("Check"). In case of an incomplete operation manual, water level increases of about ten centimetres from the lowest to the highest possible water level are a reasonable alternative. For process-oriented management, plans and manuals need to be clear and easy to understand. Within the GIS, emergency plans that meet these needs can be prepared and transported to the staff. The output of the comparison can be displayed digitally as well as transferred into an analogue form that is available in case of a total blackout (“Act”).

To combine the site-related and the GIS-based approaches, the steps of the general “Plan-Do-Check-and-Act” approach are applied in the following order (Figure 37):

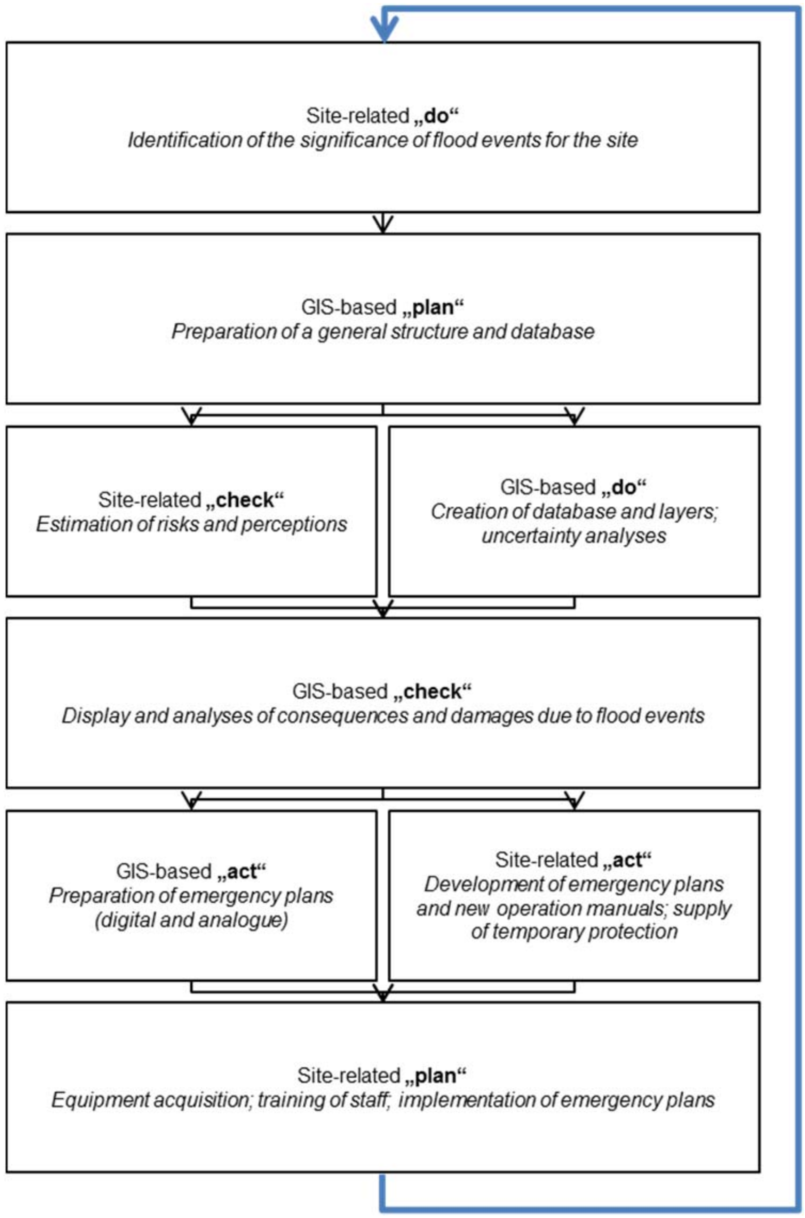


Figure 37: Application of the planning process cycle “plan, do, check and act” on the combined GIS-based and site-related approach. After the site-related “plan” the circle again continues with the site-related “do” in order to achieve a feedback loop in emergency management

Here, the two planning process cycles are combined and run in parallel. As described before, a site-related approach starts with the identification of the significance of a flood event for a site under consideration. The GIS-based approach enables the preparation of a general structure for which mapping and consequence assessment data are needed. Some of this data is readily available and some (hydraulic and hydrological calculations) will need to be generated. Thereafter, site-related risk and perception checking will run in parallel with the GIS-based creation of databases, layers and an uncertainty analysis. The following steps involve the display of data and analyse of the consequences of, and damages from, the flood event. Here, consequences mean an identification of buildings and structures affected by flood water. This is a step can be conducted by an optical map overview but the GIS can offer additional data such as clear identification clippings and calculations of distances. Potential damages might be assessed by combining spatial information on buildings and structures with interior values. Inundation heights in the buildings could be identified by comparing information on ground level elevation and flood heights in the same area. The level of detail highly depends on the available information. As this information is classified as confidential, the analyses during the research need to stay superficial.

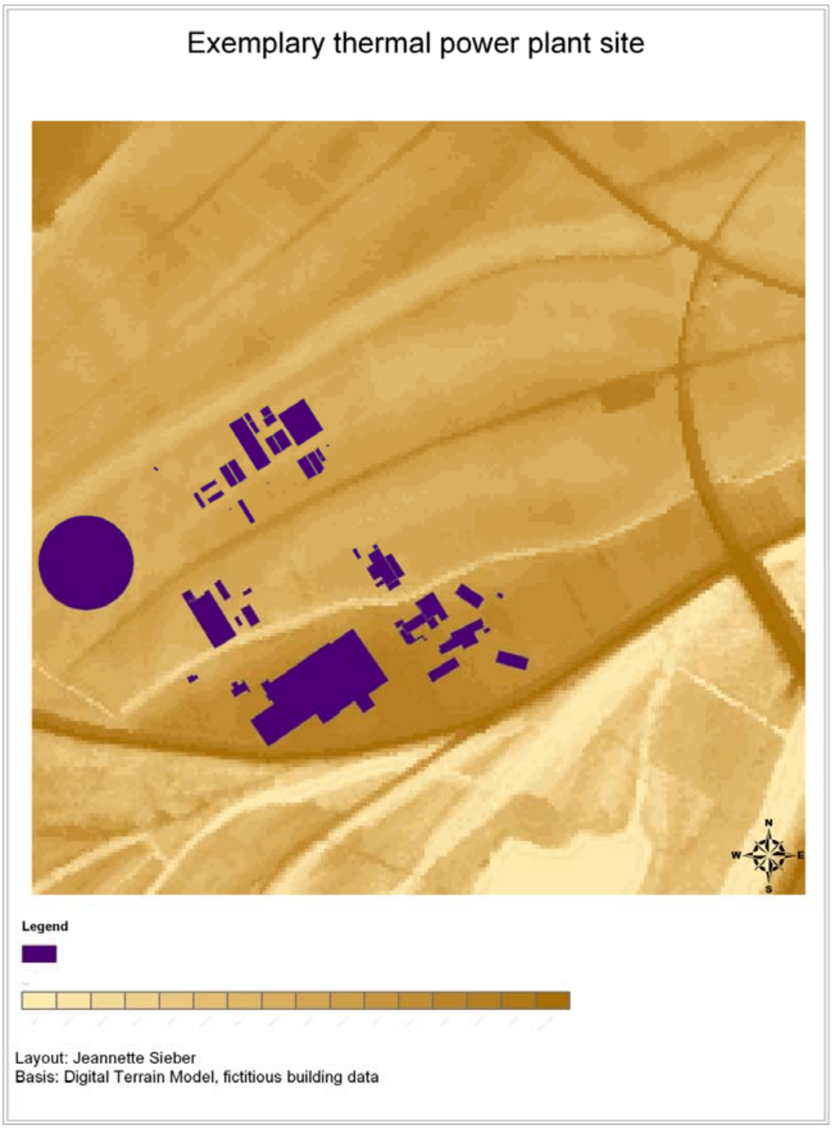
These five steps lead to the “Act” phase in which emergency plans are created in the GIS using all possibly accessible information. The maps for emergency management need to be digital and analogue in case flooding or another extreme weather event affects the IT systems or the administrative buildings. Another proposal by decision-makers is putting copy emergency plans in other locations or in a separated administrative department. Simultaneously, the site-specific emergency plan and operation manual need to be revised and, if identified, missing or additional temporary or fixed protection measures should be supplied. After this, the staff must be informed and trained according to the new plans, operations and procedures for a flood event. The long-term acquisition of protection measures occurs during this last phase.

A continuous update of this planning process occurs when the cycle begins again with the identification aspect. If a flood occurs at the site after the implementation of the renewed emergency plan, experience can be used for further improvement of the first turn.

5.3.3 Mapping Flood Risk at an Exemplary Power Plant Site

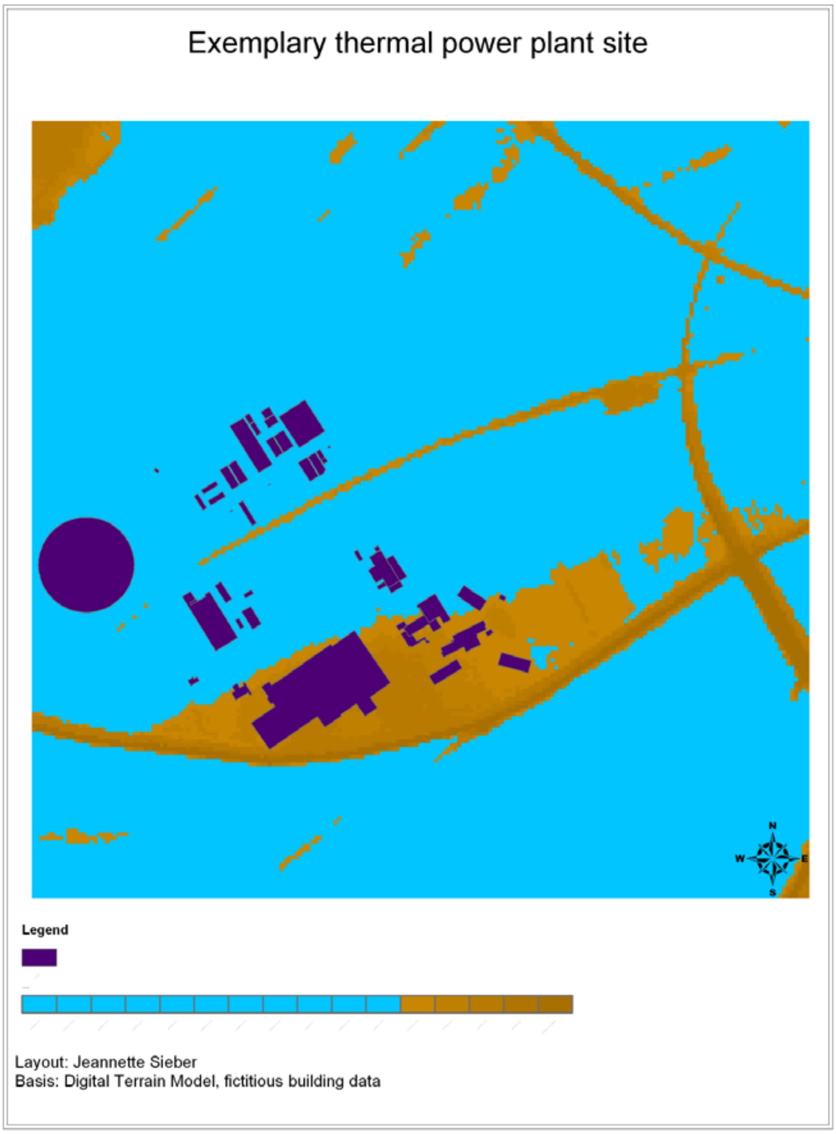
This example shows a rough estimate of flood events at an exemplary power plant site. Data from a Digital Terrain Model are combined with building and structural data. The heights of the flooding events are defined as an x-years flood, an x-years +50 flood and an x^{10}-years flood respectively representing the protection levels of a 100-years flood for conventional thermal power plants and 10,000-years flood for nuclear power plants. The x-years +50 approach shows especially for conventional thermal plants and exceedance by an annuality of 50 years more, i.e. a 150-years flood. Finally, the x^{10}-years flood represents an extreme event where the power plant is intentionally flooded in order to demonstrate which areas are still suitable for evacuation or for the storage of protection measures and which areas need to be accessible during inundation of the site.

In the first Map 28, the cooling tower (the only round structure) is placed in a low-lying area. Several storage warehouses are located north-east of the cooling tower. The southern area consists of the biggest building, the boiler or reactor structure together with administrative buildings, chimneys and other processing structures. It would be possible to install storage areas, among other things for coal, in the northern area.



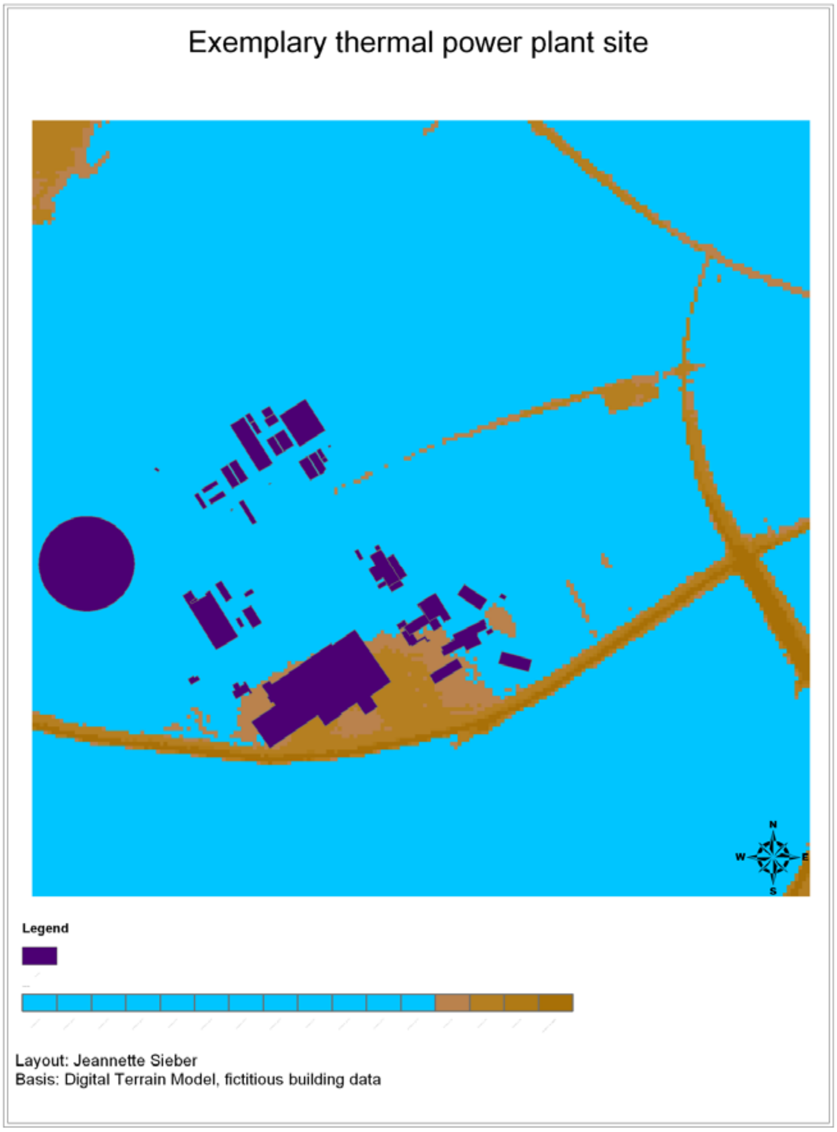
Map 28: Exemplary thermal power plant site – dry. Low lying areas are displayed as light brown areas, darker brown colours represent higher areas or – with linear structures – dams as in case of the crossing and access roads. Buildings and structures are purple

The first flooding example represents the x-years flood (Map 29). Blue areas indicate flooded areas, whereas brown areas have higher elevations and are not inundated. The boiler building is constructed on high ground and, therefore, no direct impacts are expected. The cooling tower is constructed at a lower elevation and is flooded. Some of the administrative buildings are built flood safe but storage buildings and warehouses next to the cooling tower are affected by the flood. At this point, the cooling tower pond has already been flooded to avoid that it comes to floating. This is because the upward pressing groundwater would lift the cooling tower pond if it were to be left empty and therefore, the pond is filled to make it heavier and increase its downward pressure. Storage warehouses should store hazardous substances on higher shelves rather than directly on the ground. Flood-proof boxes and canisters with non-hazardous liquids or insensitive equipment should be stored at ground level. By this time, the power plant should have already shut down completely for security reasons.



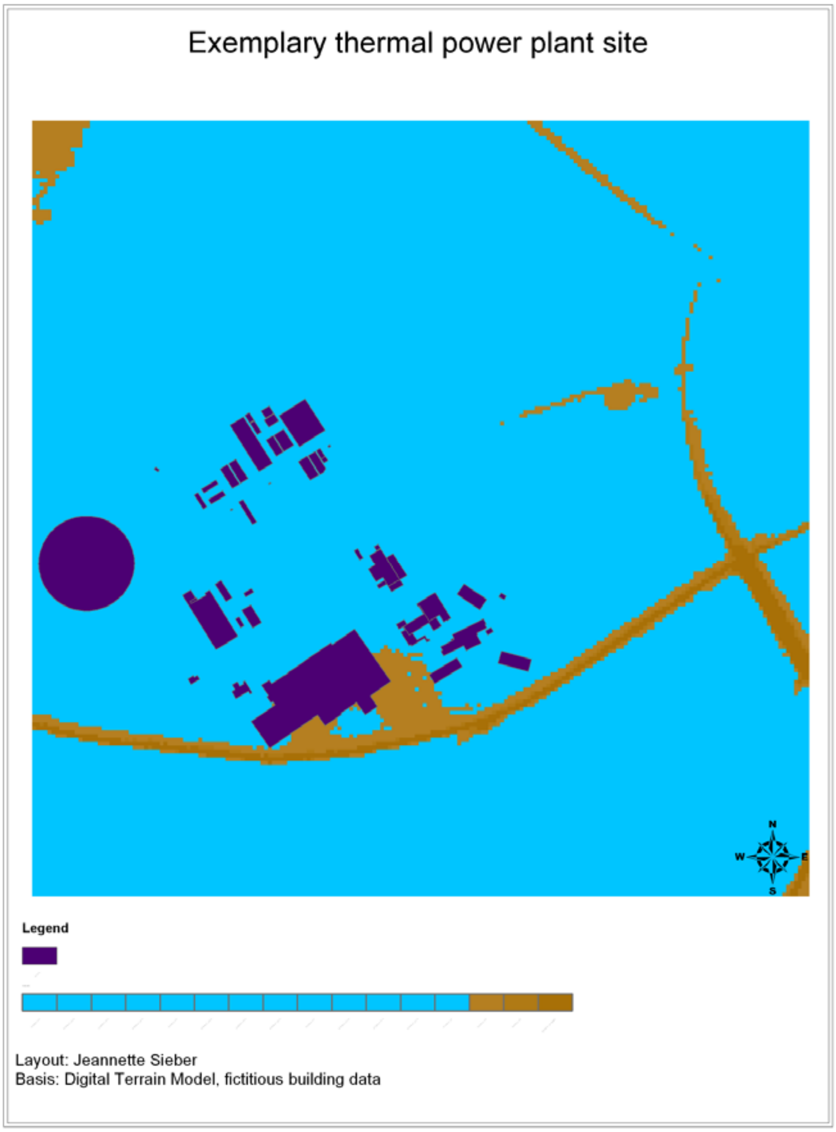
Map 29: Example of an x-years flood at a power plant site

The second flooding example shows more flooded areas but that the boiler/reactor building remains in a dry area (Map 30). Moreover, this building is still accessible via the adjacent access road. A safe evacuation of staff would be possible, along with the supply of temporary protection measures to this building. Nevertheless, all administrative buildings are affected by water so IT rooms may not be accessible and the IT infrastructure might fail.



Map 30: Example of an x-year +50 flood. Blue areas are inundated, brown areas are dry

The third example of flooding shows that the designed extreme flood has been exceeded (Map 31). Here, the boiler building has been affected by water, but some entrances might still be accessible. Dry areas in brown represent dams and secure areas for possible staff evacuation. All the connected buildings, cooling tower and process facilities are flooded.



Map 31: Example of an x[10]-years flood. Blue areas are inundated, brown areas are dry. Here, the boiler building is finally affected by water, but some entrances might still be accessible. Dry areas in brown represent dams and secure areas for possible staff evacuation

In the figures, the available DEM data, the site and the design water level, implemented in a GIS, are displayed. The design water level is calculated to have an overview section through the terrain level, but no real simulation was calculated due to lack of data. A hydraulic and hydrologic calculation of design flood levels is essential for a site specific application of this method. However, for an initial view in the context of this work, layers in GIS containing simple height information are sufficient. This first visualisation can be used as an overview of the situation at a site and can be easily read - even by laymen.

Beyond this, a lot of areas are neither flooded nor covered with buildings, so those areas might be possible storage places for mobile protection measures or shelters. Areas surrounding the flooded space are either dams or high terrain levels. In this case, no modification of the dams is needed since there is no expected dam overflow. As seen in Map

29 containing the design flood level for thermal power plants, this exemplary power plant does not have to adapt to the current flood level situation. Flood protection in the form of elevated ground level was created before the power plant was built. Further calculations, including climate change effects, might show an increase in the design water level as indicated by the climate change factor. For this, further maps must be created in order to make site-specific water level assessment. In addition to the maps, a manual for map-making and interpretation as well as a standardised procedure for emergency decision-making (during high water levels) needs to be established. The responsible persons at the power plant site will be able to react to changes in the operating procedure. Power plant sites are bound to be independent in their planning, that means a person in-situ needs the knowledge and the ability to create different maps by theirself. This is especially important during flooding, when the information flow from outside the power plant might be disrupted. In comparison to an analogue map, mapping within the GIS is fast and includes a high resolution DEM rather than contour lines, which increases accuracy. Moreover, background information, e.g. values of buildings and height of entrances, can be stored and retrieved by selecting them directly in the GIS. Furthermore, a comparison of terrain and water levels reveals the depth of flooding, so that an analysis can be calculated, for example indicating if a flooded street is still accessible with heavy equipment.

5.4 Synthesis

Section 5 focused on thermal power plants being subject to corporate risk management. Up until now, risk management of thermal power plants relates to how the infrastructures influence the environment and less how the (changing) environment affects structures and processes. Environmental management systems like EMAS, ISO 14 000 or the SEVESO-II guidelines concentrate on the environmental impact due to emissions and hazardous substances. The enhanced approaches of this work complement these systems by implementing the components of extreme hydro-meteorological events and the use of GIS-analyses.

The GIS-analyses carried out in this section show that the impacts on thermal power plants due to extreme hydro-meteorological events are not very common but have large consequences. Thermal power plants are especially vulnerable to combined events and long period events, like hot temperatures and their consequences than to single event of short duration.

Therefore, the case study deals with the integration of a bi-cycle process: the site-related and the GIS-based approach. These two cycles of plan, do, check and act run in parallel but need to be combined to establish site-specific recommendations and emergency plans. This is illustrated by an exemplary power plant site and the protection against flooding where regulations on flooding are taken into account.

The GIS-based assessments help to visualize and realise where high risk areas are on a small scale and where on the other hand protected areas can be found in case of emergency. At this point, the differences in local planning approaches and corporate risk management where the operator is in charge stand out. Local planning and corporate risk management need a variety of spatial resolutions in the GIS-based assessments to gain insight into the relevant planning level.

6. Operationalisation and Implementation

6.1 Enhanced Disaster Risk Management in Corporate Risk Management and Climate Mitigation Concepts

The work presented here shows that the impact of extreme hydro-meteorological events on electricity generation can be implemented, analysed and displayed effectively in Geographical Information Systems. The concept fits into the regulatory framework by several ISO norms and guidelines and the general approach of Industrial Environmental Information Systems. Nevertheless, it was identified that GIS is not used as an integrated tool for environmental or risk management until now, but it is used as a tool for display (see Section 2.4 and 5.1). In this work, the approaches are combined in order to identify the local impact of extreme weather on power plant sites and to characterise the additional use of GIS for adaptation planning and measure localisation. The described approach contains data on measured extreme events, specific site information and the potential for on-site use, also by untrained staff.

Using the methodology of fishbone diagrams as proposed by CHANG & LIN (2006), the results can be displayed for decision-making support. The first fishbone diagram (Figure 38) shows the impacts of a flooding event on thermal power plants and is leading to a plan, do, check and act cycle approach.

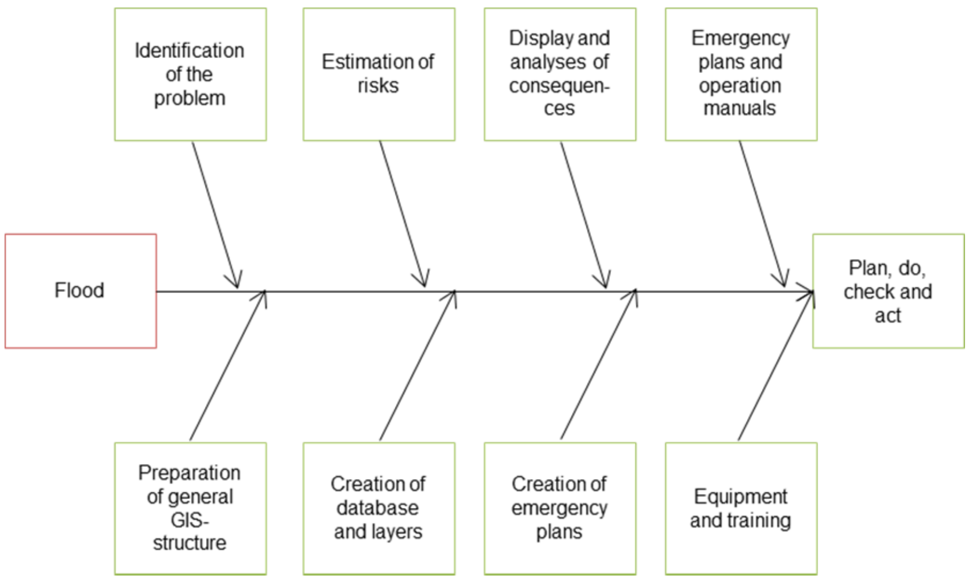


Figure 38: Fishbone diagram for adapting thermal power plants to flood events. The red outline shows the impact of a flood, the green outlines represent positive responses that lead to the green outlined result of the presented environmental risk management cycle

The fishbone diagram allows practitioners to represent the impact (red), the consequently following responses needed (green for positive responses, orange for negative consequences) and final stage of the plant (green for a positive result, orange for a neutral result and red for a negative result). In the case displayed, the negative impact of a flood can be managed by the eight stages of the presented environmental risk management cycle so that in the end an adapted thermal power plant is the final, positive result.

The second fishbone diagram (Figure 39) represents the impact of increased runoff on a hydropower plant.

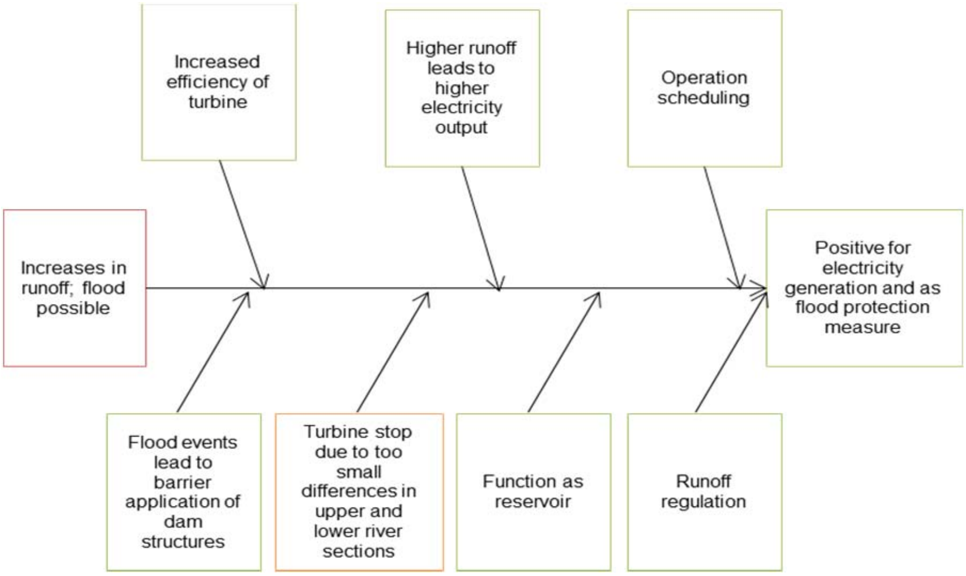


Figure 39: Fishbone diagram of the impact of increased runoff and a possible flood on a hydropower plant

In this second fishbone diagram, the impact is an increase in runoff that may result in a flood event. The positive green responses are an increase in efficiency and an optimal operation scheduling with high load. Additional positive impacts, not for the hydropower plant but for the management of the flood risk in general, are the barrier function of the dam structures and the runoff regulation. In a flood situation, the turbines have to stop due to too small differences in the upper and lower rivers sections so that no electricity is generated at that time. The positive results are the increase in electricity output during increased runoff and the protection function of the hydropower plant for downstream structures and settlements.

The third diagram shows how wind turbine operators respond to ice throw incidents (Figure 40).

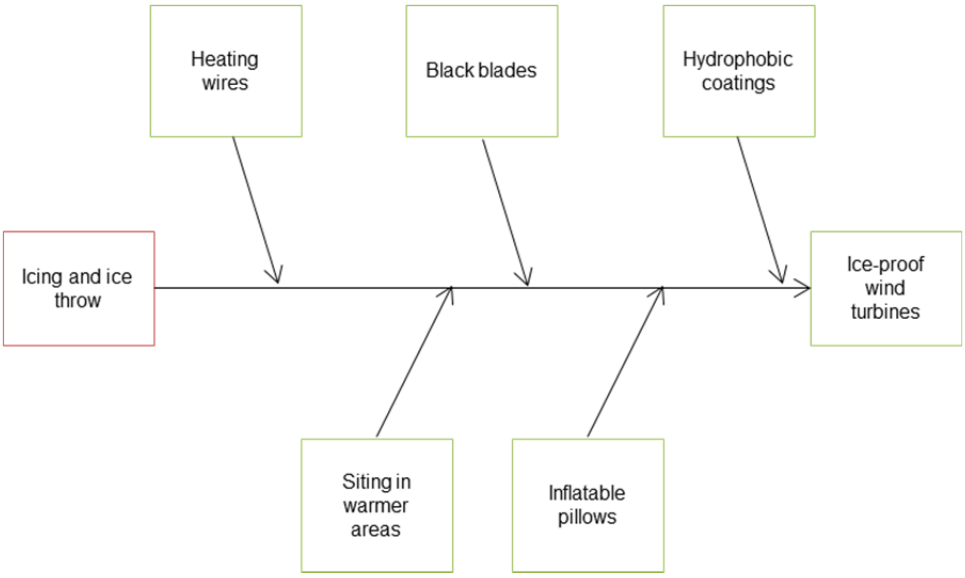


Figure 40: Fishbone diagram of the impact of icing and ice throw, possible adaptation measures and the result of an ice-proof wind turbine

By implementing adaptive measures like heating wires, black painted blades, or inflatable pillows along the rims of a wind turbine's blade, the impact of icing during cold conditions and freezing precipitation can be managed. Here, only positive consequences and response can be found according to the literature. The final positive result is an ice-proof wind turbine.

The last fishbone diagram shows the impacts of hail and thunderstorms on PV installation, possible adaptation measures and neutral but necessary improvements for adapting this technology to extreme weather (Figure 41).

Here, hail and thunderstorms lead to severe effects on PV installations. In order to avoid failures, rules and regulations need to be followed. This can be reached by intensive training of staff to implement these rules in the set up of PV installations. Moreover, lightning rods should be installed; a decision that is to be made by the owner of the panels. In addition, the owner must pay attention to hail-proof materials and wind-proof mounting. A negative or neutral response is the difficulty in fire extinguishing of burning PV installations due to conducting parts. Nevertheless, the result is rather positive as the positive measures predominate.

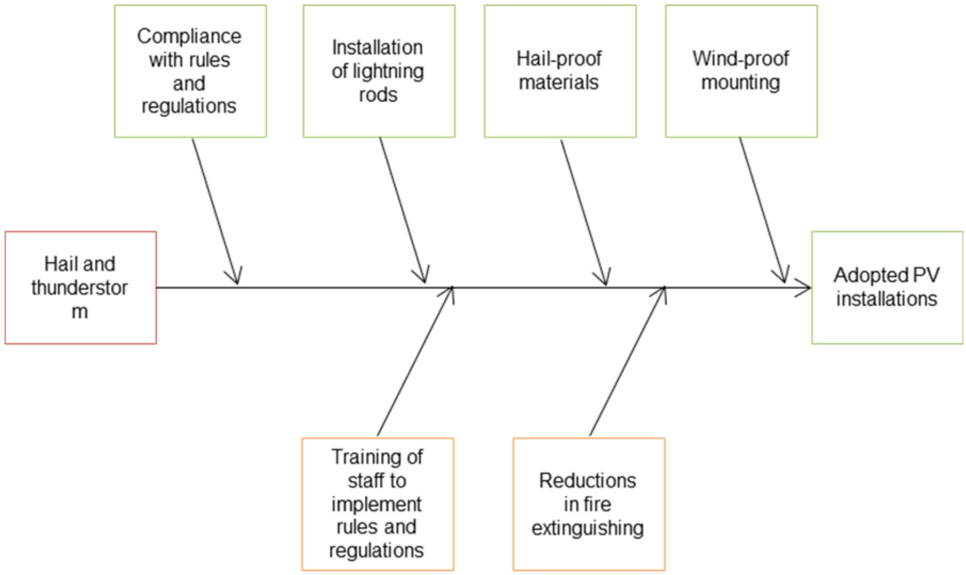


Figure 41: Fishbone diagram for the impact of hail and thunderstorms on PV installations

The following paragraphs indicate adaptation costs related to an increase in extreme events with regard to the topics in this study. Sections 2 to 5 gave an overview of the identified effects of climate change on electricity generation for Europe as stated by RADEMAEKERS ET AL. (2011). Thermal generation is affected by air and water temperatures and flooding but only the latter is quantified for nuclear generation by an investment in protection measures (of 100 €/kW) against an expected 25 % increase in the occurrence of flooding. Flooding here incurs preventive measures valued up to 100 - 125 €/kW.

In renewable electricity generation, wind electricity generation is calculated to decrease by 1 % per 1 % increase in storm occurrence. Other investments relate to offshore generation. Hydropower investments amount up to 100 €/kW in the case of 25 % more intensive floods. For PV installations no relevant investments are mentioned. Nevertheless, not all power plants can be insured against the extreme events analysed in this work, and one event might cause considerable damages with consequently high costs for repair and new construction.

6.2 Implementation of the Risk Index for Climate Mitigation Concepts

The analyses demonstrate that adaptation and environmental risk management are the task of big power plant operators in Germany. Here, a wide variety of adaptation measures was introduced and where they need to be applied.

Especially for renewable energies like photovoltaic installations, wind turbines and small hydro power plants, private owners, projects with public participation and small investors are the responsible bodies. With climate mitigation concepts and the plan of the German Energy

Turnaround, investments into renewable energies are guided and controlled. Until now, the assessment emphasises that enhanced climate mitigation concepts including adaptation options and risk identification could lead to an even more sustainable development in electricity supply.

To support decision making in climate mitigation concepts, a risk index is created on a district level. In order to achieve a matrix the number of events in three categories "wind-related events", "precipitation-related events" and "combined events" is linked to the number of installed renewable energies. The category "temperature-related events" is excluded from the analyses as the database is not reliable enough due to the IDW interpolation to use it on a district level and temperature-related events seemed to have more an additional effect on renewable energies than a direct one. For further assessments the numbers of installed renewable energies are classified into the following groups:

- the number of hydropower plants is divided into 1-10, 11-50 and more than 50 units,
- the number of wind turbines ranges as follows: 1-10, 11-100 and more than 100, and
- the number of PV installations is categorised as 1-1,000, 1,001-2,500 and more than 2,500.

The events describe three ranges of 1 event, 2 to 10 events and more than 10 events. Each category was highlighted either green for the lowest number of events or units, yellow for the middle category and orange for the category with the most events or number of installations. Afterwards the time slice categories were combined again (see Table 46):

Table 46: Matrix of number of installations and number of events leading to consequence categories of low (green), low-medium (yellow), medium (yellow), medium-high (orange) and high (orange)

Number of installations / number of events	1 event	2 - 10 events	> 10 events
1 - 10 wind turbines	Low	Low-medium	Medium
11 - 100 wind turbines	Low-medium	Medium	Medium-high
> 100 wind turbines	Medium	Medium-high	High
1 – 1,000 PV installations	Low	Low-medium	Medium
1,001 – 2,500 PV installations	Low-medium	Medium	Medium-high
> 2,500 PV installations	Medium	Medium-high	High
1 - 10 hydro power plants	Low	Low-medium	Medium
11 - 50 hydro power plants	Low-medium	Medium	Medium-high
> 50 hydro power plants	Medium	Medium-high	high

Where a number of zero events occurred, the district was categorised as a no-consequence district. The same applies for districts where no installations are recorded.

Below, the results of this analysis are described in more detail for the so-called consequence categories and the corresponding renewable energy installation in the two time slides 1990 - 1999 and 2000 - 2009.

Consequence categories of 402 districts for hydro power plants

For the analysis of hydropower plant consequence categories, wind-related events include storms, tornadoes, funnel clouds and gustnadoes. Precipitation-related events are characterised by hail and heavy rain events, while combined events list floods and flash floods (Table 47).

Table 47: Number of affected districts with hydropower plants as consequence categories; arrows up or down indicate an increase or decrease respectively between the period 1990 - 1999 and 2000 - 2009

	Wind 1990s	Wind 2000s	Precipitation 1990s	Precipitation 2000s	Combined 1990s	Combined 2000s
none	323	155↓	364	168↓	362	301↓
low	38	39↑	20	35↑	18	13↓
low-medium	33	86↑	11	108↑	17	43↑
medium	7	82↑	7	62↑	5	32↑
medium-high	1	30↑	0	27↑	0	13↑
high	0	10↑	0	2↑	0	0↔

For the impacts of wind- and precipitation-related as well as combined events, analyses are performed as well. The results are described as follows.

Wind-related events like storms, tornadoes, gustnadoes and funnel clouds had impacts on 79 districts in the period 1990 - 1999 and increased to 247 districts in the period 2000 - 2009. The difference between low consequences is one additional district (38 in the 1990s, 39 in the 2000s) but low-medium to medium consequences increased from 40 affected districts to 168 affected districts. Also the medium-high to high consequences rose from one district in the 1990s to 40 districts in the 2000s. As wind-related events have minor impact on the power plant structures (here especially the weathering of buildings), adaptation options are rather rare.

The number of impacts of precipitation on hydropower plants also increased. In the 1990 only 38 of 402 districts were influenced while in the 2000s already 234 districts suffered from effects. Also here, the low consequence category documents a slight increase from 20 districts 1990 - 1999 to 35 districts 2000 - 2009 respectively. In the categories low-medium to medium, the number of affected districts changed from 18 to 170. But also the categories of medium-high to high account for higher numbers. Here zero districts are listed in the 1990s and 29 in the 2000s.

Also the number of affected districts with hydropower plants due to combined events (here: floods and flash floods) increased between the two time periods under investigation. The number of affected districts in the 1990s amounts up to 40, which is relatively low, but increased to 101 in the 2000s. While the number in the category low consequences sank (18 to 13 in the 2000s respectively), the numbers in all other categories rose. In the 1990s 22 districts fell into the categories low-medium to medium, whereas the 2000s list 75 affected ones. In the categories medium-high to high zero districts are listed between 1990 and 1999, which changed to 13 districts between 2000 and 2009. As hydropower plants depend on runoff, high water levels and floods may damage the installation and reduce the electricity output significantly. In the affected districts, adaptation needs to be taken into account in climate mitigation concepts as much as the installation of further renewable energies and especially hydropower plants.

Consequence categories of 402 districts for wind turbines

In this compilation, all wind-related events (storms, tornadoes, funnel clouds and gustnadoes) are counted. For the precipitation-related events, hail and heavy rain measurements are listed and the combined events include thunderstorms and lightning (Table 48).

Table 48: Number of affected districts with wind turbines as consequence categories; arrows up or down indicate an increase or decrease respectively between the period 1990 - 1999 and 2000 - 2009

	Wind 1990s	Wind 2000s	Precipitation 1990s	Precipitation 2000s	Combined 1990s	Combined 2000s
none	327	153 ↓	372	172↓	385	330↓
low	20	29↑	13	27↑	8	17↑
low-medium	37	74↑	13	77↑	8	28↑
medium	15	78↑	4	78↑	1	14↑
medium-high	3	41↑	0	44↑	0	13↑
high	0	27↑	0	4↑	0	0↔

This first analysis on the possible impacts of wind- and precipitation-related as well as combined events on wind turbines points to the following results:

Regarding wind-related events no consequences are found in 327 of 402 districts in the 1990s, while this number sinks to 153 of 402 districts in the 2000s. In total, 75 districts were affected in the 1990s and 249 in the 2000s respectively. While 20 districts had low consequences (green), 52 had to suffer low-medium to medium consequences (yellow). Merely three districts already were influenced medium-high and none high (red). In the period 2000 - 2009 29 districts had low impact, while the numbers of low-medium and medium increased to 152 and of medium-high and high to 68. This highlights the increased risk of being affected by wind-related events in the 2000s. A number of potential adaptation measures for this category of influences is shown in section 2.3. Especially lattice steel pylons could help to lower the consequences for single wind turbines (see Section 2.3.2).

Regarding precipitation-related events, in the 1990s 30 districts suffered from impacts, while in the 2000s the number rose to 230 districts. Overall, 13 districts had low consequences, 17 low-medium to medium and none were classified as medium-high to high. In the 2000s those numbers increased to 27 low impacted, 155 low-medium to medium impacted and 48 medium-high to high impacted districts. Again, there is a clear increase in affected districts to be seen. In this case, especially the blades of wind turbines suffer from the direct impacts of rain drops and hailstones at the rims. Therefore, construction needs to adapt and built more robust blades.

When combined events are considered, for wind turbines this means lightning and thunderstorm as floods and flash floods should not affect wind turbines at all. Here, an increase of a total of 17 affected districts in the 1990s to 72 affected districts in the 2000s is recognized. In the 1990s only 8 districts suffered from low impact and another 9 from low-medium to medium impact. All other districts were not affected either due to missing events or missing installations. In the 2000s the picture changes. Now 17 districts record low impacts, 42 of them fall into the categories of low-medium to medium impact and another 13 were affected in the category of medium-high. No high impacted districts are listed. Once more, the trend shows an increase to a higher number of affected districts and a higher severity for districts. Adaptation options for thunderstorm and lightning impacts can be found in section 2.3.

Consequence categories of 402 districts for photovoltaic installations

Table 49 shows all districts with PV installations as consequence categories. The assessment of wind- and precipitation-related as well as combined events impacts on PV installations results as follows:

Table 49: Number of affected districts with PV installations as consequence categories; arrows up or down indicate an increase or decrease respectively between the period 1990 - 1999 and 2000 - 2009

	Wind 1990s	Wind 2000s	Precipitation 1990s	Precipitation 2000s	Combined 1990s	Combined 2000s
none	297	92↓	352	114↓	363	298↓
low	67	46↓	35	33↓	23	24↑
low-medium	38	99↑	15	117↑	16	32↑
medium	0	87↑	0	78↑	0	22↑
medium-high	0	60↑	0	54↑	0	25↑
high	0	18↑	0	6↑	0	1↑

Wind-related impacts are relatively high. Already in the period 1990 - 1999 105 of 402 districts were under the influence of either tornado, storm, gustnado or funnel clouds. The number increased in the period 2000 - 2009 to 310 influenced districts. While the number of districts with low impact decreased from 67 to 46, low-medium and medium increased from 38 to 186, the districts with medium-high to high impact rose from zero to 78. Here, safe mounting as the main adaptation measure needs to be controlled carefully.

Regarding precipitation-related impacts, the number of affected districts rose from 50 to 288 between the 1990s and the 2000s. While again the number of districts with low impact decreased from 35 to 33, the numbers of low-medium to medium impact increased from 15 to 195 and the numbers of medium-high to high impacts rose from zero to 60. While heavy rain usually influences the electricity output, hail might also destroy parts of the PV panel due to direct hit of hailstones.

Combined events include thunderstorms and lightning for the assessment of PV installations. Here an increase from 39 affected districts in the 1990s to 104 affected districts in the 2000s is monitored. In each category numbers increased at least slightly. Low from 23 to 24, low-medium to medium from 16 to 54 and in the categories medium-high to high from zero to 26. Especially since lightning impact usually leads to a complete destruction of the PV panel and potentially also the building, the installation of lightning rods and the connection to the lightning protection system of the building are important factors to take into account.

Regardless of the kind of extreme event, a spatial assessment was done in the categories of extreme hydro-meteorological events. The analysis for the time period 1990 - 1999 shows the following results:

- 219 districts did not suffer from any type of consequence,
- 128 districts suffered from one type of extreme event,

- another 45 districts encountered two types of extreme hydro-meteorological event and
- 10 districts are listed for having consequences in every category of extreme events.

Furthermore, the analysis shows great shifts concerning the consequences in the period 2000 to 2009:

- 32 districts were not subject to any type of extreme event,
- while 83 districts suffered consequences in one type of extreme hydro-meteorological event,
- furthermore, 169 districts encountered two types of consequences and
- 118 districts are listed in all three types of categories for having impacts of extreme events on any kind of renewable energy infrastructure.

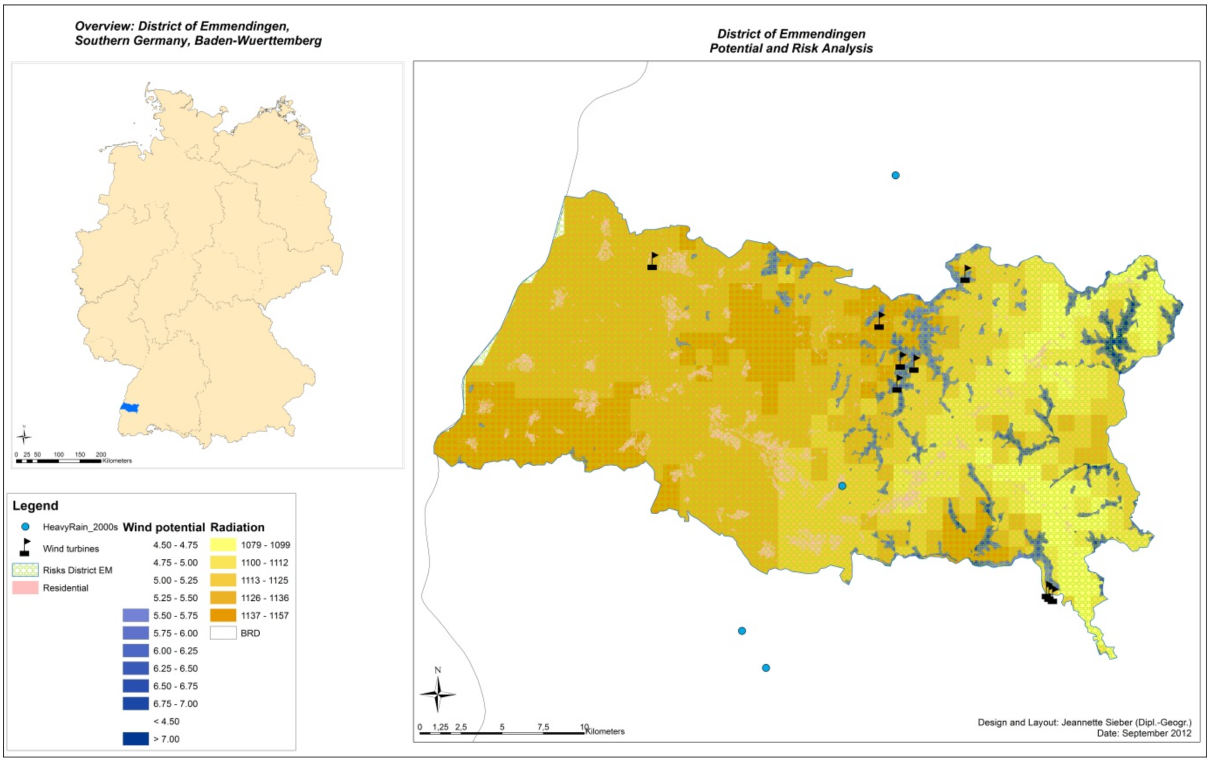
Especially this analysis demonstrates that a shift in the vulnerability of renewable energy infrastructure occurred between 1990 - 1999 and 2000 - 2009. This is due to the fact that (1) more extreme hydro-meteorological events were registered in the latter period while (2) more renewable energies were installed in the districts. This becomes also apparent when looking at the analysis of severity and the increase in numbers of low, medium and highly affected districts. It does not necessarily mean that districts have to avoid the installation of particular renewable energies but they need to be aware of adapted construction and adapted objects. Moreover, they need to keep in mind the high potential areas from the climate mitigation concept and the endangered areas from the vulnerability analysis at the same time.

6.3 Comparison of Two Districts Regarding Climate Mitigation Concepts

At this point, two examples are stressed to demonstrate the applicability of the proposed method in the planning process as well as the risk index.

The district of Emmendingen (Baden-Wuerttemberg) established a climate mitigation concept in 2011/2012 for the base year 2009 (*Business Development Cooperation of the District of Emmendingen Ltd.*/Wirtschaftsförderungsgesellschaft des Landkreises Emmendingen mbH 2013). The potential analysis shows high potentials in the fields of solar power and wind energy. Therefore, the catalogue of measures includes two measures for these activities: (1) the installation of a solar cadastre in order to give advice to private investors on where thermic systems or PV installations would be feasible and (2) the support for the installation of new wind turbines and retrofitting of older installations. Both measures are rated as short-term and high priority.

Regarding these two aspects - which are categorized as short term mitigation measures with a high priority - the analysis of the potential risk in the district showed a low consequence risk for precipitation impacts on wind turbines in the period 2000 - 2009 and a medium consequence risk for precipitation on PV installations in the same period. The following Map 32 illustrates these findings.



Map 32: Potential and risk analysis for the district of Emmendingen

Localising the heavy rain events for the district showed that only one event is registered here in an area with rather medium solar radiation and outside of wind potential areas. Due to 2,512 installed PV panels and 10 installed wind turbines in this district in said period and one direct heavy rain event in the zip code area of Sexau, the risk categories for the whole district are low for wind turbines and medium for PV installations. The potential map for wind shows small areas of said zip code area for future development in wind energy. Using exclusively areas with more than 1.5 ha with good mean wind speeds and accounting for array losses in wind farms, Sexau shows the potential for two wind turbines. In total, the district Emmendingen offers a potential of about 60 new wind turbine installations. With respect to the risk categories, one heavy rain event per decade would lead to a “low-medium” risk. Regarding the low(-medium) risk for a heavy rain event, emphasis should be put on reliable blades of wind turbines. Moreover, one storm event was registered in the

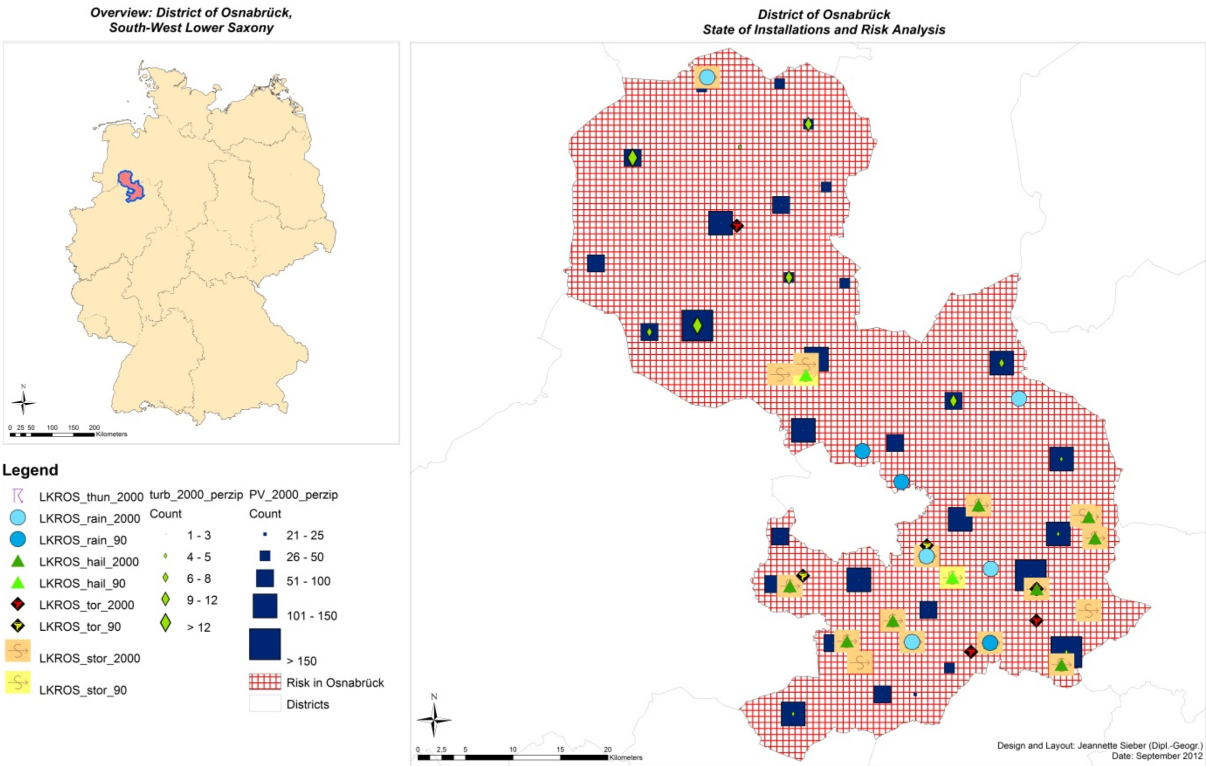
1990s but in the same period, no wind turbines were installed. Transferred to the period 2000 - 2009 with 10 wind turbines, the risk category would also have been low. Taking into account that Emmendingen reaches out into the Black Forest with higher elevations, it should be kept in mind that a detailed wind assessment report needs to consider areas of forest windfall due to high speed storms.

On the other hand, the potential map for PV installations shows global solar radiation values between 1,079 and 1,157 kWh/m² which is a good mean for southern Germany. Using roof pitch, roof orientation, shading, construction barriers and the structural design as a reduction in the exploitation of the theoretical solar potential, the potential amounts up to 292,436 MWh/a. About 8.2 % of this potential were used in 2009. One heavy rain event in the period 2000 - 2009 should rather be regarded as a low impact on the high number of PV installations. This is also true for one storm event in the earlier period 1990 - 1999. In this case, if standards for installation and panel construction are followed, the risk of either wind impacts or precipitation impacts on the district of Emmendingen should be regarded as existing but minor. If the district of Emmendingen exploits the full PV potential, this would mean a total number of about 30,000 PV installations. Even with this extremely high number of PV installations, the risk would – due to only one heavy rain event per decade – be still "medium". Adaptation measures as listed in Appendix A should be appropriate to create a secure future development of renewable energies in the region. As standard PV modules are not susceptible to rain events, a few heavy rain events during the operating life span should not increase the vulnerability.

The second example covers the district of Osnabrück (Lower Saxony). Osnabrück established a climate mitigation concept in 2011 with the base year 2008 (WITTE ET AL. 2011). Here too, the potential analysis as well as the catalogue of measures show a high preference for the installation of further wind turbines and PV panels. The first measure concentrates on the "wind energy strategy" – a short-term high-priority measure. A second measure focuses on PV installations on fallow land, a short-term mid-priority measure; and the third measure in the same context of the installation of renewable energies is "PV panels on district owned areas" with a short-term perspective and a medium priority. The climate mitigation concept for the district of Osnabrück contains comprehensive GIS-based analyses especially on the energy demand in small scale areas. Nevertheless, this climate mitigation concept does not include any assessment of the potential risks due to extreme hydro-meteorological events.

In the period 1990 - 1999, already 24 wind turbines were installed in this district, and the number increased to 120 in the later time frame. The intersection of the number of wind turbines with the three categories of impacts (wind, precipitation, combined events) shows that due to five resp. 23 wind-related events, seven resp. 19 precipitation-related events and one combined event in the 2000s, the risk categories of wind turbine impacts are either medium or high. Also the numbers of PV installations (17 in the 1990s, 2,876 in the 2000s) lead to medium or even high risk in combination with the number of events. Since there were no reported hydropower plants, there is no risk to be stated for this category.

The GIS-based analysis in the district of Osnabrück calculates the potential areas for the installation of new wind turbines. Therein, wind farm effects like array losses and distance regulations require an area of 40 ha per new wind turbine. The assessment results in the possibility for 188 new wind turbines in the district within the coming decades. The GIS-analysis in this work shows two hail and five heavy rain events in the 1990s and 14 hail and five heavy rain events in the 2000s. The precipitation-related events are concentrated in the southern part of the district. On the other hand, the localisation displays two storms and three tornadoes in the period 1990 - 1999 and 18 storms and six tornadoes in the period 2000 - 2009. As for the precipitation-related events, wind-related events concentrate in the southern part of the district. Moreover, one thunderstorm is registered for the period 2000 - 2009. Due to the high numbers in installations, the risk regarding wind- and precipitation-related events in the period 2000 - 2009 is high in all categories (see Map 33).



Map 33: State of installations and risk potential for the district of Osnabrück

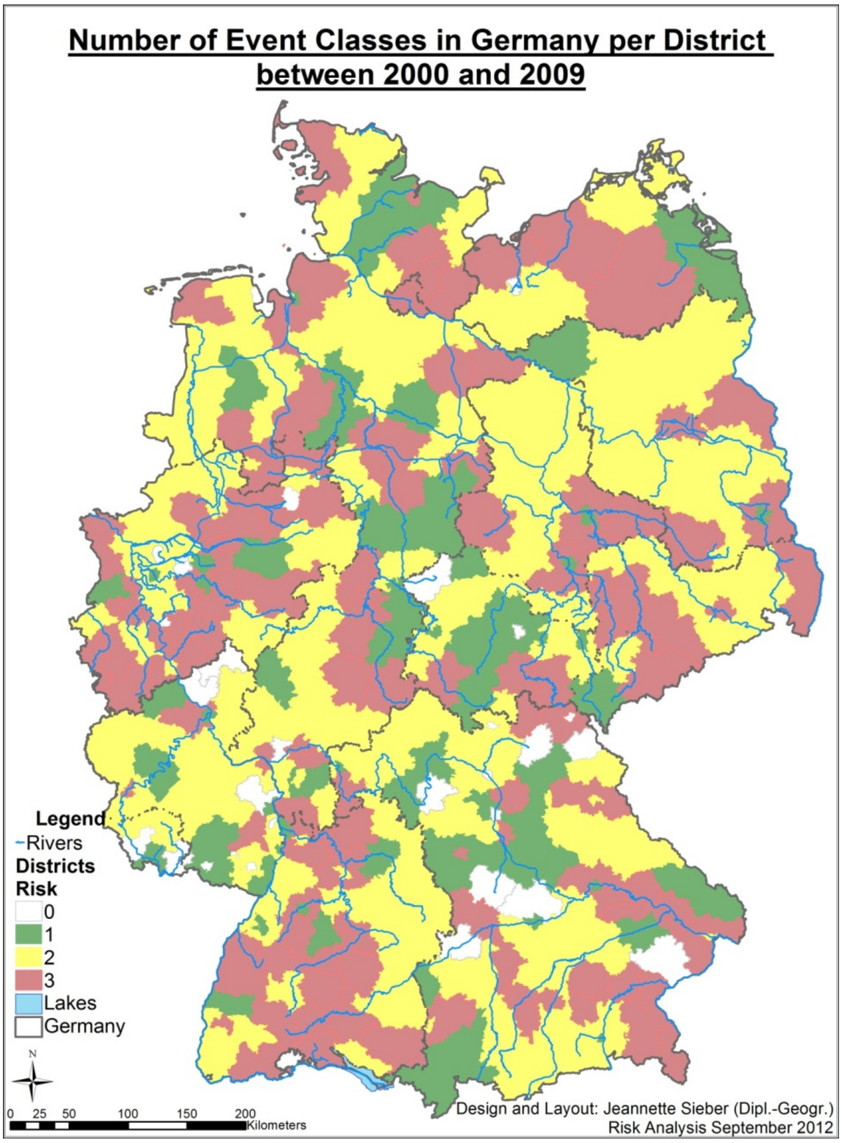
While the wind turbines in the 2000s are installed preferably in the northern part of the district, PV installations concentrate in the south. This means that also PV installations are more at risk than the wind turbines. The differences in the area of construction for the two types of renewable energies are a result of the population density in these regions, as the northern part of the district consists mostly of so-called “Samtgemeinden”, an administrative unit of smaller communities and unincorporated areas.

As a consequence, the district of Osnabrück needs to take into account adaptation options for future installations. Detailed analysis on the exact sites for further installations especially for wind turbines needs to be done in order to avoid negative impacts of storm and tornado events. Also, PV installations need to be mounted according to standards. In this case, standards may need to be revised to assure secure future developments.

6.4 Overall Implementation

The results of the previous sections need to be taken into account for future development planning on a local level. To give a first overview on the risk categories in the 2000s, the following map shows how many types of extreme hydro-meteorological events the districts were affected in the period 2000 to 2009. Only 32 districts did not suffer any type of extreme event, while 83 districts encountered one type of extreme event, 169 districts registered two types of events and 118 districts experienced every type of extreme event, wind- and precipitation-related as well as combined events. Map 34 illustrates some regional specifications:

- Along the rims of the Central Uplands of the Black Forest, the Eifel and the Westerwald, the Ore Mountains and the Bavarian Forest, extreme hydro-meteorological events are more common than in the depressions. Therefore, these districts show usually two or three classes of events.
- Almost all States encounter all variations. That means that either one, two or three different types of extreme events are registered in each state. Only in the eastern States except Thuringia all districts are exposed to at least one type of extreme event. None of the districts showed zero influences.
- According to the display, no tendencies north-south or east-west can be found. Due to medium scale geomorphologic influences, the distribution of extreme hydro-meteorological events is rather even all over Germany.



Map 34: Risk Categories in Germany per District between 2000 and 2009, marked green = districts with events of one type of event class, marked yellow = districts with events of two types of event class, marked red = districts with events of all types of event classes (i.e. wind-related, precipitation-related, combined events)

The map provides an overview on past extreme events and therefore past risk. Nevertheless, there is the possibility to have an increased risk per districts as shown in Tables 47 to 49. Moreover, future risk can evolve in districts with no risk when the number of installations is zero until now. Considering an increase in installations in said districts, the risk would also increase if there were registered extreme events. The outlook also highlights that according to the forecast more events are supposed to happen in the future. Here, no differentiation can be made regarding the spatial distribution.

Again, taking a look at the climate mitigation concept structure as proposed by the FEDERAL MINISTRY FOR THE ENVIRONMENT, NATURE CONSERVATION AND NUCLEAR SAFETY (2010), the steps are

1. CO_2 and energy balances
2. Assessment of potentials for mitigation
3. Cooperation with responsible parties
4. Catalogue of measures
5. Performance monitoring and
6. Concept for public relations.

Based on the analysis, adaptation to extreme hydro-meteorological events should be integrated into the concept in step 2 “assessment of potentials for mitigation” by adding adaptation and into step 4 “catalogue of measures”. In step 2 the potentials for the installation of renewable energies are analysed and calculated. Here, highly affected regions should be mapped and excluded from further calculation to avoid extreme hydro-meteorological impacts. Since the extreme events are available as single point information and experience underlines the dimensions of events such as thunderstorms, small scale resolutions for vulnerable regions are elementary information. Such regions can be clipped for example from wind energy potentials. The results are maps that illustrate high potential areas without risks. Step 4 includes recommendations for future planning. At this point, information on best solutions (e.g. lightning rods, a list of resistant surfaces of wind turbine blades or PV panels) should be included in the catalogue in order to tie potentials and adapted structures together into decision making. A catalogue of adaptation measures can be found in Appendix A which gives a first overview on best practice.

So how should the two aspects of adaptation and mitigation be balanced in local planning? Climate mitigation concepts offer the possibilities to integrate both aspects into decision making. By analysing the occurrence of extreme hydro-meteorological events – and as additional information also regional climate model information – districts are able to actively manage the development of renewable energies. Regarding the national instruments of the German Energy Turnaround and global to regional goals concerning climate change, a reasonable planning is necessary to avoid failures in electricity supply. This work includes guiding analyses on which extreme hydro-meteorological events are influencing selected infrastructures, how these infrastructures can be adapted and where adaptation needs to take place. Even though the resolution of the maps can still be refined, these analyses link to vulnerable regions and point out options for structured action when it comes to detailed site expertise.

Planning approaches in cities and districts need to consider all sectors, e.g. industry, households, trades and services as well as traffic. Yet, all of these sectors depend on electricity supply, even more so due to new electro-mobility approaches. Therefore, the study conducted here fits into the concept of critical infrastructures with a changing climate and extreme hydro-meteorological events as external influence factors. The general knowledge of the higher quantity and more intense extreme events already leads to a revision of safety standards and rules for infrastructure. One example is the new technical rule for plant safety taking into account extreme precipitation and floods released in December 2011 (COMMISSION ON PROCESS SAFETY/Kommission für Anlagensicherheit 2012). Furthermore, there are recommendations for including a so-called climate change factor into standard setting. The climate change factor, nevertheless, needs to be calculated on a regional level and also for different parameters. For example, in Baden-Wuerttemberg a climate change factor for floods was calculated based on the frequency of occurrence. As a consequence, Baden-Wuerttemberg was split into five regions with similar conditions where factors between 1.03 and 1.75 for planning issues are applied (see Section 5.3, RESEARCH GROUP KLIWA 2006). A typical case for the application would be the construction of flood protection dams and result in an increase of the freeboard. Also the system of rules DIN 1055 effects on bearing structures was revised in the 2000s. Especially the standards for the impact of wind loads (No. 4, *GERMAN INSTITUTE FOR STANDARDS*/Deutsches Institut für Normung e.V. DIN 2005a) and the impacts of snow and ice loads (No. 5, *GERMAN INSTITUTE FOR STANDARDS*/Deutsches Institut für Normung e.V. DIN 2005b) need to be mentioned in this context. Still, the standards put focus on mean values and do not deal with extreme events.

7. Conclusions, Critical Review and Outlook

7.1 Conclusions on the Results for Thermal Power Plants

The distributions of icing, frost and heat days are different. Icing in the periods 1990 - 1999 and 2000 - 2009 occurred all over Germany. Some regions with extremely cold conditions shifted from the most southern part of Germany and the north-eastern part of Germany in the 1990s to the Central Uplands and southern Germany in the 2000s. Also frost conditions can be found nationwide. Here, no obvious shift in cold conditions could be found between the two periods under investigation. Due to this, almost all thermal power plant sites experience very cold temperatures with freezing conditions. Cooler temperatures increase efficiency, according to the Carnot efficiency between the hot source in the combustion and the cold sink, e.g. air temperatures around the condenser. In contrast, coal stockpiles are affected by cold temperatures, which result in freezing coal lumps and therefore increased efforts in coal preparation.

In contrast, heat conditions were concentrated in the period 1990 - 1999 to eastern Germany and some “hot spots” well distributed over Germany. In the period 2000 - 2009, hot conditions shifted more to the western part of Germany and the northern Upper Rhine Valley. Here, rising temperatures reduce the Carnot efficiency and warmer water temperatures may lead to losses in cooling capacity due to exceeded temperature thresholds.

Hail seems to be well distributed over Germany; the GIS-based analysis for the time frame 2000 - 2009 shows most possibly affected thermal power plants rather in the northern part of Germany not going far more to the south than a virtual limit between the Rhine-Ruhr area to Dresden.

Like hail events, rain usually leads to increased weathering of building structures but seems to have no direct effects on the reliability of electricity supply. Nonetheless, heavy rain events and large hail can lead to an overflowing of power plant site drainage and can consequently cause internal flooding. A separate aspect is the erosion of coal stored on-site and the removal of large amounts of coal dust into the receiving stream.

Wind-related events like storms and tornadoes affect the electricity network around thermal power plants. Erosion of coal stockpiles is again an important point to consider. Nevertheless, severe wind gusts, storms and tornadoes can damage the towers and insulation; even damage to cooling towers was reported.

The GIS-based analyses of thunderstorm impacts on thermal power plants show four affected thermal power plants due to direct correlation. Using a 25 km buffer for a multicell influence of thunderstorms, a total number of 122 possibly affected thermal power plants is counted. This does not necessarily mean that other power plants were not influenced, but the relationship of unaffected and affected power plants outlines the importance of preparation for thunderstorm events including heavy lightning, heavy precipitation and higher than usual wind speeds. As floods and flood management are described in more detail in the case study section, no further reference is given here.

7.2 Conclusions on the Results for Hydropower Plants

For hydropower plants only few of the effects are discussed. Air temperatures are identified to have no direct effect on hydropower plants, except (pumped) storage plants which are not considered here. Heavy precipitation may lead to increased runoff and therefore increased efficiency until a runoff threshold is exceeded and the plant has to be shut down. In the period 1990 - 1999 419 hydropower plants were most likely under the influence of heavy rain events (22 %). Between 2000 and 2009 this number decreased slightly to 407 (~ 6 %) while the total number of hydropower plants increased times 3.65. Winter rain and cold temperatures, leading to snowfall, can cause blockages in the system from freezing water body surface and ice jam.

In the GIS, tornado occurrence is clipped with the zip-code accurate hydropower plants. In the period 1990 to 1999 28 hydropower plants were likely affected by tornadoes (~ 1.5 %), whereas the period 2000 to 2009 already lists 289 possibly impacted units (~ 4.2 %). Using the time slide 1990 - 1999 with a total number of 138 recorded tornado events and the time slide 2000 - 2009 with 409 recorded tornado events as the initial states for further planning, hydropower plants need to adapt against tornado impacts.

The most important effects appear to be flooding events. Increased runoff leads to increased efficiency, as long as the capacity of the turbine is not exceeded. Rising water levels can result in the plant acting as a barrier rather than an electricity supplier. That means, in case of floods, hydropower plants are used as flood protection instead of as a provider of base load electricity. In total four possibly influenced hydropower plants were registered in the period 1990 - 1999 and 96 in the period 2000 - 2009. For flash floods, 23 units are registered for 1990 - 1999 and 76 for the later period.

7.3 Conclusions on the Results for Wind Turbines

The impacts of combined rain and cold temperatures, and high wind speeds and thunderstorms, including lightning have a considerable impact on wind turbines. Low air temperatures and precipitation can lead to ice accretion that reduces efficiency and threatens the environment and the public, in the case of ice throw.

The analyses also expose an effect of hail impacts on wind turbines, which in the 1990s might have affected 14 wind turbines (< 0.5 %). In the 2000s the clipping reveals 2,498 possibly influenced wind power units (~ 13 %).

Storms and tornadoes can lead to the collapse of a tower or heavy losses, e.g. of blades. GIS analyses as well as the CWIF accident list, indicate that wind turbines are extremely vulnerable to strong winds due to their exposed location. The period 1990 - 1999 documents 179 possibly affected wind turbines due to tornadoes (3.4 %) and 25 by storms (~ 0.5 %). Between 2000 and 2009 1,778 possibly affected wind turbines are listed for tornado impacts (9 %) and 2,970 for storm impacts (15 %). Due to the lack of official information in Germany, there might have been further damages.

Lightning strike on wind turbines often leads to a complete burn down of the turbine, as their remote locations are often not accessible by the fire brigade and the nacelle is installed at heights that cannot be reached with the ladder. 24 reported accidents are due to lightning, and while only one of 5,266 wind turbine is situated in a zip code area affected by thunderstorm in the 1990s, the 2000s show 149 possibly influenced units. A buffering of 25 km around the thunderstorm single event data displays 4,682 most likely influenced turbines between 2000 and 2009. That means, about 24 % of all wind turbines in Germany might have been subject to thunderstorms. Wind turbines are discussed in more detail in Section 4. Therein, the influences and the adaptation options are implemented into the risk management concept.

7.4 Conclusions on the Results for PV Installations

Air temperatures and snowfall seem to influence the efficiency of PV installations. Nevertheless, snow loads are mentioned as one of the main causes of PV installation failure. As no precise data was found on this topic, the section shows maps, but no calculations are made.

On the other hand, sufficient data was found on the impact of hail on PV panels. The calculations reveal that in the period 1990 - 1999 about 1 % (82 in total) of all PV installations might have been subject to hail stone impact, in the period 2000 - 2009 the numbers amount to about 11 % (68,245 in total). Precise damage data can usually be found with insurance companies, although this information is not available to the public. Moreover, insurance companies can exclusively collect data which is actively reported to them.

The influences of wind, storm and tornado are not obvious, as damage is highly dependent on the accuracy of module installation and mounting. The analyses of the period 1990 - 1999 lists about 80 PV installations possibly under the influence of storms and 187 PV installations possibly under the influence of tornadoes. In the period 2000 - 2009 the numbers rose to 57,877 installations and 30,902 installations respectively. Regarding the percentages of possibly affected PV installations a clear increase is calculated for storms from about 1 % to more than 9 %, whereas the percentages of PV installations influenced by tornadoes increased from more than 2 % to about 5 %.

PV installations are also affected by thunderstorm and lightning occurrence. The maps show clearly that events are well distributed all over Germany and that cities with a high concentration of PV installation are a focus of impact. Evaluating the numbers of PV installations possibly affected therein, 114 (~ 1.5 %) installations are accounted for in the 1990s and 11,386 (~ 1.8 %) in the 2000s. As the literature study shows, in 2008, a total number of 4,200 installations were damaged, mostly due to extreme weather events.

7.5 Discussion

This subsection will provide some initial answers to the questions raised throughout the work. During the adjustment of the adaptation management process five main questions according to THOMALLA ET AL. (2006) were proposed (see Section 3.1.5):

1. *"Who and what are the exposure units?"*
2. *"What hazards and stresses are they exposed to?"*
3. *"How resilient are the exposure units to current stresses?"*
4. *"Are the exposure units and stresses changing? In what ways?"* and
5. *"What is a core set of indicators?"*

The exposure units as mentioned in Point 1 are the electricity generating units of thermal power plants, hydropower plants, wind turbines and PV installations as described in detail in Section 1. Biomass power plants are not included in this research as they are not categorised as large thermal power plants nor as electricity generating units as such. Deep geothermal power plants on the other hand are not included since they are usually not subject to extreme hydro-meteorological events. Near surface geothermal units are not listed as electricity generating units but heat generating units and are not affected by extreme events. Moreover, additional impacts compared to conventional building structures, e. g. housing or thermal power plant buildings, are not expected.

The hazards, respectively stresses, the identified exposure units are affected by are the extreme hydro-meteorological event defined in Section 2.1. Here, the types of temperature-, precipitation- and wind-related events as well as combined events are distinguished.

The question on resiliency might be answered by referring to standards and rules for planning, construction, set up and operation. Nevertheless, the resiliency is highly site-specific and cannot be answered in general.

The exposure units as well as the stresses are changing. By installing new capacity an increase in number of exposure units is expected. Moreover, the statistical analyses showed that the number of extreme events increased in the past decades (see Section 3.3).

The work established a core set of indicators by introducing the risk index into the analyses (Section 6.2) and combined the current approaches of risk management into enhanced approaches of climate mitigation concepts and corporate risk management with regard to climate change adaptation. Current risk management chains and even the risk management cycles show gaps regarding integrated sustainable planning. Nevertheless, this initial state could be used to enlarge and complement the cycles as shown in Section 5.3 for thermal power plants.

This cycle of plan, do, check and act can be used for local planning in the same way as for corporate risk management (Figure 42). Using the same steps as in the case study, the flow chart looks as follows:

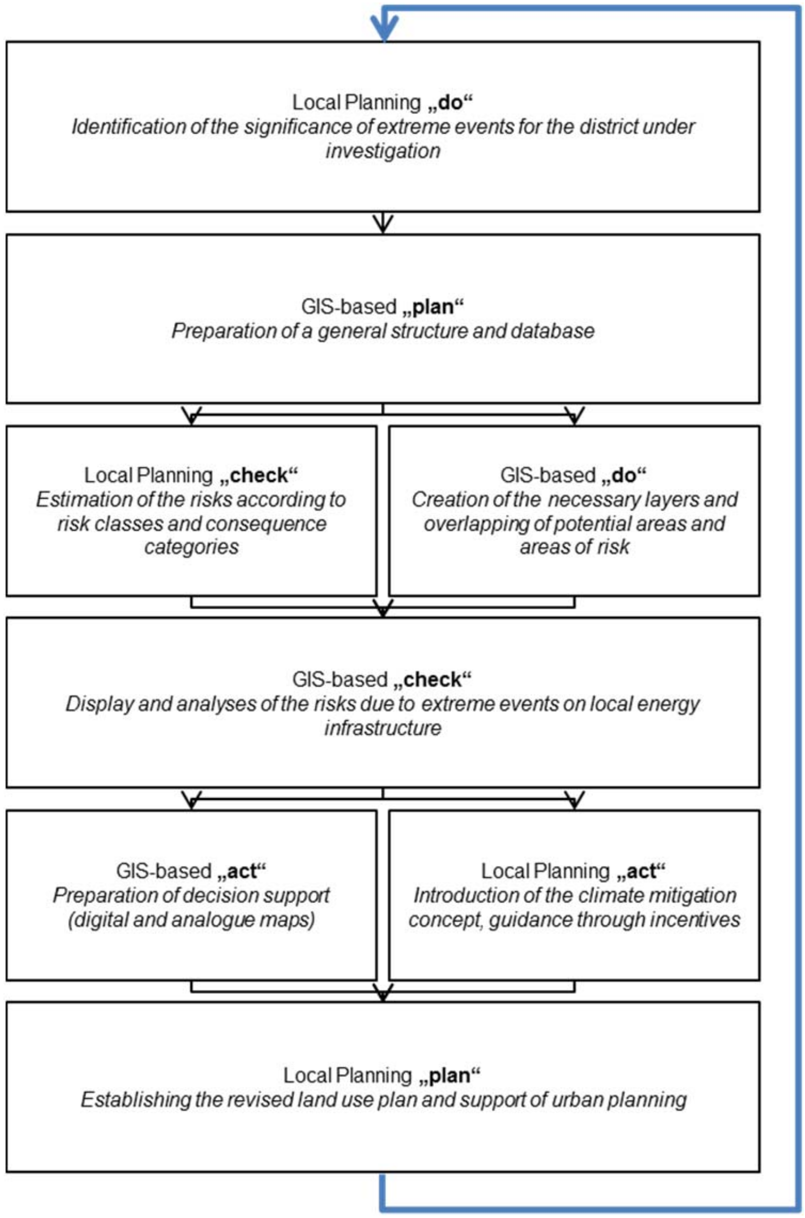


Figure 42: Plan, do, check and act cycle for local planning and implementation into enhanced climate mitigation concepts

Step 1 local planning “do” represents the identification of the significance of extreme hydro-meteorological events for the districts. The section on the risk index facilitates this identification. The GIS-based “plan” is the preparation of the general structure and database for the assessments needed in a climate mitigation concept and represents the basic step of every GIS-application. While local planning “check” and GIS-based “do” run in parallel, the necessary estimation of the risk classes and consequence categories as well as the creation of layers and overlappings are conducted. Within the GIS-based “check” the results of the analyses are displayed for the local electricity infrastructure. Here, outlooks on infrastructure to be installed can be mapped by using potential areas and an overlay with risk areas. Then again, GIS-based “act” and local planning “act” run in parallel. By preparing the decision support in form of maps and introducing the established climate mitigation concept to the public. The last step of local planning “plan” finalises the management cycle. Here, a revision of the land use plan takes place as described in Section 4.1 to support the installation of new renewable energy units.

This is a first design on how the plan, do, check and act cycle can be introduced into local planning as a standard concept which is in line with the common approaches of climate mitigation concepts. Until now, using GIS-based analysis in detail is not yet regular procedure. Instead, a lot of potential analyses are based on statistical information on land use, population and other demographic facts. Moreover, by using GIS for the estimation of potentials, information on extreme events and possible exclusion areas could be implemented easily and add to the quality of the assessment.

The working group “ACCLIMATISE” in the Oxford Carbon Disclosure Project (2008) proposed a catalogue of ten questions for directors and operators. The work presented here provides first answers to these questions in terms of corporate risk management (Table 50 and 51).

Table 50: 10 questions to directors and operators (ACCLIMATISE 2008, pp. 16-17) (continued on following page)

Question	Possible answers derived from analyses
1. “What are the operational impacts of climate change on your company?”	The possible effects are listed in section 2 “identification of influences on power plants and structures”.
2. “Which of your company’s key operating assets are located in areas vulnerable to climate change impacts and what are the implications?”	Cost calculations are highly confidential and can therefore not be done here.
3. “How sensitive is demand for your products and services to climate change impacts?”	Customers of electricity request a high amount of renewable energies. Still, there is need to provide base load which is until now not possible only by using renewable energies. Moreover, a blackout due to changing climate parameters needs to be avoided.
4. “How could current and future climate change regulations and industry standard affect your organisation and its reputation?”	Yes, renewed standards need to be implemented in risk management and emergency planning. Media, NGO and public awareness is high.
5. “What new and enhanced existing products and services can you offer yours customers?”	Services might change from conventional to renewable energies. Products and services for public adaptation depend on type of power plant. Adaptation measures will increase the reliability
6. “What operational benefits could you enjoy from managing your response to climate change?”	Not all influences of extreme weather have negative consequences, higher runoff leads to an increase in electricity production in hydropower plants, less cloudiness increases generation in PV installations and temperatures have influences on generation and transport.
7. “How clear and effective are your company’s internal management responsibilities for climate change and your engagement with stakeholders?”	These are internal information and therefore not included here.

Table 51: 10 questions to directors and operators (ACCLIMATISE 2008, pp. 16-17) (continued from previous page)

8. "How well structured is your company's approach for managing climate change?"	The identification of the general risks is made in the analyses here and can be used to generate site-specific information and procedures.
9. "How can you ensure your company's approach is based on robust information and assumptions?"	Power plant operators have to make sure to take robust information as a basis, e.g. by the *German Weather Service* including fore- and hindcasts. Own GIS-based analyses can back their capacity to use this information properly.
10. "How can you demonstrate that your company's climate business resilience plans are realistic and financially viable?"	Management and financial plans are updated regularly and declared to the public in quarterly terms. The involvement of staff is important especially in case of an emergency.

A similar questionnaire can be established for cities and districts in order to get prepared. The ten questions and possible answers are now provided in the following Table 52 and 53:

Table 52: 10 questions to local planners and operators of distributed renewable energies (adapted according to ACCLIMATISE 2008, pp. 16-17) (continued on following page)

Question	Possible answers derived from analyses
1. "What are the impacts of climate change on your district?"	The possible effects are analysed in sections 4.2 and 5.2
2. "Which of your cities/districts key assets are located in areas vulnerable to climate change impacts and what are the implications?"	This question can only be answered after a detailed evaluation of the land use plan
3. "How sensitive is demand for your products and services to climate change impacts?"	Each sector and infrastructure has demand for electricity, therefore, districts are very sensitive to potential blackouts
4. "How could current and future climate change regulations affect your organisation and its reputation?"	New regulations on potentials (e.g. priority areas for wind turbine installation) are supposed to simplify the installation of renewable energies in the German Energy Turnaround process. Other regulations address the safety of the installation itself. Thus, climate change regulations should have a positive effect for districts and local planning
5. "What new and enhanced existing products and services can you offer yours customers?"	The catalogue of measures usually includes general measures addressing incentives, consulting services and role model character
6. "What benefits could you enjoy from managing your response to climate change?"	Benefits are individual for each district and need further analyses
7. "How clear and effective are your management responsibilities for climate change and your engagement with stakeholders?"	Climate change management should be included in every land use planning. For the implementation of climate mitigation concepts new positions can be created (called Klimaschutzberater/climate mitigation consultant) or the responsibilities within the departments can be re-structured

Table 53: 10 questions to local planners and operators of distributed renewable energies (continued from previous page)

8. "How well structured is your district's/city's approach for managing climate change?"	Leads to another question: is there already a climate mitigation concept and in which phase is it? Do we need to implement extreme weather events as a regulating factor or is the district's infrastructure not at risk? Those questions cannot be answered in the context of this work.
9. "How can you ensure your district's / city's approach is based on robust information and assumptions?"	This question must be answered by the district. Recommendations are to ensure to implement a robust climate mitigation concept and access robust data sources (e.g. census, *German Weather Service*).
10. "How can you demonstrate that your climate mitigation concept is realistic and financially viable?"	The answer to that question evolves in time. Still, there are possibilities to check climate mitigation concepts regularly (e.g. every five years) to ensure that the catalogue of measures leads to the district's goals.

Both questionnaires can implement a GIS-based approach as describes throughout this work especially in questions No. 1, 2, 7, 9 and 10. In each case the GIS-based approach as developed throughout this work can answer the questions of the temporal and spatial distributions of impacts by using its strength as an analysis tool and support demonstration and public relations by applying its advantages as a mapping tool.

7.6 Outlook and Critical Review

A focus on the extreme hydro-meteorological events heavy rain, hail, storms, floods and flash floods, thunderstorms and lightning and tornadoes displays the forecast and the 30 year moving average from 1980 - 2009 into the future until 2030. Here it becomes clear that all of these extreme events show an upward trend. The forecast function as provided by Excel 2010® with a linear regression analysis into the future should not be regarded as a sufficient forecast tool for extreme events but it is used in this context as an instrument to illustrate the upward trend. Therefore, adaptation measures as described in the Section 2.3.2 for hydropower plants, wind turbines and PV installations become more necessary in the future in order to provide a sustainable and secure electricity supply.

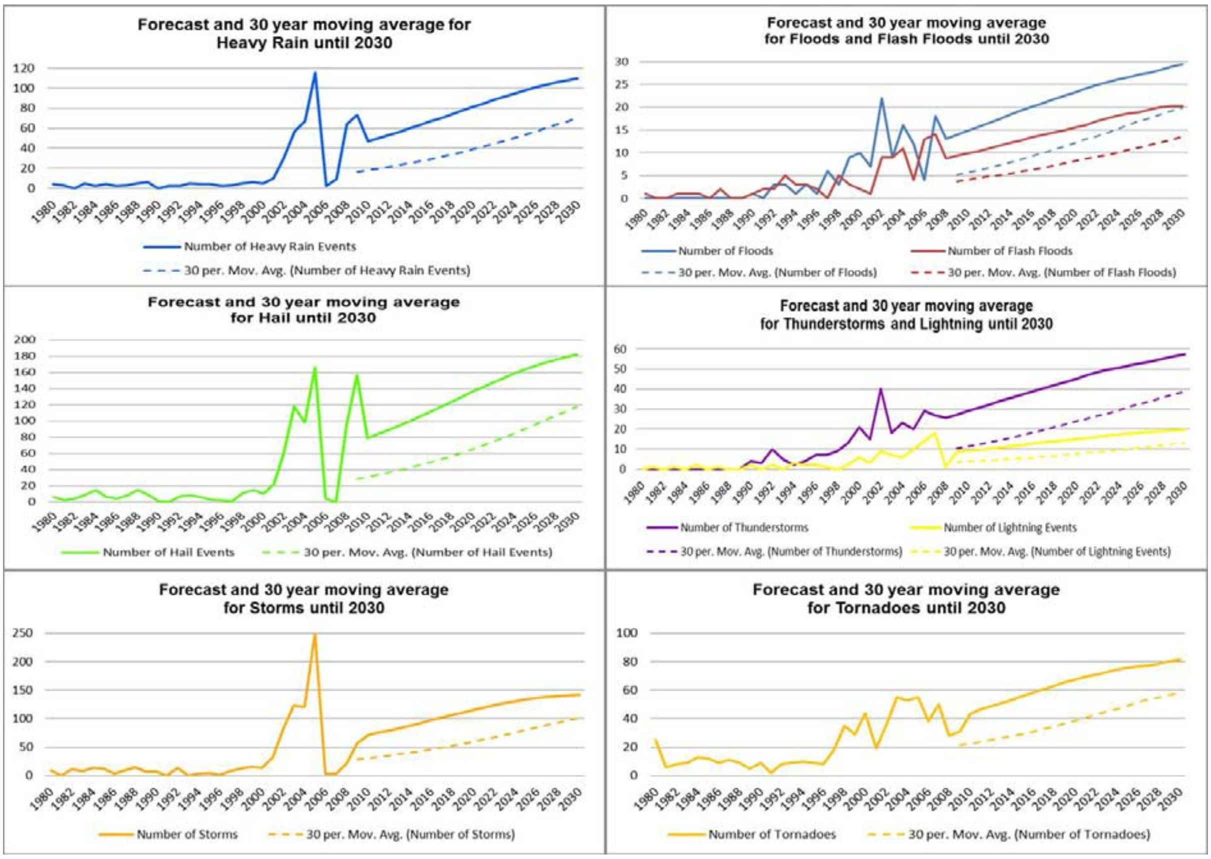


Figure 43: Forecast and 30 year moving averages for the extreme hydro-meteorological events heavy rain, hail, floods and flash floods, thunderstorms and lightning, storms and tornadoes

Referring to the terms of a “low carbon society” or the “2 °C” goal, the renewable energies of PV installations, wind turbines and hydropower plants were investigated more detailed in this risk analysis. By analysing the consequence categories for renewable energies it could be demonstrated that the risk increased from the period 1990 - 1999 to 2000 - 2009. In almost any case the number of none or low affected districts decreased while the number of medium to highly affected areas increased. Some considerable changes are highlighted again:

- Concerning affected districts with hydropower plants, the numbers in the consequence categories from medium to high increased for all impacts. The total number of eight wind affected districts in the 1990s increased to 122 districts in the 2000s. The precipitation consequences shifted from seven affected districts to 91 districts and the number of affected districts due to thunderstorms and lightning rose from five between 1990 - 1999 to 45 between 2000 - 2009 respectively.
- Pointing out the situation of PV installations, only the categories of no or low consequences decreased while every other category gained in the count of affected districts. This is mainly because of the extremely rising number of installed PV panels. Here, the difference between consequence categories due to precipitation-

related events is highest. While in the 1990s 352 districts were not affected, only 114 districts were left in this category in the 2000s. However, PV installations are well protected against the influence of heavy rain events.

- The effects of extreme wind- and precipitation-related events on wind turbines resulting in medium-high to high consequences increased from 3 districts in the 1990s to 68 districts in the 2000s. Reasons for this shift cannot only be explained by the installation of a high number of new wind turbines but also by the increased number of extreme events in these categories.

The results of the analyses and the previous discussion leads back to the initial research questions:

The first question deals with vulnerability: Which regions or districts in Germany and which electricity generating units are especially influenced by extreme weather events?

This question was mostly answered in Sections 2.2, 4.2 and 5.2. Section 2.2 showed in a literature review which electricity generating infrastructures already are subject to impacts of extreme hydro-meteorological events. In order to structure the information, extreme hydro-meteorological events are categorised as “temperature-related”, “precipitation-related” and “wind-related” events as well as combined events where several parameters occur in combination. Moreover, electricity generating infrastructure was separated into thermal fossil-fuel power plants, nuclear power plants and the renewable energies of hydropower plants, wind turbines and PV installations. Complementary information on on-site distribution and storage infrastructure completed this first part of the thesis. In Sections 4.2 and 5.2 the information is combined into GIS-based analyses of the spatial and temporal distribution of extreme hydro-meteorological events of all types and the possibly affected infrastructure. In this analysis, districts with possibly affected infrastructure are highlighted according to the number of installations and the type of extreme event in the period 1990 - 1999 and 2000 - 2009. As additional results the analyses illustrate the development of the installation of electricity generating units as well as the development of extreme events. The increase in risk is based on the construction of additional infrastructure but also on increasing numbers of extreme events.

The second question on adaptation and risk management is: How can electricity generating units or regions be protected?

The corporate risk management as well as the enhanced climate mitigation concepts exemplified in sections 4.3 and 5.3 are basic approaches for future development of energy infrastructure. The catalogue and analysis of adaptation measures (section 2.3 and

Appendix A) give an overview on options already available. Still, there is the possibility to improve infrastructure as well as planning approaches considering climate change as a major influence. This thesis should be perceived as a foundation for further work in the light of the German Energy Turnaround and the national and regional climate change goals.

The third main question includes the decision-making process: How do local planning or corporate risk management deal with this vulnerability?

Classical management processes and cycles are very useful for the set-up of site-specific or local planning. Sections 4.1 and 5.1 focused on the background and development of climate mitigation concepts and corporate risk management and where the gaps are addressed. Until now, for climate mitigation concepts adaptation is considered a less important topic so that especially the potential analysis and the catalogue of measures concentrate on mitigation and how to secure electricity supply. In this context, (high) risk areas are not excluded from the potential areas. Sometimes very high potentials are identified even though the district should pay attention to the possibility and severity of the impacts of extreme hydro-meteorological events. The example of Osnabrück in section 6.3 illustrates this conflict explicitly. Nevertheless, the basic concept by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety includes the option to combine adaptation and mitigation. Even more, some districts used GIS-based approaches for the potential analysis where the implementation of further databases on risks and consequences can be easily done and adds to the quality of information. On the other hand, corporate risk management until now focuses strictly on the impacts the facility might have on the environment and excludes an analysis of environmental impacts on the facility. Regulations like the EMAS or ISO 14 000 underline this with experience. This thesis showed that influences by extreme events as well as adaptation options should be considered in corporate risk management and emergency planning at all industrial and electricity generating sites. The work on NaTechs emphasizes this conclusion. There is no final answer on how local planning and corporate risk management deal with the vulnerability as this is an individual task. Hence, the present assessment can only guide local planning and corporate risk management to implement adaptation as well as mitigation into future concepts and solutions.

As TEUTEBERG & STRAßENBURG (2009) point out, more research needs to be conducted to join practical site information and risk management with extreme weather impacts as a driving force for considerable company performance. A principle recommendation is established in this work on the "Impacts of extreme hydro-meteorological events on electricity generation and possible adaptation measures – a GIS-based approach for corporate risk management and enhanced climate mitigation concepts in Germany".

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8.4 Sources of Figures

Coverpage: Collage of a thermal power plant, a bank dam and wind energy plants in the United States of America: Private archive SIEBER 2011, PV installations damaged by snow load: courtesy of ©GESAMTVERBAND DER DEUTSCHEN VERSICHERUNGSWIRTSCHAFT (GDV) n.d. (http://service.gdv.de/fotoservice/cgi-bin/page.pl?page=521&cat=3)

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Appendices

Appendix A: Overview on Adaptation Measures

List of adaptation measures. The first column names the technology of electricity generation for which the adaptation measure in the second column applies most commonly. The third column contains the context (time frame, hard/soft measure). The fourth column contains the parameter on which the measure has an effect, the last column contains the source

Technology	Adaptation measure	Context	Extreme Weather Parameter	Source
conventional	Robustness improvement in resource mining (coal, gas, oil, nuclear)	hard, structural	storms (esp. offshore)	The World Bank, ESMAP (n.d.)
conventional	Robustness improvement in resource mining (coal, gas, oil, nuclear)	hard, structural	flood/low water (inland)	The World Bank, ESMAP (n.d.)
conventional	Cooling system adaptation (from wet to dry cooling options)	soft	low water/high water temperatures	The World Bank, ESMAP (n.d.), Krysanova & Hattermann (2009)
conventional	Recirculation cooling systems	soft	low water/high water temperatures	The World Bank, ESMAP (n.d.)
conventional	Design of gas turbines improvement	soft	air temperature	The World Bank, ESMAP (n.d.)
conventional	Underground transfer and distribution structures	soft	air temperature, runoff, precipitation, wind	The World Bank, ESMAP (n.d.)
conventional	Relocation	behavioral	flood/low water (inland)	The World Bank, ESMAP (n.d.)
conventional	emergency planning	anticipation	all	The World Bank, ESMAP (n.d.)
conventional	on-site drainage improvement	operation & maintenance	precipitation, flood	The World Bank, ESMAP (n.d.)
conventional	Coal handling	operation & maintenance	precipitation, wind	The World Bank, ESMAP (n.d.)
conventional	regulation renewal	operation & maintenance	all	The World Bank, ESMAP (n.d.), Mirza (2006)
conventional	Increase re-use of water	operation & maintenance	precipitation, runoff, air temperatures	The World Bank, ESMAP (n.d.)
hydropower	increase dam heights	hard, structural	runoff	The World Bank, ESMAP (n.d.)
hydropower	construction of dams upstream	hard, structural	runoff	The World Bank, ESMAP (n.d.)

List of adaptation measures (continued)

Technology	Adaptation measure	Context	Extreme Weather Parameter	Source
hydropower	increase river channel capacity	hard, structural	runoff	The World Bank, ESMAP (n.d.)
hydropower	Optimise reservoir management	soft	runoff	The World Bank, ESMAP (n.d.)
hydropower	location planning improvement	behavioral, (re)location	runoff	The World Bank, ESMAP (n.d.)
hydropower	runoff adapted scheduling	anticipation	runoff, precipitation	The World Bank, ESMAP (n.d.)
wind energy	Turbine design improvement	soft	wind speed	The World Bank, ESMAP (n.d.)
wind energy	location planning improvement	behavioral, (re)location	wind speed, flood, sea level rise	The World Bank, ESMAP (n.d.)
PV installations	Panel design improvement	soft	storms	The World Bank, ESMAP (n.d.)
PV installations	location planning improvement	behavioral, (re)location	cloudiness	The World Bank, ESMAP (n.d.)
PV installations	emergency planning	anticipation	all	The World Bank, ESMAP (n.d.)
water management	central data collection and handling	low-regret	all	Wilby & Dessai (2010)
water management	Monitoring of reference parameters	low-regret	all	Wilby & Dessai (2010)
water management	Model improvement	low-regret	all	Wilby & Dessai (2010), Fankhauser et al. (1999), Auld, MacIver & Klaassen (2007)
water management	Increase of understanding and research	low-regret	all	Wilby & Dessai (2010), Fankhauser et al. (1999), Mirza (2006), Auld, MacIver & Klaassen (2007)
water management	Improvement of forecast capacity	low-regret	all	Wilby & Dessai (2010), Auld, MacIver & Klaassen (2007)
water management	High resolution models, forecasts and monitoring (temporal and spatial)	low-regret	all	Wilby & Dessai (2010)
generating facilities	Increasing local flood protection	hard, structural	flood	Rademaekers et al. (2011)

List of adaptation measures (continued)

Technology	Adaptation measure	Context	Extreme Weather Parameter	Source
generating facilities	supply of mobile flood protection measures	hard, structural	flood	Rademaekers et al. (2011)
generating facilities	(re)location of structures	hard, structural	flood	Rademaekers et al. (2011)
transport/distribution	Gas Insulated Lines	hard, structural	drought/air temperature	Rademaekers et al. (2011)
transport/distribution	Soil conditions monitoring (underground cables)	soft	drought	Rademaekers et al. (2011)
transport/distribution	Management of lines	soft	air temperature	Rademaekers et al. (2011)
transport/distribution	Temperature-adapted transformers	hard, structural	air temperature	Rademaekers et al. (2011)
transport/distribution	Temperature-adapted lines and conductors	hard, structural	air temperature	Rademaekers et al. (2011)
connected infrastructure	adapted construction of roofs and fundaments	hard, structural	n.s.	Ott & Richter (2008)
connected infrastructure/electricity generating facilities	protection measures construction	hard, structural	all	Ott & Richter (2008)
connected infrastructure/electricity generating facilities	retrofitting of protection measures	hard, structural	all	Ott & Richter (2008)
conventional	alternative cooling systems	hard, structural	air temperature, water temperature, runoff	Ott & Richter (2008)
transport/distribution	underground cables instead of overhead wires	hard, structural	air temperature, wind, thunderstorm & lightning	Ott & Richter (2008)
electricity generating facilities	protection by dikes, dams and floodplain management	hard, structural	flood	Ott & Richter (2008)
wind energy	anti-freeze technologies and coatings	hard	air temperature, precipitation	Clariant (2010), BASF (2010)

List of adaptation measures (continued)

Techno-logy	Adaptation measure	Context	Extreme Weather Parameter	Source
	dams, dikes, embankments	hard, structural	flood	Kundzewicz & Kaczmarek (2000), Hooijer et al. 2004), Green (2004), EEA (2004), Mansanet-Bataller et al. (2008)
	flood control reservoirs	hard, structural	flood	Kundzewicz & Kaczmarek (2000), Hooijer et al. 2004), Government of Canada (2009)
	channel capacity planning	hard, structural	flood	Kundzewicz & Kaczmarek (2000), Government of Canada (2009)
	polders, ponds	hard, structural	flood	Kundzewicz & Kaczmarek (2000)
	land-use planning and flood area planning	hard, structural	flood	Kundzewicz & Kaczmarek (2000), Hooijer et al. 2004)
	flood proofing	hard, structural	flood	Kundzewicz & Kaczmarek (2000)
	zoning	soft	flood	Kundzewicz & Kaczmarek (2000)
	restricted or prohibited land	soft	flood	Kundzewicz & Kaczmarek (2000)
	careful planning of housing and structuring	soft	flood	Kundzewicz & Kaczmarek (2000), Hooijer et al. 2004)
	flood insurance	soft	flood	Kundzewicz & Kaczmarek (2000)
	flood forecasting and warning	soft	flood	Hooijer et al. (2004), Government of Canada (2009)
	controlled and uncontrolled retention	hard, structural	flood	Hooijer et al. (2004)
	Coal stockpile covering	hard, structural	wind, precipitation, thunderstorm & lightning	Fierro et al. (1999)
	renew and improve plans	soft	all	Fankhauser et al. (1999)
	concepts of legal, regulatory and socio-economic thresholds	soft	all	Fankhauser et al. (1999), Energy Networks Association (2009), Auld, MacIver & Klaassen (2007)
	emergency planning	soft	all	EEA (2010)

List of adaptation measures (continued)

Technology	Adaptation measure	Context	Extreme Weather Parameter	Source
	building of resistant and solid infrastructure	hard, structural	wind	EEA (2010)
hydropower	operation planning, resource scheduling	hard, structural, soft	runoff, precipitation	EEA (2004), Government of Canada (2009), Leipprand et al. (2008)
connected infrastructure	poles and masts replacement	hard, structural	thunderstorm & lightning, wind	Energy Networks Association (2009), Bailey & Levitan (2008)
connected infrastructure	increase clearance to overhead wires	hard	thunderstorm & lightning, wind	Energy Networks Association (2009)
connected infrastructure	replace overhead networks with underground cabling	hard	thunderstorm & lightning, wind, precipitation	Energy Networks Association (2009)
coal stockpiles, connected infrastructure	protective walls	hard, structural	wind, precipitation, thunderstorm & lightning, air temperature (icing effects)	Chakraborti (1995), Cal et al. (1983)
coal stockpiles, connected infrastructure	agent spraying	hard, structural	wind, precipitation, air temperature (icing effects)	Chakraborti (1995)
coal stockpiles, connected infrastructure	drainage system improvement	hard, structural	precipitation, runoff	Chakraborti (1995), Auld, Klaassen & Comer 2007
conventional	water re-use and recovery	hard, structural, cooling system	runoff, precipitation, water temperatures	U.S. DOE/NETL (2006)
conventional	use of non-traditional waters	hard, structural, cooling system	runoff, precipitation, water temperatures	U.S. DOE/NETL (2006)
coal stockpiles, connected infrastructure	stockpile shape and orientation optimisation	hard, structural	wind, precipitation, runoff	Cal et al. (1983)
connected infrastructure	improvement of metal-sided structures, replacement with concrete-sided structures	hard, structural	wind, precipitation, thunderstorm & lightning, runoff	Budnitz (1984)

List of adaptation measures (continued)

Technology	Adaptation measure	Context	Extreme Weather Parameter	Source
connected infrastructure	ring walls and levees	hard, structural	runoff	Abi-Samra & Henry (2011)
connected infrastructure	elevated installation	hard, structural	runoff	Abi-Samra & Henry (2011)
connected infrastructure	permanent and non-permanent barriers	hard, structural	runoff	Abi-Samra & Henry (2011), van der Vat (2007)
wind energy	heating systems for gearboxes, blades and other moving parts	hard, structural	air temperature, wind, precipitation	Ackermann & Söder (2000), Laakso et al. (2003)
conventional	use of treated and recirculated process water	hard, structural	water temperature, runoff	Feeley III et al. (2008)
conventional	recovery of flue gas	hard, structural	water temperature, runoff	Feeley III et al. (2008)
connected infrastructure	modification of transmission lines, generators, transformers	hard, structural	runoff, precipitation, wind	Government of Canada (2009)
connected infrastructure	waterproof membranes for concrete-sided structures	hard, structural	runoff, precipitation, (wind)	Auld, Klaassen & Comer (2006)
connected infrastructure	relocation and re-elevation	hard, structural	runoff, precipitation	Pirker & Wiesinger (2005), Auld, MacIver & Klaassen (2007)
PV, wind energy	lightning protection (rods)	hard, structural	thunderstorm & lightning	GDV (2003)
hydropower	installation/retrofitting of turbines	hard, structural	runoff, precipitation	Leipprand et al. (2008), Rademaekers et al. (2011)
conventional, hydropower	reductions in demand	soft	drought, water temperature	Kundzewicz & Kackmarek (2000)
conventional, hydropower	"room-for-rivers"-concept	hard, soft	runoff	Hooijer et al. (2004)
	increase knowledge, awareness, training, management	soft	all	Auld, MacIver & Klaassen (2007)
	"climate change adaptation factors "in planning	soft	all	Auld, MacIver & Klaassen (2007)
	include climate change in engineering practice	hard, soft	all	Auld, MacIver & Klaassen (2007)

Appendix B: Comments on Heavy Precipitation Events

Comments on heavy precipitation events, units are kept and are indicated individually

Location	Date	Comment	Location	Date	Comment
München	14.06.2005	64 mm/30 min	Audenhain	12.04.2008	33 mm/8 h
Eschwege	03.06.1981	> 100 mm/24 h	Consrade	22.06.2008	33.1 mm/3 h
Eltmannshausen	03.06.1981	> 100 mm/24 h	Langeln i. Harz	21.06.2005	34.1 mm/1.5 h
Wernigerode, Blankenburg	21.06.2005	100 mm/12 h	Freiburg, -Zähringen	29.05.2008	34.4 mm/1 h
München	17.05.2000	100mm/1 h	r. Sankt Wendel	30.05.2008	35 mm/ 30 min
Teublitz	12.09.2008	108.4 mm/6 h	Staßfurt	31.05.2008	35 mm/6 h
Puch b. Fürstenfeldbruck	18.05.2002	109 mm/6.5 h	Kirchlinteln	03.07.2008	36 mm/1 h
Dingelbe	26.05.2009	11 mm/ 5min	Dresden, -Gruna	31.05.2008	36 mm/90 min
Dülmen	01.05.2004	110mm / 12 h	Irschenberg	18.07.2005	37 mm/1 h
Buldern	01.05.2004	110mm / 12 h	Balingen	16.07.2003	37.1 mm / 1 h
Russee	21.05.1983	12 mm in 8 min	Deutsch Evern	15.07.2005	38.7 mm/6 h
Quickborn	23.07.2001	120mm / 4 h	Wendisch Evern	15.07.2005	38.7 mm/6 h
Detmold	08.06.2003	121 mm/4 h, 54mm/ 1 h	Groß Börnecke	31.05.2008	39 mm/6 h
Bad Königshofen	09.08.1988	126.8 mm / 5 h	Schwarze Ahe	07.08.2004	40 mm/12 h
Bischofswiesen b. Berchtesgaden	06.08.2002	131 mm/12 h	Siegburg	07.08.2004	40 mm/15 min
Nürnberg	29.07.2005	14 mm/12 min	Köln	29.07.2005	40 mm/3 h
Dortmund	26.07.2008	148 mm/90 min	München-Flughafen	15.06.2007	40.5 mm/3 h
Nordenham	27.03.2006	15 mm/1 h	Dieskau b. Halle a.d. Saale	29.07.2005	40.7 mm/1 h
Lübbenau	26.05.2009	15 mm/15 min	Kyritz	17.07.2009	41 mm/1 h
Klotzsche	12.08.2002	158 mm/24 h	Bad Salzuflen	08.10.2009	41 mm/12 h
Marienberg i. Erzgebirge	05.07.1999	160 mm/2h	Lützel, Altenteich, Erndtebrück	09.07.1995	42 mm/1 h
Riestedt	31.05.2008	17 mm/25 min	Audenhain	29.07.2005	42 mm/1.5 h
Oppenau	27.06.1994	177 m/1.25 h	Wunstorf	08.10.2009	42 mm/12 h
Bayern, Baden-Württemberg	20.05.1999	177mm/24 h (Landsberg)	Straelen	23.11.2009	42.6 mm/12 h
Groß-Rohrheim	31.05.2008	18 mm/ 15 min	Neukirchen	17.07.2003	42-52 mm/1 h
Hersbruck	29.06.2005	180 mm/1 h	Teisendorf	17.07.2003	42-52 mm/1 h
Kaisheim	22.05.2009	20 mm/1 H	Osnabrück	08.10.2009	43 mm/12 h

Comments on heavy precipitation events, units are kept and are indicated individually (continued)

Location	Date	Comment	Location	Date	Comment
Gunzenheim	22.05.2009	20 mm/1 h	Balingen	25.06.2005	43 mm/24 h
Weilmünster	15.07.2005	20 mm/10 min	Lichtenberg	02.07.2009	44 mm /1 h
Achtum	26.05.2009	20 mm/20 min	Neuenstadt am Kocher	01.09.2008	44.1 mm/1 h
Jerichow	21.06.2005	20 mm/30 min	Geldern-Walbeck	29.07.2005	45 mm/1 h
Mannheim	31.05.2008	21.2 mm/15 min	Burscheid	06.08.2007	45 mm/2 h
Ludwigsburg	29.07.2005	21.3 mm/5 min	Rulle	02.06.1993	45 mm/45 min
Ahrensfelde	01.09.2008	22 mm/ 20 min	Metzingen-Neuhausen	25.06.2005	46 mm/24 h
Grissenbach	25.05.2009	23.5 mm/30 min	Wustweiler	27.07.2008	47 mm/1 h
Schuttertal	29.05.2008	25.2 mm/30 min	Naumburg a.d. Saale	21.07.2004	47 mm/45 min
Aachen	25.04.2006	26 mm/2 h	Birkigt	31.05.2008	48 mm/ 1 h
Zwickau	29.07.2005	26 mm/37 min	Sexau b. Freiburg	09.09.2005	48 mm/1 h
Freudenstadt	29.07.2005	27 mm/10 min	Elbtal	26.07.2008	48.3 mm/45 min
Eutingen	29.07.2005	27 mm/10 min	Berlin	30.06.2009	49 mm/45 min
Ebersdorf	25.06.2005	27 mm/20 min	Bischofsgrün	18.04.2009	49.3 mm/24 h
Ringsleben	11.07.2008	27 mm/45 min	Neustrelitz	09.07.2005	50 mm/1 h
Biebesheim	31.05.2008	28 mm/ 25 min	Wangerooge	03.10.2008	50 mm/24 h
Sonsbeck	29.05.2008	28.1 mm/20 min	Winhöring	22.05.2005	50 mm/30 min
Dösen	02.07.2009	30 mm/ 20 min	Neuenbau	01.10.2008	50.1 mm/24 h
Petershausen	26.05.2009	30 mm/ 30 min	Eckenhagen	01.10.2008	50.2 mm/ 24 h
Lütgendortmund	26.07.2008	30 mm/15 min	Pellworm	03.10.2008	50.5 mm / 24 h
Lübeck	28.07.2005	30 mm/30 min	Bückeburg	08.10.2009	51 mm/12 h
Travemünde	28.07.2005	30 mm/30 min	Duisburg	08.06.2003	51.4 mm/24 h
r. Bautzen	31.05.2008	30 mm/30 min	Höckendorf	02.07.2009	52 mm/1 h
Bad Salzuflen	29.07.2005	30.8 mm/1 h	Winnweiler	31.07.2008	52.3mm/24 h
Kritzow	22.06.2008	31 mm/10 min, 44 mm/6 h	Augsburg	12.04.1994	52.9 mm/24 h
Hilter	08.06.2003	31 mm/30 min	Bamberg	07.07.1996	53.7 mm/24 h
Gesmold	08.06.2003	31 mm/30 min	Offenbach	23.07.2004	53.8 mm/1 h
Bissendorf	08.06.2003	31 mm/30 min	Redlendorf	01.10.2008	53.9 mm/24 h
Zinnwald	12.08.2002	312 mm/24 h	Bissendorf	29.06.1997	54 mm / 30 min
Südkamen	26.07.2008	32 mm/30 min	Hilter	29.06.1997	54 mm/30 min
Tübingen	12.06.2003	66mm/1 h	Wellingholz-hausen	29.06.1997	54 mm/30 min
Memmingen	05.06.2002	67 mm/ 24 h	Klotzsche	31.08.1995	54.3mm / 24 h
Munderkingen	25.06.2005	67 mm/2 h	Bad Bentheim	01.10.2008	55 mm/24 h
Stromberg	31.07.2008	67 mm/24 h	Helgoland	03.10.2008	56.8 mm/ 24 h
Zinnwald	08.07.2004	67.2 mm/1 h	Sotzweiler	27.07.2008	57 mm/1 h

Comments on heavy precipitation events, units are kept and are indicated individually (continued)

Location	Date	Comment	Location	Date	Comment
Potsdam	01.08.1991	68 mm/24 h	Baruth Kr. Teltow-Fäming	29.07.2005	57 mm/12 h
Markdorf	26.05.2009	69 mm/ 10 h	Bonn	23.07.2004	57.5 mm/75 min
Röbel a.d. Müritz	09.07.2005	70 mm/1 h	Augsburg	21.05.1999	57.7 mm/24 h
Hakeborn	31.05.2008	70 mm/6 h	Altenberg	08.07.2004	57.8 mm/1 h
Pulheim	11.09.2008	71 mm /24 h	Echternach b. Trier	29.07.2005	58 mm/2.5 h
Grüngräbchen	02.07.2009	74 mm/1 h	Schierke	04.07.2008	59.6 mm/24 h
Klotzsche	06.07.1999	76.6 mm/24 h	Thailen	27.07.2008	60 mm/1 h
Greiz b. Gera	25.07.1989	77 mm / 0.5 h	Monheim a. Rhein	05.06.1992	60 mm/1 h, 75 mm/2 h
Klotzsche	02.08.1998	77.4 mm/ 24 h	Diedorf b. Augsburg	07.06.2002	60 mm/2 h
Schwenda	10.05.2004	78 mm/1 h	Klotzsche	13.05.1995	60.4mm /24 h
Auerberg	10.05.2004	78 mm/1 h	Eilenburg b. Leipzig	29.07.2005	62 mm/12 h
Bergheim	08.08.2007	79.3 mm/15 h	Spiekeroog	03.10.2008	63.5 mm/24 h
Ahlen	16.07.2003	79.4 mm / 24 h	Berlin	04.07.1992	64.9 mm/24 h
Drensteinfurt	16.07.2003	79.4 mm / 24 h	Goslar	30.06.1988	65 mm/1 h
Forndorf	31.05.2003	80 mm/1 h	Osnabrück	28.07.2005	65 mm/2.5 h
Rheinsberg	29.06.1994	81.4mm/24 h	Deutschneudorf	26.05.2003	65 mm/30 min, hail layer 50 cm
Neuruppin	12.06.1993	83.1 mm/24 h	Seiffen	26.05.2003	65 mm/30 min, hail layer 50 cm
Potsdam	12.08.2002	84.1 mm/24 h	Neuhausen	26.05.2003	65 mm/30 min, hail layer 50 cm
Rheinbach	25.05.2009	85 mm/ 12 h	Neuruppin	29.06.1994	65.3 mm/24 h
Ahlen, Oberberg. Kreis	03.05.2001	86 mm/2 h	Osnabrück	29.07.2005	65mm/6 h
Schönstedt	03.07.2008	91.8 mm/1 h 45 min	Sohland Sachsen	02.07.2009	66 mm/1 h
Steißlingen, Stahringen, Roßberg	24.03.2005	92 mm/30 min	Belm	02.06.1993	96 mm/45 min
Trier	11.05.2000	93 mm/24 h	Schlieben	02.07.2009	99 mm/1 h

Appendix C: 51 Monitoring Stations of the GWS used for the Analyses

Monitoring stations used for analyses, in the first column the 51 station names are listed, followed by original coordinates, station height and Gauß-Krüger transformed eastings and northings

Station Name	Latitude	Longitude	Station Height [m]	GK easting	GK northing
Aachen	50.7839	6.0947	202	3295151.3335	5631493.4151
Alzey	49.7506	8.1217	166	3436712.5878	5512913.0013
Augsburg	48.4278	10.9303	461	3642833.7924	5367249.2051
Bamberg	49.8806	10.915	239	3637616.0087	5528759.3821
Berlin-Schönefeld	52.3822	13.5325	46	3808505.3727	5814947.9835
Braunschweig	52.2903	10.4486	81.2	3598827.4227	5796037.1368
Bremen	53.0464	8.7994	4	3486548.3696	5879196.6490
Cottbus	51.7775	14.3186	69	3866910.4512	5751392.7435
Cuxhaven	53.8731	8.7069	5	3480723.7209	5971214.5404
Diepholz	52.6114	8.3825	37	3458176.8314	5830954.3432
Dresden-Klotzsche	51.1342	13.775	222	3834103.0136	5677284.7290
Düsseldorf	51.2903	6.7817	37	3345281.5095	5686135.7243
Ebrach	49.8506	10.4914	360	3607242.9365	5524731.0016
Eschwege	51.1808	10.0672	205	3574613.4046	5672158.6995
Feldberg/Schwarzwald	47.8758	8.0047	1489.6	3425556.7032	5304556.6891
Frankfurt/Main	50.0464	8.5986	113	3471252.5774	5545517.1979
Freudenstadt	48.4544	8.41	797	3456364.4739	5368574.5823
Fulda	50.5347	9.6761	255	3547927.7032	5599968.0253
Garmisch-Partenkirchen	47.4839	11.0636	719	3655504.7515	5262573.4984
Göttingen	51.5428	9.9489	175	3565821.6491	5712313.8818
Greifswald	54.0978	13.4075	2	3788223.1703	6005169.2446
Hamburg-Fuhlsbüttel	53.6394	9.9964	13	3565894.0201	5945628.2319
Hannover	52.4661	9.7006	53	3547608.3673	5814839.3235
Heidelberg	49.4181	8.6703	111	3476080.7686	5475618.2220
Helgoland	54.1764	7.8931	4	3427731.6686	6005495.8081
Hof	50.3133	11.8775	565.1	3704919.9260	5579085.9961
Hohenpeißenberg	47.8019	11.0119	977	3650691.3320	5297821.6851
Kahler Asten	51.1814	8.4897	839	3464322.4438	5671807.8041
Kassel	51.2978	9.4436	231	3530936.0831	5684725.8292
Kempten	47.7244	10.3364	705	3600246.2951	5288110.4771
Köln-Bonn	50.8697	7.1361	73	3368813.1187	5638667.2340
Konstanz	47.6781	9.1911	443	3514347.6475	5282115.7898
Leipzig/Halle	51.4214	12.2228	131	3724124.0458	5703311.8946
Mainz-Lerchenberg	49.9881	8.2614	125	3447039.1552	5539217.5251
Meiningen	50.5625	10.3772	450	3597568.8573	5603747.5342
München-Stadt	48.1372	11.5522	535	3689923.3905	5336290.2735
Nürnberg	49.4958	11.0819	310.4	3650795.0482	5486290.1964
Potsdam	52.3836	13.0639	81	3776615.7430	5813205.6596
Regensburg	49.0428	12.1044	366	3726916.6582	5438476.6226
Reit im Winkl	47.6769	12.4825	695	3761454.6863	5287842.9286
Rheinfelden	47.5658	7.7964	287	3409441.4347	5270315.7187
Rothenburg ob der Tauber	49.3769	10.1958	421	3586825.1846	5471672.0607
Saarbrücken-Ensheim	49.2197	7.1122	323	3362495.2365	5455218.8155
Sankt Peter-Ording	54.2997	8.6464	4	3476982.1472	6018710.3061

Monitoring stations used for analyses, in the first column the 51 station names are listed, followed by original coordinates, station height and Gauß-Krüger transformed eastings and northings (continued)

Station Name	Latitude	Longitude	Station Height [m]	GK easting	GK northing
Schwerin	53.6442	11.3886	59	3657933.9777	5948352.8865
Stuttgart-Echterdingen	48.6889	9.2211	373	3516276.8170	5394503.8164
Trier-Petrisberg	49.7492	6.6592	265	3331331.4062	5515017.3868
Ulm	48.3847	9.9539	566.8	3570645.3103	5361096.4491
Wasserkuppe	50.4978	9.9439	921	3566963.5458	5596071.0817
Würzburg	49.8056	9.9067	268	3565259.8823	5519053.8758
Zugspitze	47.4222	10.9867	2964	3649885.3522	5255563.7999

Appendix D: Accidents of Wind Energy Plants

Accidents of wind energy plants due to storm as reported (compilation according to CWIF, update 06/04/2011, source online)

Accident type	Cause	Date	Site/area	Details
Blade failure	storm	28.05.2000	Norderney / Lower Saxony	Storm tore the rotor nacelle and cover off. One blade travelled between 100m and 150m, landing on a factory and private house (family Zilles). It pierced a 24cm thick stone wall, timber floor and roof of the house. Luckily, the factory was closed due to holidays, and the family was absent on vacation. Turbine was constructed in 1986. The turbines were subsequently shut down on 30 August 2000 following a court ruling on safety grounds and that they were too close to housing
Blade failure	storm	22.02.2002	Huppelbroich, Gem. Simmerath / Aachen, Westphalia	Turbine blade torn off during snow storm. 7.5m blade part reported to travel 40m. Turbine 10 years old.
Blade failure	storm	13.03.2002	Dörenhagen / Paderborn, Westphalia	Loss of blade at night during storm. One blade section 30m long weighing 5.5 Te fell off. Smaller blade parts covered an area 400m from the turbine. Turbine only 2.5 years old
Blade failure	storm	29.04.2002	Lohe / Lippstadt, Westphalia	Blade broke off during storm
Blade failure	storm	27.10.2002	Kaiserslautern	Storm damage to blade - blade broke off. It was later admitted by operators that there was a known defect in the blade prior to storm but they had ignored it.
Blade failure	storm	27.10.2002	Loehme, Werneuchen, Brandenburg	Storm tore off two of three blades on a turbine at Loehme (Barnim). Pieces hurled "far" but no distance data
Blade failure	storm	27.10.2002	Duelken, Viersen, Westphalia	Blade bent then broke in storm
Blade failure	storm	16.12.2003	Windpark Grevenbroich / Neuss, Westphalia	37m long blade section bent in storm. Turbine safely shut down. Blade did not fall off
Blade failure	storm	09.02.2004	Groß Bieberau-Hippelsbach / Darmstadt-Dieburg / Hesse	Blades torn off during storm. Small 5kW turbine only, initially constructed as a pilot project in 1995
Blade failure	storm	22.02.2004	Puschwitz near Bautzen / Saxony	10m section of blade broken off by the wind, travelled 20m. A further 6m piece travelled 40m. Pieces confirmed to 200m from turbine. Constructed in 2001. A similar (almost identical) incident took place at the same site on 5/4/2004. Lightning damage in mid-February suspected to have weakened the blades.

Accidents of wind energy plants due to storm as reported (compilation according to CWIF, update 06/04/2011, source online)

Accident type	Cause	Date	Site/area	Details
Blade failure	storm	21.03.2004	Carolinensiel / Lower Saxony	Rotor blade bent during storm. Some pieces flew off. No further data
Blade failure	storm	05.04.2004	Puschwitz near Bautzen / Saxony	10m section of blade broken off by the wind. TV pictures showed blade part hanging from the rotor. Constructed in 2001. Second such accident at the same site - previous one on 22/2/2004
Blade failure	storm	04.06.2005	Eggstedt / Schleswig-Holstein	Turbine blade was broken off during a storm at Eggstedt. Further report will follow. One turbine only in place - operational since April 1998
Blade failure	storm	16.12.2005	Sefferweich, Rhineland-Palatinate	One of three blades broke off turbine following a minor storm. Blade travelled several meters only and landed close to the tower. Other turbines on site were shut down
Blade failure	storm	01.10.2006	Jawe, a site near Herzogenrath	Repower Systems 2 MW turbine "Repower 2MW wind turbine loses blade tip". A Repower Systems 2 MW turbine, newly installed near Herzogenrath, lost a blade tip during high winds in early September requiring a main road to be closed for several hours "The fault appears to have been in the charger for the batteries operating the blade brakes and the sensor system that should have signalled that the batteries were not charged
Blade failure	storm	01.11.2006	Aschenstedt near Oldenburg/ Lower Saxony	Village of Aschenstedt in Oldenburg has a luck escape". During a storm a 10m long piece of rotor blade was torn off. The main piece of blade travelled approx 200m before landing in a field. Very lucky escape for the village. Vestas claim that the accident was "unexplainable" and the "first time".
Blade failure	storm	08.12.2006	Mehring near Trier- Saarburg, Rhineland-Palatinate	a 35m long piece of rotor blade broke in strong wind. Mehring circle and adjacent road was closed. The police communicated that the blade splintered into many parts, which were scattered over a wide area. Luckily no-one was hurt. A later message confirmed that a driver informed the police that the turbine had been turning very fast prior to the accident. Extent of property damage unknown
Blade failure	storm	20.01.2007	Scheid near Kronenburg, Rhineland-Palatinate	During a storm a rotor blade broke off. Parts were thrown about 100m. The turbine stands directly beside an access road used by walkers, the post office, milkman and garbage disposal. Source is an eye witness account from two individual neighbours

Accidents of wind energy plants due to storm as reported (compilation according to CWIF, update 06/04/2011, source online)

Accident type	Cause	Date	Site/area	Details
Blade failure	storm	28.01.2007	Testorf near Nordwestmecklenburg, Mecklenburg- West Pomerania	Destroyed the three blades on one of the Luttuschka turbines. One of four installed and operational since 1998
Blade failure	storm	30.07.2007	Uelvesbüll near Husum / Schleswig-Holstein	Rotor blade lost from a turbine in Nordfriesland. The turbine was 17 years old. The blade was lost on the Monday morning (30 July) in Uelvesbuell following a loud cracking noise, as the police communicated. There were no injuries. The police closed off the approach road to the plant
Structural failure	storm	28.01.2002	Husum / Schleswig-Holstein	Turbine completely destroyed during storm. 28m tower, 25 Tonnes.
Structural failure	storm	27.10.2002	Goldenstedt Ellenstedt, Lower Saxony	Turbine completely toppled in storm - concrete base pulled out of ground. Operational since 1/1/1997.
Structural failure	storm	05.04.2003	Reinsberg near Freiberg / Saxony	Automatic shut down failed and it ran out of control prior to destruction. Rotor blade points computed to reach speeds of 800km/hr. Blade pieces were found 500m away from the turbine. Houses are situated 400m from the turbine - luckily in the opposite direction. Surrounding roads were closed off. Year of construction 1999. Oil also spilled into the surrounding ground
Structural failure	storm	16.12.2005	Delmenhorst near Bremen, Lower Saxony	Germany Small private turbine, 15m high The turbine fell into the owner's garden. Rotor blades were torn off and "flew through the air". Parts pierced a garage droof and destroyed a car within. Another rotor blade ended in a neighbours garden. The turbine had been in place for 20 years.
Structural failure	storm	13.01.2007	Windpark Raden /Besdorf near Steinburg, Schleswig- Holstein	Police message reads: A 70m high wind turbine completely collapsed tonight in the Raaden windpark at Besdorf. The tower fell in a northeast direction. The turbine was completely destroyed. No-one was injured, but there was spillage of a large quantity of transmission oil, which had to be specially treated and cleaned up. The Besdorf firebrigade and the Wilster police managed the incident.

Appendix E: 29 key points of the integrated energy and climate programme and main goals (Meseberg-Programme)

1. Combined heat-and-power generation: the main goal is the doubling of the share of electricity generated from CHP to ~ 25 % until 2020.
2. Expansion of renewable energies in electricity generation: the share of electricity generation by renewable energies should increase to 25 - 30 % until 2020 and further increase until 2030. Moreover, electricity grids should be enhanced to ensure the integration of renewable energies and the security of supply.
3. CCS technologies: demonstration power plants are supposed to show the technical, environmental and economic feasibility of CCS. Storage projects for several thousand tonnes CO_2 are envisaged. Moreover, a legal framework concerning CCS is needed – also on a EU level.
4. Smart Meter Monitoring: The goal is the fast dissemination of new technologies for real-time in situ monitoring of consumption.
5. Clean power technologies: In order to achieve climate protection and immission control, installed systems should always be the most advanced technical solutions. Moreover, increased pollution loads (e.g. from nitrogen oxides) should be avoided by using new technologies. The upcoming NEC Directive standards also need to be met.
6. Introduction of advanced energy management systems: The potential for efficiency improvements especially in the industry need to be analysed in this context.
7. Support programmes for climate protection and energy efficiency (non-building context): In order to meet the legislation and standards concerning climate protection and energy efficiency, support programmes should be expanded or set up (e.g. in the sectors trade and services, agriculture, forestry and transport).
8. Energy efficient products: Broad-based introduction of energy efficient products by using standards and consumer-friendly labelling.
9. Provisions on the feed-in of biogas into the natural gas grid: This measure should reduce the dependence of Germany on imports of natural gas. Moreover, biogas should be used more efficient, e.g. by using it as fuel and in CHP.
10. Energy saving ordinance: This building-related measure includes the adjustment to requirements concerning energy efficiency and the reduction of fossil fuel-based heating until 2020.
11. Operating costs of rental accommodation: This measure is related to energy efficient modernisation and renovation to use the energy conservation potential of rental housing.
12. Modernisation programme for CO_2 emission reductions: Enhancing the existent programme and exploiting the energy conservation potential in urban structure.
13. Energy efficient modernisation of social infrastructure: this includes schools, youth facilities and others. The goal is to save up to 50 % of primary energy.
14. Renewable energies heat act: the goal is to increase the share of renewable energies to 14 % of the total heat consumption until 2020.
15. Programme for energy efficient modernisation of federal buildings: In this measure no exact values are given. Still, the goal is to act as a role model in energy and cost savings and to reduce CO_2 emissions.

16. CO_2 strategy for motorised private transport: the goal is to reduce the mean emission of new cars to 120 g CO_2 per km by 2012.
17. Expansion of the biofuels market: use the potential of biofuels to reduce greenhouse gas emissions and support the development of raw materials to produce biofuels
18. CO_2 emissions-based vehicle tax: Until 2012, the EU legislation does not allow more than 130 g CO_2 per km in new cars. A CO_2 emissions-based tax should give incentives to purchase a new vehicle.
19. Energy labelling of passenger cars: the goal is to establish a CO_2 emissions-based labelling of passenger cars. This labelling has been introduced in 2011.
20. Reinforcing the influence of the HGV toll: This toll is supposed to further reduce emission from the transport of goods, to adopt least polluting vehicle and to prevent evasive strategies.
21. Aviation: this topic is described by measures instead of goals. One measure is to constrain air traffic with emission trade certificates. Another measure is an emissions-based landing charge on airports.
22. Shipping: As with aviation, shipping is described by measures. Also here, emission trading is the main topic.
23. Emission reductions of fluorinated greenhouse gases: No values are given but the overall aim to reduce fluorinated greenhouse gases.
24. Procurement of energy efficient products and services: The goal is to introduce the Federal Government as a role model concerning consumption and implementation of energy efficient technologies.
25. Energy research and innovation: An energy research roadmap should be established.
26. Electric mobility: Support of hybrid and electric vehicles and the integration of e-mobility into the electricity grids.
27. International projects regarding climate protection and energy efficiency: Supporting the participation of German companies in international projects and supporting the export of climate secure and energy efficient products.
28. German embassies and consulates should report on energy and climate policies
29. Transatlantic climate and technology initiative: the goal is to form a closer cooperation regarding climate protection and technologies on a transatlantic level especially concerning clean coal, renewable energies and energy efficiency.