

ESPON Climate
Climate Change and Territorial Effects on Regions
and Local Economies

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Final Report

Annex 3

Case Study North Rhine-Westphalia (NRW)

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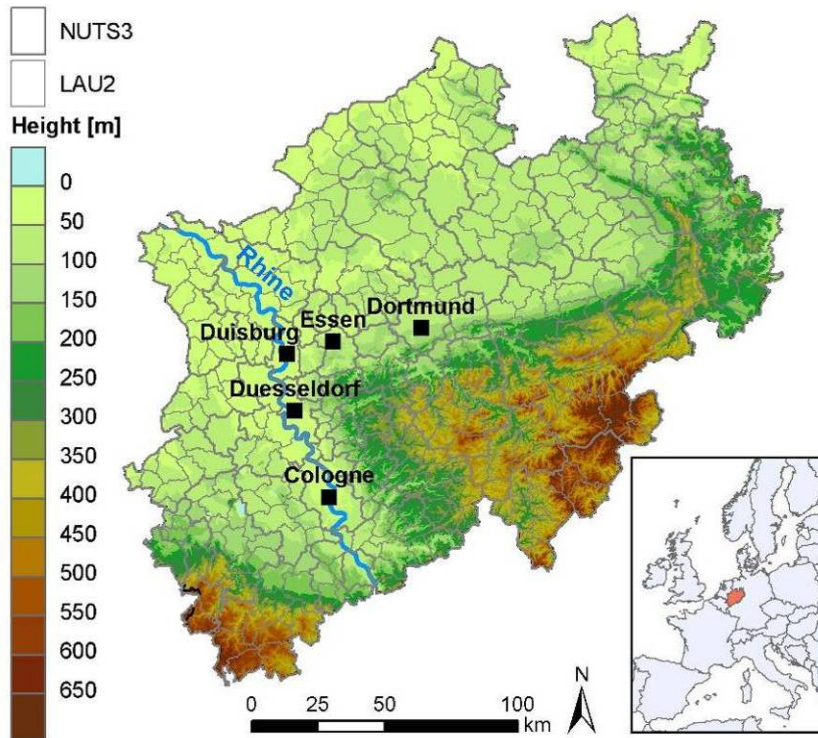
Abbreviations

A1B	Emission scenario according to Nakicenovic and Swart (2000) with a balanced use of energy sources, very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies, convergence among regions, capacity building and increased cultural and social interactions.
A2	Emission scenario according to Nakicenovic and Swart (2000), describing a very heterogeneous world characterized by self-reliance and preservation of local identities and slower and per capita economic growth and technological change than in other storylines.
ATKIS	Authoritative Topographic-Cartographic Information System (land use data)

CEV	Changes in annual mean actual evaporation
CFD	Changes in annual number of frost days
CHD	Changes in annual number of heat days
CHR	Changes in annual number of days with heavy rainfall
CRF	Changes in river floods
CSC	Changes in annual number of days with snow cover
CSD	Changes in annual number of storm days
CSP	Changes in annual mean summer precipitation
CTP	Changes in annual mean temperature
CWP	Changes in annual mean winter precipitation
DEM	Digital elevation model
GIS	Geographic Information System
HQ	Average maximum river discharge
HQ100, HQ200, HQ500	Maximum river discharge according to a high discharge event occurring every 100, 200 or 500 years
JRC	Joint Research Centre (scientific institute of the European Commission)
NRW	North Rhine-Westphalia
SAC	Special Areas of Conservation (SAC) according to the EU-Habitats Directive (92/43/EEC)
UHI	Urban heat island

1. General characterisation of NRW

The federal state of North Rhine-Westphalia (NRW) is situated in the north-west of Germany, sharing borders with Belgium and the Netherlands and comprising 396 municipalities (396 LAU2), 31 administrative districts and 23 independent cities (54 NUTS3, end of 2009), see Map 1.



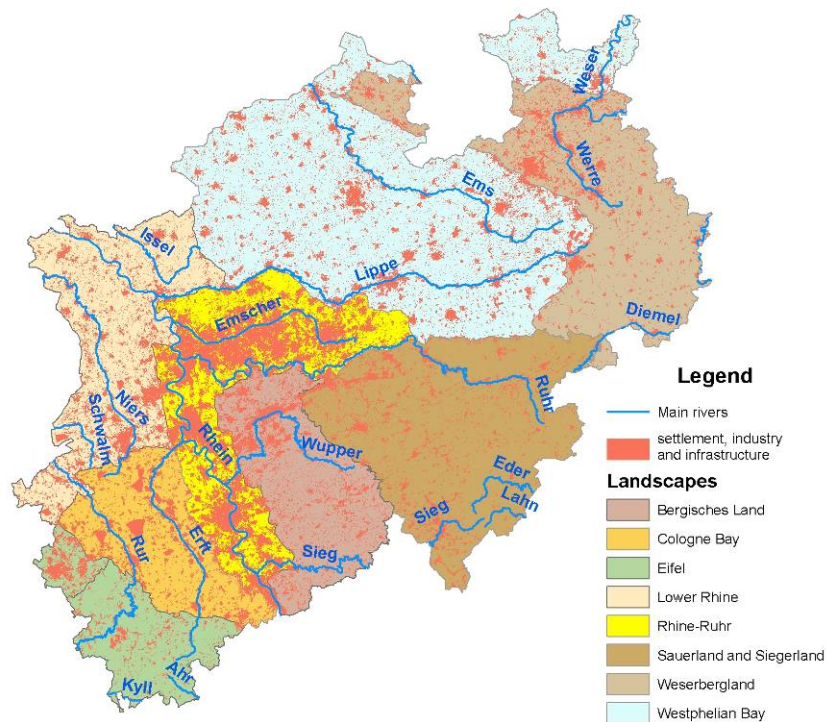
Map 1: Topography and administrative units (NUTS3 and LAU2) in North Rhine-Westphalia and its location within Europe (red inlet)

With a population of 18 million (2008) and an average population density of over 500 persons/km² NRW is the most populous and at the same time the most densely populated state in Germany. Regional characteristics are quite diverse in terms of climate and geomorphology as well as in socio-economic structure. Two main types of landscapes can be found in NRW, namely the North German Lowlands with elevations just a few meters above sea level and the North German Low Mountain Range (Sauerland, Eifel Mountains) with elevations of up to 850m. The lowlands comprise the Rhine-Ruhr Area which is one of the largest metropolitan areas with a population of approx. 10 million and a very high population density of 2,100 persons/km². Opposed to this in the mountain regions population density is rather low with 150 persons /km². Demographic change towards an elderly population is apparent in NRW; in the year 2008, 19 % of the population were over 65 years old and an increase up to 29 % is expected until 2030 (IT.NRW, 2010).

The above mentioned two main landscape types are also distinguishable in the climatic characteristics of the region: Annual mean temperature amounts to approximately 10 °C

(1961-1990)¹ in the lowlands and about 5 °C in the mountain regions. Yearly mean precipitation of up to 1500 mm has been recorded in higher elevations, while the Rhine Valley received a mean sum of 620 mm per year.

Thus, while in summer it can become very hot in the Rhine-Ruhr Basin, the temperature in the highlands and mountainous regions is more moderate. The latter are recreational regions for the densely populated Rhine-Ruhr area. More detailed landscape types, the main rivers and the distribution of settlement, industry and infrastructure is shown in Map 2.



Map 2: Main landscape types, rivers, settlements and industrial areas²

NRW contributes with over 20 % to the overall German GDP (IT NRW 2009), thus possible adverse impacts of climate change may have severe consequences in reducing the overall economic performance of Germany.

As a montane region, NRW was an engine of economic growth after the second world war (Storchmann 2005) with over 600.000 employees in the coal and steel industry in the Ruhr area (Bross and Walter 2000). In the second half of the 20th century, the region underwent a radical structural change to around 35.000 people employed in mining in 2009 (IT NRW 2010). Despite the fact that this transition is generally regarded as a success, the state is still largely dependent

¹ Measured temperature and precipitation values for the baseline period as provided in the regional climate model STARII (Werner and Gerstengarbe 1997; Orłowsky 2007)

² Landscape types and river data according to Environmental Agency NRW (LANUV NRW), 2008, land use data from Authoritative Topographic-Cartographic Information System (ATKIS)

on specific sectors (Bross and Walter 2000), especially the energy sector, albeit employees in this field are rather small in number.

Other sectors like media etc. have substituted the montane economy so that the total amount of workers increased by 4 % between 1998 and 2006. A spatial trend to decentralisation is apparent; between 1960 and 2000 population increased by 40 % while at the same time population decreased by 9 % (Mielke and Schulze 2008).

Currently more than 60 % of the people are employed within the service sector (Figure 1). Despite the rather small share of employees within the energy supply sector of 1 %, NRW can be regarded as an energy state, producing one third of the overall electricity of Germany (Energie Agentur NRW 2007). In total, 98 % of the electricity produced in NRW derives from fossil fuels, largely from coal (88 %). Renewable resources make up only 2 % of the primary energy sources and the sources for electricity production.

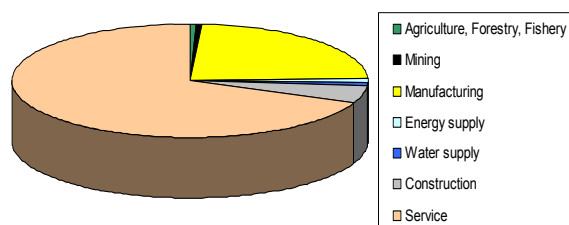


Figure 1: Share of employees of different sectors in NRW in 2009 (after IT NRW 2009)

The assessment of the regional vulnerability of regions in NRW is of special interest to decision-makers of the state, which is apparent from previous vulnerability studies financed by the state (cf. Gerstengarbe et al. 2004; Kropp et al. 2006; Kropp et al. 2009b). Besides sectors which have been traditionally subject to climate change investigations like agriculture, water, forestry or nature conservation, also urban development, tourism and health play an important role for this densely populated region.

For this case study, the developed European-wide vulnerability system of the ESPON Climate project will be applied in a systematic way and adapted to the characteristics of this region. Thereby the sensitivity analysis will focus on the environmental, economic, social and physical dimensions, as these are expected to be most affected under the projected climatic changes.

Sensitivity will be developed on a spatial scale of LAU2 (municipalities) to provide more detailed spatial information than on the European level focusing on NUTS3 regions.

Further, it is intended to compare some of the obtained results based on the climate model CCLM with results based on other models, e.g. the regional statistical model STARII (Werner and Gerstengarbe 1997; Orłowsky 2007).

2. Climatic changes in the past

Complete weather measurements in North Rhine-Westphalia are available since the beginning of the 20th century. Average air temperature in this area rose from 8.4 °C to 9.6 °C until today. This increase occurred in every season, particularly during autumn (MUNLV 2009a). Warming took place between 1951 and 2000 on a higher rate than the global average and temperatures increased by up to 1.5 °C in some regions during this time period (Gerstengarbe et al. 2004). Thereby, an acceleration of mean temperature rise between 1991-2000 compared to the 30 years before has been observed (Spekat et al. 2006).

Generally a decrease in winter and an increase in summer temperature has been recorded. Consequently, the amount of frost and ice days between 1951 and 2000 declined (average decreases of up to 20 and 9 days, respectively). In contrast, the number of summer days rose up to 20 days, particularly in the South of NRW, and hot days increased by up to 8 days (Gerstengarbe et al. 2004).

Also the water temperatures increased during the last decades: Since 1977 the Lower Rhine has warmed by 1.2 °C at the gauge Lobith and temperatures reached values of more than 25 °C several times during the last 10 years (MUNLV 2009a). Significant increases in extreme water temperatures of several gauges of the Rhine were observed in the last decades in the summer months (Greis 2007). Recent warming trend of river water is likely to result from climate change, since heat discharges of power plants into the rivers have decreased between 1998 and 2004 by 7 % (IKSR 2006).

The warming trend can also be seen by the reaction of species to climatic conditions. For some bushes, bloom beginning today starts up to 20 days earlier than in the 1950s (MUNLV 2009a). When regarding a multitude of onset dates of such phenological events (e.g. blossoming, fruit ripening, leave falling) as calendrical phases, spring and summer have advanced by around 6-11 days and the early autumn by around 7-14 days within the main regions in NRW and the vegetation period increased by 5-9 days from 1971-2007 (Kropp et al. 2009b).

Regarding precipitation, trends are not so clear. Average annual precipitation changed from around 790 mm towards the end of the 19th century to 910 mm today, which amounts to an increase of around 15 %. This trend is mainly apparent from 1960 onwards, thenceforth especially years with an annual precipitation of more than 1000 mm occurred much more often. This increase, however, has not been observed during summer months (MUNLV 2009a). Trends in precipitation also differ regionally: while from 1951 until 2000 precipitation increased by 100 mm per year in some regions no trend was apparent in others (Gerstengarbe et al. 2004).

Further, days with rainfall above 20 mm have increased since the 1950s (Gerstengarbe et al. 2004; auqa plan GmbH 2009), particularly during winter and in areas of high annual precipitation (Gerstengarbe et al. 2004). These events are likely to have led to flash floods, which occur in NRW at a rate above the average for Germany with a concentration in the Rhine valley and between May and September (Castro et al. 2008).

River floods have occurred regularly, especially along the Rhine. Severe ones were recorded in the years 1993, 1995 (Disse and Engel 2001) causing damages of more than 1.5 billion DM (Munich Re 1999).

Ground water level recovered during the last years from the low values of the previous decades and reaches similar levels as recorded in the 1960s (Friedrich et al. 2002).

Evidences for trend in storm activity are highly dependent on space and time. A period of stronger winds was observed in the mid 1970s and in the beginning of the 1990s at Düsseldorf Airport (Kasperski 2002) and the annual number of days with wind speeds above Beaufort 8 has increased by 40% in Düsseldorf between 1969-1999 (Otte 1999). However, in the higher altitude of the Sauerland mountains, a decrease in wind speed above 10 Beaufort in the recent 20 years has been recorded (Klaus 2010).

3. Exposure to climate change in the future

In the following the exposure of NRW to climatic changes in the future will be assessed. Exposure to climatic stimuli represents the nature and degree to which a system is exposed to climatic variations (IPCC 2007a). We distinguish between exposure to direct climate change, expressed by changes in climatological variables and the exposure to indirect climate change, such as inundation.

3.1 Exposure to direct climate change

Within the current research framework exposure direct to climatic change is understood resulting directly from climate stimuli as from direct impacts of concentrations of greenhouse gases. Thereby, it is necessary to gain evidence on the spatio-temporal distribution and variability of projected climate change developments.

For the ESPON project these climate projections are based on results derived from the COSMO-CLM (or CCLM) model (Rockel et al. 2008; Lautenschlager et al. 2009). This non-hydrostatic unified weather forecast and regional climate model was developed by the COnsortium for SMall scale MOdelling (COSMO) and the Climate Limited-area Modelling Community (CLM). The spatial resolution amounts to ~20 km (can be varied) and the temporal horizon spans from 1960-2100. Climate change data applied within this project from the model CCLM are based on the emission scenario A1B, characterising a balanced use of all energy sources in a convergent world with a global population peak around the middle of this century (Nakicenovic and Swart 2000).

We are aware of the shortcomings associated with the use of a single climate model and a single emission scenario, which is founded in the limitations of this project. Results from the CCLM model will be compared to a statistical regional model STAR II for exemplary sectors.

Uncertainty is especially high for extreme events, since they are generally poorly represented within climate models. Moreover, they represent rare events with high magnitudes (e.g. heavy precipitation events), which are often restricted in their spatial extent. Climate models can indicate average changes of these events. How these average values correspond to empirical

extreme values such as precipitation and wind speed is still under ongoing research (Tebaldi et al. 2007; Alexander et al. 2009).

Besides uncertainties deriving from climate models the future socioeconomic development is largely uncertain. Thus, future climate projections are dependent on current decisions, which may differ based on the underlying assumptions behind the developed emissions scenarios, like the chosen A1B scenario in this study.

The European wide exposure analysis of this project has been developed further and adapted for the case study NRW. A slightly different set of exposure variables was applied to account for the characteristics of the region. The variables were averaged over the model runs and over the time periods 1961-1990 (reference period) and 2071-2100 (scenario-period). Absolute changes were then calculated between these time frames. For the analysis the area around NRW including a buffer of around 40km (see Map 3) was considered, thus in total 23*15 cells (342 land cells, 3 sea cells not considered).

As a first set of variables the following were selected:

- Changes in annual mean temperature (CTP)
- Changes in the annual number of heat days (maximum temperature $\geq 30^{\circ}\text{C}$) (CHD)
- Changes in the annual number of frost days (CFD)
- Changes in the annual number of days with snow cover (CSC)
- Changes in annual mean winter precipitation (months 12-2) (CWP)
- Changes in annual mean summer precipitation (months 6-8) (CSP)
- Changes in the annual number of days with heavy rainfall (≥ 10 mm) (CHR)
- Changes in annual mean actual evaporation (CEV)
- Changes in the annual number of storm days (≥ 20.8 m/s, representing a strong gale according to the Beaufort scale above which structural damages occur (Ahrens 2007)) (CSD)

In contrast to the European wide analysis ranging from the dry Mediterranean climate to the cold and wet Scandinavian conditions, absolute changes instead of relative changes were considered for the hydrologic variables due to the smaller ranges of values, respectively more similar climate within the study area. Heat days were applied for this case study instead of summer days in the European wide analysis, since the additional calculation of heat days from the maximum daily temperatures could be carried out for this region of lesser extent.

The European wide analysis showed a low number of days with rainfall values above 20 mm for large parts of Europe including NRW with 4.5 days per year in 1961-1990 and 5.8 days per year in 2071-2100, thus a lower threshold of 10 mm was chosen here. The number of days with this 10 mm precipitation event increases only slightly between these two periods to around 25.4 days per year at the end of the century in NRW. Observed climate data from the past indicate that heavy rainfall events occur mostly in the winter season and show a temporal minimum in April.

Storm days were added in this case study, since wind speeds are generally better represented by the model CCLM within the study region than over some European areas (Hollweg et al. 2008).

Deviations for the mean wind velocity for 1979-1993 of about 1 m/s to observed data could be shown for CCLM (Walter et al. 2006). The model also underestimates gust speeds by around 26 % compared to observed wind speeds in Germany. Nevertheless, CCLM is able to reproduce the spatial distribution of storm climatology over Germany (Kunz et al. 2010). For NRW it has been shown that CCLM underestimates gust velocities in areas of higher altitude, whereas the model results agree well with observed data in the low lying regions (Klaus et al. 2011).

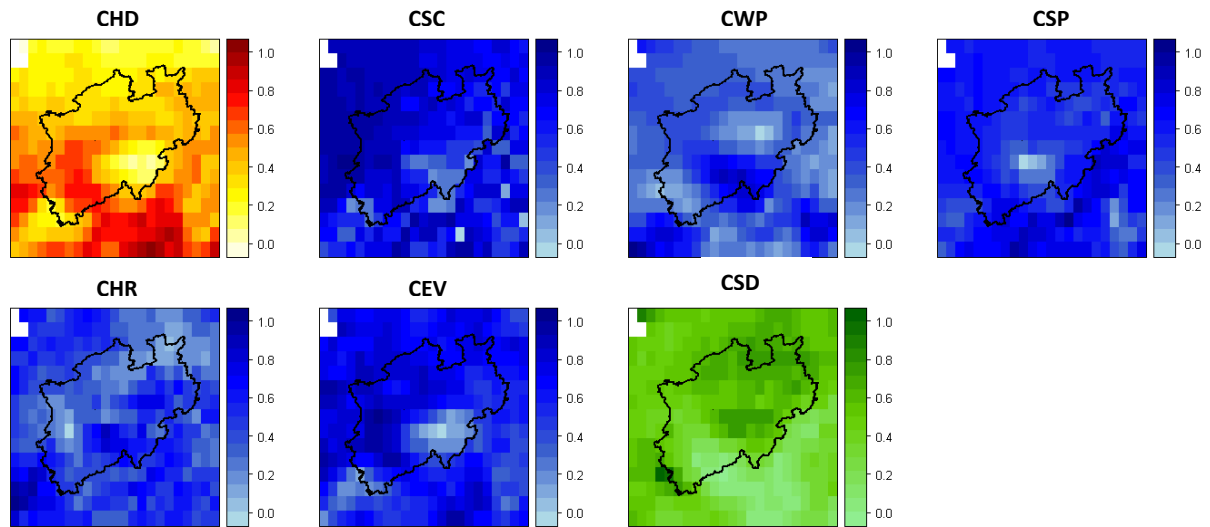
The future development of winter temperatures and thus snow conditions in Europe is uncertain. This is due to interactions between sea ice reductions and atmospheric circulations over the Northern Hemisphere, which have led to relatively cold winters in recent years (Francis et al. 2009; Honda et al. 2009). This mechanism however is expected to weaken in the course of further strong reductions of sea ice extent (Petoukhov and Semenov 2010).

A correlation analysis showed high correlations ($R^2 > 0.7$) between the variables CTP with CHD or CSD (Table 1). Also, the variable CFD is strongly correlated with CSD and CEV. Thus, for the further analysis, these two variables CTP and CFD were excluded, resulting in a total of 7 variables (CHD, CSC, CWP, CSP, CHR, CEV, and CSD). The spatial distribution of the variables within the study region is shown in Map 3.

*Table 1: Correlation between climate variables from the CCLM model for NRW
Correlation factors above 0.7 are marked with red font, the corresponding excluded variables in yellow. Note that evaporation is quantified in negative values, due to the direction of this flux.*

	CTP	CHD	CFD	CSC	CWP	CSP	CHR	CEV	CSD
CTP	1	0.83	-0.55	-0.28	0.17	0.16	0.2	-0.11	-0.72
CHD		1	-0.09	0.15	-0.1	0.26	0.11	0.34	-0.7
CFD			1	0.74	-0.31	-0.02	-0.21	0.75	0.29
CSC				1	-0.4	0.38	-0.12	0.68	0.01
CWP					1	-0.48	0.35	-0.37	-0.16
CSP						1	-0.04	0.19	-0.33
CHR							1	-0.35	-0.2
CEV								1	-0.09
CSD									1

Map 3: Normalised changes of the seven climate variables between 1961-1990 and 2071-2100 according to the model CCLM, emission scenario A1B



The frequency distribution of the seven climate variables assessed (see Figure 2) shows positive changes for CHD, CWP and CSD, only negative changes for CSC and CSP and a variation of positive and negative changes for CHR and CEV. The distributions of all seven variables are unimodal – that means they have only one peak (maxima). CHR is nearly symmetric while CHD, CWP, CHR are skewed to the left and CSD, CSC, CEV are skewed to the right.

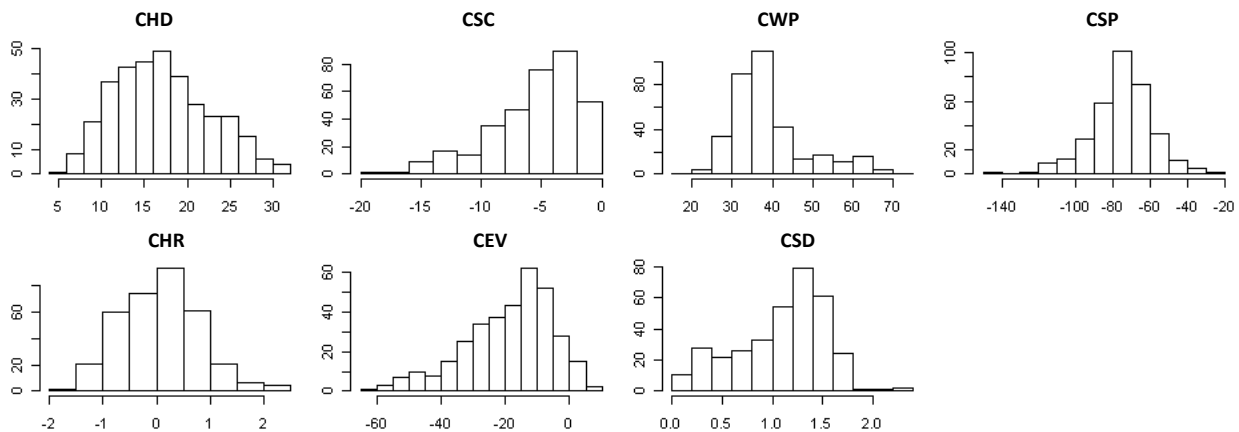


Figure 2: Frequency distribution of the normalised climate change variables for the considered cells (n=342). Note that evaporation is quantified in negative values, due to the direction of this flux.

In the next step, the seven exposure variables were aggregated to the municipal level. Thereby, values were weighted by the area covered by the overlying CCLM cell. It has to be noted that large uncertainties exist due to the small area of the municipalities, since many are assigned to only one grid cell of the climate model.

For aggregation of the variables with the sensitivity measures (ranging from 0-1), the values have to be normalised beforehand to the metrical same scale. Most of the variables show uniform trends, e.g. increase in heat days over the entire spatial scale. The number of heavy

rainfall days and the amount of evaporation, however are projected to increase in some municipalities, whereas some are subject to decreases.

To consider positive as well as negative changes, exposure variables (as changes between 1961-1990 and 2071-2100) are normalised between -1 and 1, whereby no changes are represented by 0. The values -1 or 1 reflect the most extreme normalised value in the direction with the most extreme absolute values (Figure 3: S). In other words, if the most extreme value of change in absolute terms indicated positive changes (e.g. + 5 days with heavy rainfall), the values 5 and consequently -5 are applied as maximum and minimum values for normalisation, albeit the most negative projected changes amount to less than this value (e.g. -1 days). This ensures on the one hand the consistent definition of zero changes and on the other hand the maintenance of relative relation between the values in both direction of change.

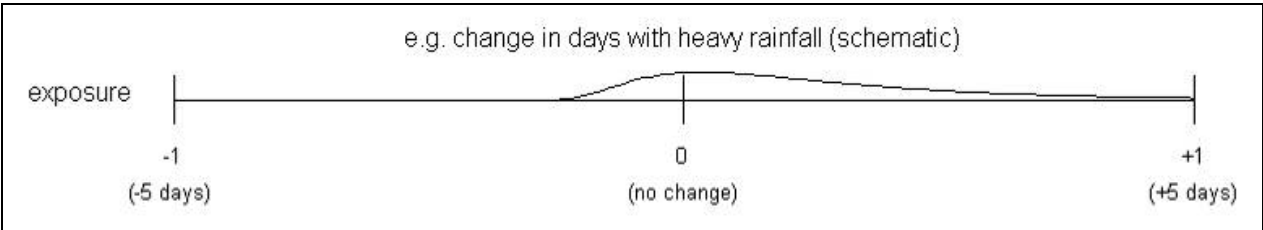
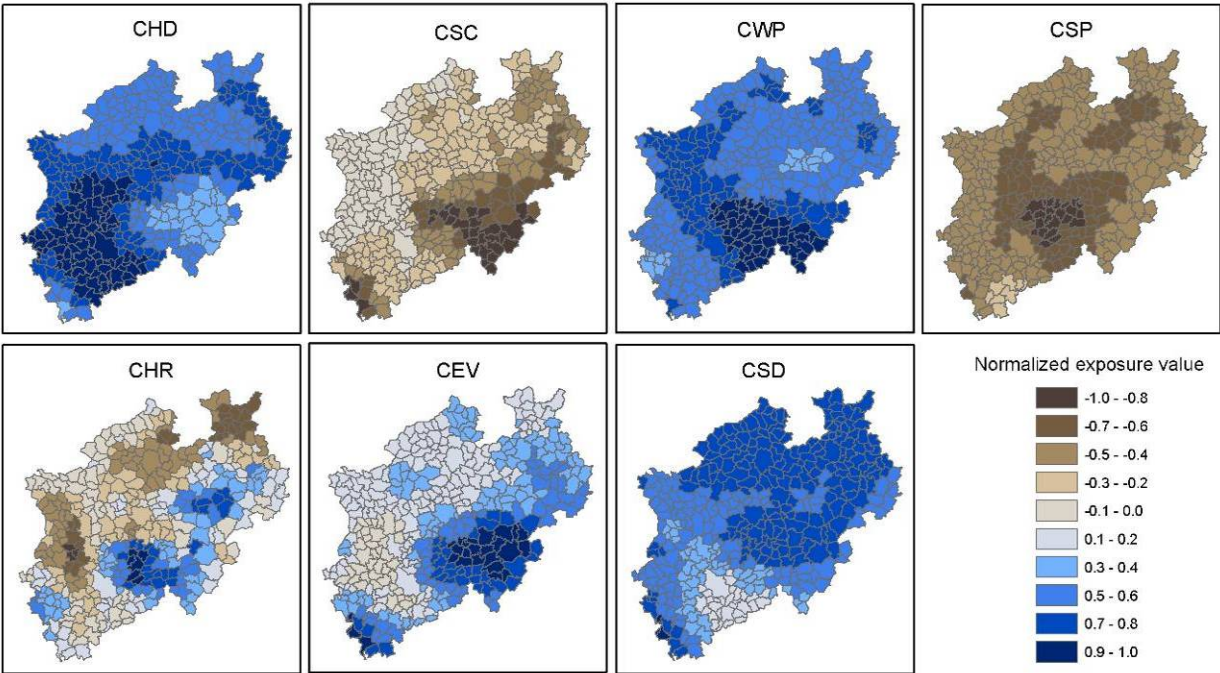


Figure 3: Schematic distribution of absolute and normalised exposure indicator values with projected negative and positive changes

The normalised exposure values for the municipalities are shown in Map 4. The variables CHD, CWP, and CSD indicate increases over all municipalities, whereas days with heavy rainfall and evaporation show trends in both directions.



Map 4: Normalised exposure values for the municipalities

Typology of climate change in North Rhine-Westphalia

Typologies of climate change regions are developed by means of a cluster analysis, based on the projected changes in the seven climate variables from the CCLM model between the time periods 1961-1990 to 2071-2100 under the A1B scenario for the NRW region (342 cells).

We applied the cluster analysis itself and the determination of the cluster number as described for the European wide analysis. All input variables were standardised by their range to values between 0 and 1 (Milligan and Cooper 1988).

Technique of cluster analysis

A cluster analysis categorizes the dimensions of a data set by allocating the objects into groups in such a way, that the objects within these groups are more similar to each other than to objects in different groups. The cluster mechanisms can be distinguished in hierarchical, partitioning and density-based methods (Handl et al. 2005). In our analysis the first two methods have been combined.

In a hierarchical clustering the data set is transformed into a distance matrix containing all pair wise distances between the objects in the data set. Using specific amalgamation rules, at first the objects and further the accumulated groups were merged. The “Ward”-method has been applied which merges the pair of groups that contributes least to the within-cluster-variance of the whole partition (Ward 1963).

Hierarchical clustering was used to cluster a small subset of objects to create a starting partition for the subsequent partitioning method. For discovering the structure in the data set the widely known partitioning method of K-means has been applied (MacQueen 1967). This algorithm minimizes the total within-cluster sum-of-squares (TSS) criterion. If the data set consists of P variables and the number of groups was chosen to K, the criterion is defined by (Steinley 2006):

$$TSS = \sum_{j=1}^P \sum_{k=1}^K \sum_{i \in C_k} (x_{ij} - \bar{x}_j^{(k)})^2$$

The objects are assigned to the k given initial cluster centres. Then the new centre is calculated as the average off all objects within the cluster and again all objects are assigned to their nearest cluster centre. This procedure is repeated until a break up criterion is reached (e.g. point's no longer change position or maximum number of loops). The largest advantages of the K-means approach are the calculation speed and the applicability for very large datasets. On the other hand there is a risk of local minima in the optimization process and the user has to choose in advance the number of cluster which he is expecting. Therefore applying a cluster analysis needs sound experience of the analyst.

Estimation of the number of clusters

For identifying the most robust and therefore most representative number of clusters a consistency measure is used, which belongs to the groups of stability based methods (see also Roth et al. 2002b; Ben-Hur et al. 2002). It follows the idea that if the pre-given selected number of clusters does not fit the underlying structure of the data, a stochastically initialized cluster algorithm will generate indefinite and different results.

The procedure of the chosen method is to generate pairs of maps, i.e. run K-means twice, for a pre-given cluster number k . Out of these pairs of maps the size of their overlap is assigned as a measure for the consistency, showing how much the two cluster results vary (see Figure 4). A lower variety and a higher value for the consistency measure imply a higher similarity between the pre-given number of clusters and the underlying structure in the analyzed data. This pair wise matching will be repeated several times (~ 200) to achieve a certain mean value for the consistency measure. The overall procedure will be repeated for different cluster numbers k whereby we can identify the k which maximizes the consistency measure.

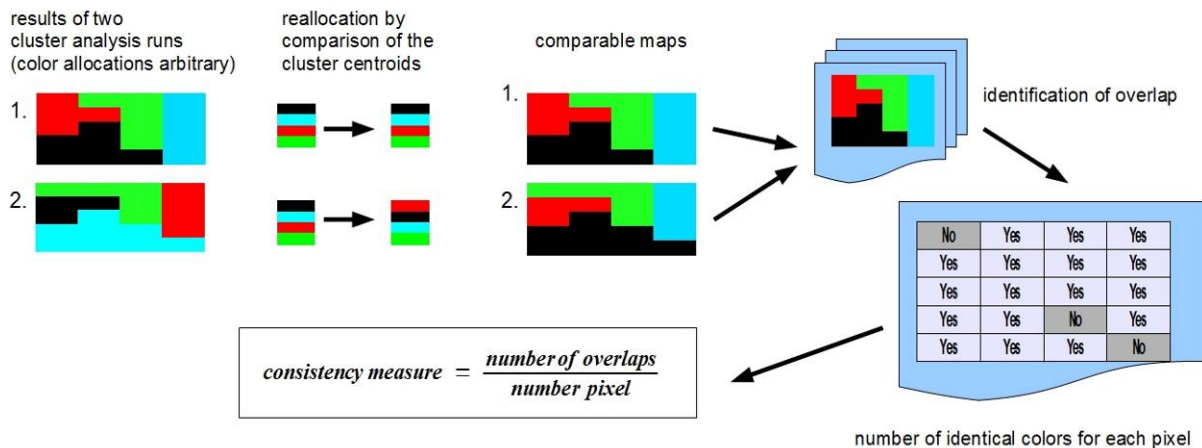


Figure 4: Overview of the determination of the optimal number of clusters by means of measuring their consistency (Sietz et al. in review)

Additionally the silhouette-width as a measure for the confidence of the observations assignment to the clusters is calculated (Kaufman and Rousseeuw 1990). The silhouette value for every single observation is defined as:

$$S(i) = \frac{b_i - a_i}{\max(b_i, a_i)}$$

With a_i as the mean distance between an object and all other data in the same cluster and b_i as the mean distance to data in the nearest neighbouring cluster. By averaging over all the silhouette values we get the silhouette width of a cluster result. This method provides clearer results than the traditional approach of elbow criterion, as can be seen in Figure 5. In the elbow-criterion, a similarity measure (like the inner-cluster-variance) is applied and the optimal number of clusters can be discerned by a clear “elbow” of the curve. Yet, with an increasing number of clusters, the clusters fit the data-set increasingly better and the detection of “elbows” becomes difficult.

The widely applied elbow-criterion points to an optimal cluster size of three (Figure 5). However, the developed consistency measure gives a clearer picture: The cluster numbers $k=3$ and $k=9$ have the highest consistency values for this data set. The silhouette width measure supports the result of the identified optimal number of clusters by means of the consistency measure. Thus, both measures show accordingly a strong maxima for $k=3$ and a weaker local maxima for $k=9$.

In order to enhance the aggregation of the vulnerability analysis we follow this case study analysis applying three ($k=3$) clusters for North Rhine-Westphalia.

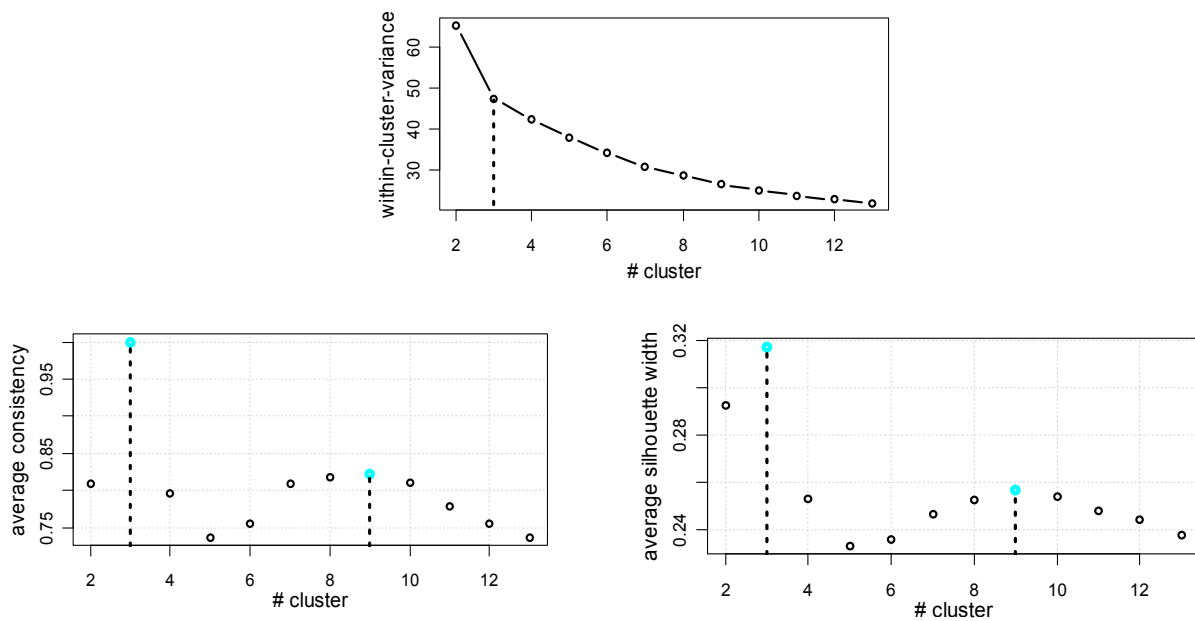


Figure 5: Determination of cluster numbers
Optimal number of clusters according to the elbow-criterion (top), consistency measure (bottom left) and silhouette index (bottom right). Local maxima are marked by dotted lines and indicate a most suitable number of clusters of $k=3$ or $k=9$.

The characteristics and the spatial distribution of the three clusters are shown in Figure 6. The red cluster “Low mountain range” is covering the higher altitudes of the study area, like the low mountain ranges “Eifel” and “Sauerland”. Here the loss of days with snow cover is strongest (see cluster feature graph, Figure 6). Winter and summer precipitations are diverging most in this group. The winter season has a higher increase and the summer season a higher loss in precipitation as the other two groups. Further this area is facing a higher increase in days with heavy rainfall.

The green cluster “Cologne Bay” covers the southern part of the Rhine-Valley within NRW. It is characterized by the strongest increase in heat days. Change in storm days and the loss in summer precipitation is smallest.

The dominating blue cluster represents mainly the low lying areas of the “Westphalian Bay - Lower Rhine”. Here the influence of the coast is apparent – with milder temperatures and more

humid conditions. Therefore loss in snow covered days is weakest and change in precipitation is moderate. The increase in storm days is stronger compared to the other clusters.

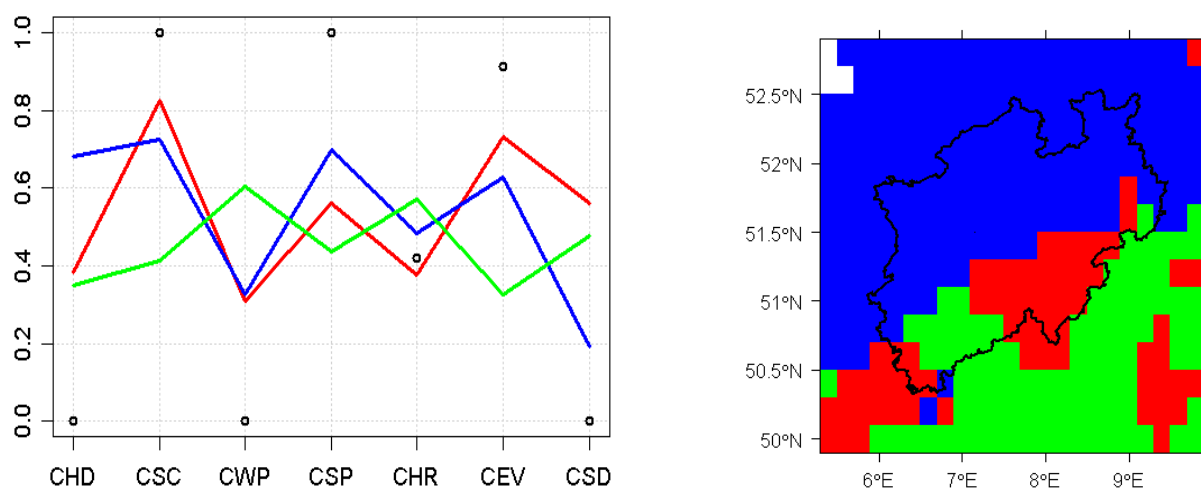


Figure 6: Results of the cluster analysis of the climate change for three clusters. Features of the three clusters (left) and spatial distribution of the clusters in NRW (right). Values of zero (no change) are indicated by black dots, thus for CHD only increases and for CSC only increases occur.

Quality of results

The former specified silhouette value (Kaufman and Rousseeuw 1990) can now be applied to display the quality of a clustering. The silhouette plot (Figure 7, left) shows this value for every object cluster wise. The higher the silhouette value of an object the better is the connectedness to its own cluster. When the index shows negative values the allocation is unfavourable. The graph further displays the mean silhouette value for each cluster, such that a comparison of clusters is possible. In $k=3$ the first cluster – “Low mountain range” cluster – exhibits the smallest value for the quality of the fit. The “Westphalian Bay- “Lower Rhine” cluster shows the best fit.

Another quality measure is depicted in Figure 7 (right). Here the distance between a model cell and its corresponding cluster centre is shown. The lighter the cell, the higher is the quality of the fit. The lowest qualities can be seen for cells adjacent or near to cluster borders (e.g. in the mountainous regions of NRW). Further, the coastal cells at the North Sea show a lower fit value than cells within the Westphalian Bay. This could stem from the model CCLM with known deviations of the results for coastal cells in Europe from reference data (Hollweg et al. 2008). A large distance to the cluster centre is also apparent for a cell in the state Hessen, in the South of NRW. This area is located in the Taunus mountains, which seem to be inadequately represented by the respective cluster.

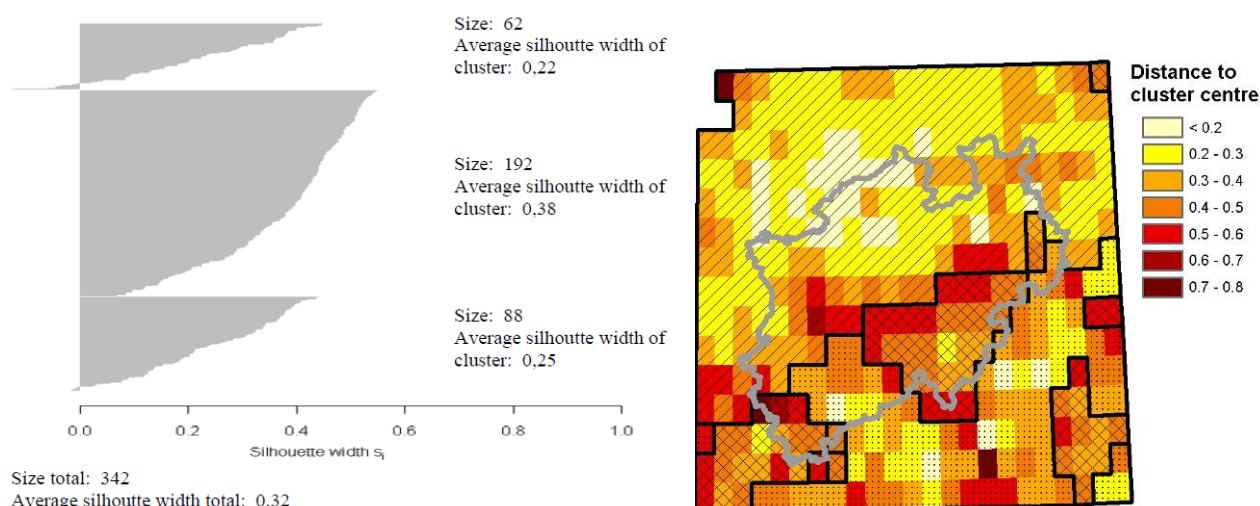


Figure 7: Quality of cluster representation
Silhouette value for every cluster (left) and distance of every cell to its corresponding cluster center (right), with respect to three clusters marked by black borders. White cells are located within the North Sea.

3.2 Exposure to indirect climate change

Besides direct exposure to climate change, based on the results of the CCLM model, inundation as an indirect exposure will be considered. Inundation cannot be represented by any of the chosen exposure variables, since these are restricted to grid cell level, thus, we quantify flood impact differently.

The main river running through NRW is the Rhine, which flows from the Alps to the North Sea. Under the projected warming, the Rhine basin is expected to shift from a partly snowmelt-driven regime to a largely rainfall-dominated regime, resulting in an increase in winter discharge as well as in frequency and height of peak flows (Barnett et al. 2005). This trend of increasing extreme discharges in winter has already been observed during the last century at the gauges Cologne, Rees and Lobith at the Rhine (Belz et al. 2007).

Climate change impacts with regard to flooding can either be described by the change in the return period of certain high discharge events, e.g. a decrease in the return period of a flood event observed for every 100 years in the past (HQ100). Or they can be assessed by the change of the discharge amount and consequently the extent of flood prone area considering the same flood event with a specific return period.

Changes in the return period of high discharge events and discharge amounts of particular events

Simulation of future peak discharges for the river Rhine, based on climate scenarios corresponding to the emission scenarios A1B and A2, show a general increase in the discharge of flooding events with a return period of 10-1250 years until 2050 (Te Linde et al. 2010). At the gauge Lobith (located in the Netherlands at the border to NRW) this is reflected by an increase

in the discharge of HQ100 by 5-9% until 2050 under scenario A1B. Moreover, the return periods of extreme flood events decreased considerably, by a factor 2.5-4.7 at the same gauge for a 1250-year event by 2050. The discharge of a return period of 100 years increases by 10-30% at the same gauging station until the end of the century under the A2 scenario (Lenderink et al. 2007).

Extreme events are also projected to increase in a hydrological simulation of the Rhine basin driven by a regional climate model with a high spatial resolution under the scenarios B1, A1B and A2 at the gauge Lobith until the mid and end of this century (Hurkmans et al. 2010). An event of the magnitude of the flooding in 1926 would occur every 10-20 years under these scenarios in this century. This flood event was caused by a discharge of more than 12.000 m³/s at Lobith, the largest measured discharge of this section of the river until 1997 (LUA 2002).

Since climate models, especially the choice of GCMs, have a large impact on the projected hydrological change, a multimodel approach can best reflect possible changes (Graham et al. 2007). Hydrological simulations driven by a multimodel ensemble of climate projections indicate an increase in the return levels of flood events up to 30 % under the A2 scenario and a slight increase to a moderate decrease under the B1 scenario for the same gauging station until 2100 (Dankers and Feyen 2009).

According to a multi-model assessment, high flows corresponding to the HQ100 event for the gauge Cologne and Lobith are projected to increase by up to 20% until 2050 or 25% by 2100 under scenario A1B. Very extreme discharges of a HQ100 events could change from -5 to +25% until 2050 or up to +30% by 2100 for Cologne (De Keizer et al. 2010).

A multimodel ensemble simulation for the Rhine basins within the currently running research project "KLIWAS" also shows an increase in mean monthly discharges in winter months at the gauge Cologne (Krahe et al. 2009), which points to an increase in the flood risk in winter.

An increase in the mean discharge of the rivers Ems, Wupper and Weser is expected in future (Kropp et al. 2009b).

In spite of this increasingly extensive information on changes in river discharges and return periods, no consistent dataset is available for all major rivers in NRW.

Furthermore, the calculation of HQ100 needs to employ extreme value statistics. Yet, such an approach has clear limitations. Frankly speaking, they assume stationary and independent distributed events, a situation which is not given under climate change. Moreover, for rivers runs large range correlations have been detected which cannot easily be separated from a trend (see Kropp and Schellnhuber 2011).

Changes in the extend of flood prone area

Simulated flood extents are available on a European scale from the hydrological LISFLOOD model (De Roo et al. 2000; Van Der Knijff et al. 2009). Recently the model has been driven by the climate model CCLM (Preliminary LISFLOOD data based on CCLM, JRC 2010). These flood maps indicate areas inundated by a 100-year event (HQ100) in 1961-1990 and 2071-2100.

For the river Rhine, only slight changes in the inundation area of a HQ100 event are simulated. However, several limitations concerning this data have to be noted. The influence of the climate model on the results of the hydrological model LISFLOOD is strong. Moreover, due to the high decadal-scale variability the selection of time slices for analysis is a major influencing factor, which can even obscure the climate change signal (Dankers and Feyen 2009). Thus, uncertainty regarding this data is high as we apply only one climate model and emission scenario and two 30-year time periods.

Also larger deviations of model simulations from observed annual maximal discharges were found for catchments dominated by snowmelt regime (Dankers and Feyen 2009). This poor reproduction of snowmelt processes could also influence the quality of results for the Rhine catchment, influenced by the alpine cryosphere. Further, the model does not take into account river regulation, which could affect the results of smaller heavy regulated rivers in NRW such as the river Wupper, where low discharge events are difficult to represent by simulations due to river regulation (Kropp et al. 2009b).

When driven with different regional climate models, global climate models and emission scenarios, the hydrological model has shown rather high mean relative errors of the mean annual maximum discharge between 12-59%. Additionally to these errors concerning the discharges during flood events, errors occur by estimating the depth and extent of the inundated area, which has been carried out by JRC based on a DEM of 100m resolution.

A comparison of the overlap of regional maps of flood prone areas with and without dykes for the river Rhine of a HQ100 event in the past³ with the inundation area for 1961-1990 based on the LISFLOOD model yielded only 36% and 64% coinciding area respectively. The largest deviations occur in the lower Rhine valley near the Dutch border.

Due to these limitations concerning the data and methods, a different approach will be followed in this case study based on fine scaled maps of flood prone area regarding several flood events for the river Rhine.

Exposure to inundation

The exposure to inundation will be based on the change in the occurrence (or return period) of flood events, which are discussed above.

A major limitation of extreme value analysis is the rare occurrence of these events. Within the considered time periods of 30 years, a 100-year event would have a high change of not being detected.. A resampling approach has been applied by Te Linde et al. (2010) to climate input data driving a hydrological model to simulate discharges of the river Rhine. Climate input data were derived from the regional climate model ECHAM5-RACMO, scenario A1B until 2050. Comparing discharges at the gauge Lobith between 1961-1995 and 2036-2065, an HQ100 event of the past would occur roughly every 50 years in the future, a HQ200 event

³ Provided by the Ministry for Climate Protection, Environment, Agriculture, Nature Conservation and Consumer Protection of NRW, 2003

approximately every 100 years and an HQ500 roughly every 200 years. However, this resampling approach was carried out in a simplified way. More advanced methods allowing for a sample extension and a reconstruction of the internal auto-correlation structure employ a combination of FARIMA models, iterative amplitude adjusted Fourier transform algorithms and bootstrapping (Rust et al. 2011). Such approaches supply distributions for HQ100 events and therefore better reflect internal uncertainties.

These return periods are applied in the project and are related to flood maps of HQ100/200/500 events in NRW³, but with changes in their occurrence. These changes in occurrence are applied as exposure variables consistently with the changes in the direct exposure variables as an output of CCLM.

Table 2: Assumed exposure to inundation based on the occurrence of flood events (based on Te Linde et al. (2010))

	HQ100	HQ200	HQ500
Occurrence within 100 years in the past	1	0.5	0.2
Occurrence within 100 years in the future	2	1	0.5
Changes in occurrence	+ 1	+0.5	+0.3

A further clear limitation of this approach is the shorter time horizon of the hydrological simulation and the restriction of the analysis to the river Rhine. It has to be noted, however, that the considered flood events are extreme events, which are difficult to project over large timescales, or only with increasing uncertainty, especially when projecting changes in the last decades of the century (see discussion above).

We therefore decided to apply the more founded regional flood maps and combine these with a climate change signal. By considering flood maps of several flood events, a more complete picture of the potential impact can be given compared to the data from the LISFLOOD model, which is available for only one flood event.

The occurrence of peak flows is only a proxy for a possible inundation event, since flow volumes are not considered. These flow volumes (as the integral of the runoff) constitute the potential water volume over the inundated area and thus serve as a basis for the design of flood protection measures (Maniak 2005). Thus we consider changes in the occurrence of peak flows, but due to lack of data assume constant flow volumes for the respective events.

4. Sensitivity to climate change

Sensitivity towards climatic changes will be expressed considering the physical, environmental, social and economic dimensions by means of certain indicators. The cultural dimension could not be included due to lack of data for the high spatial resolution of this case study. Flooding has been considered as an impact of climate change to cultural assets in the pan-European assessment. However, given the limited dataset for cultural sites (e.g. world heritage sites) on the regional level, the dome of Cologne would presumably be the only site at risk regarding river

inundation. Regarding pluvial flooding, the spatial uncertainty is very high since rain is a stochastic event with high spatial variations, Thus, statements regarding specific locations are difficult. This case study therefore focuses on the physical, environmental, social and economic dimensions. The sensitivity indicators are summarized in **Fehler! Verweisquelle konnte nicht gefunden werden.** and are assigned to distinct direct and indirect exposure variables whose processes are discussed in literature.

The indicators will be described extensively in the following chapter. Thereby their relevance and underlying processes concerning the corresponding climatic stimuli are discussed and the methodology of their application and data sources are summarized within fact sheets for each variable. For some indicators methods already available could be applied, which are briefly described in the respective sections. For further information we refer to the quoted literature. For other indicators, new methods of analysis have been developed within the project and are explained in more detail in the respective sections.

As no projections of the applied sensitivity datasets until the considered time horizon of the year 2100 exist, sensitivity is expressed by its current status.

Sensitivity is characterized by a high spatial differentiation, thus all sensitivity indicators are applied to the finer spatial resolution of municipalities (LAU2) compared to NUTS3 regions as the basis for the European wide analysis. For individual indicators the analysis is based on even more fine scaled approaches (e.g. sensitivity to flash floods for specific landscape units), which are aggregated to the level of administrative units LAU2 as the spatial entity chosen within this project.

In the process of aggregating the vulnerability components, the indicators will be aggregated to the level of NUTS3 regions for a comparison with the results of the European wide analysis.

For reasons of comparability and to facilitate aggregation, sensitivity indicators were normalized from 0-1 based on their minimum and maximum values within NRW. Thus the analysis will focus on the relative sensitivity and therefore relative vulnerability. Therefore comparative differences between the vulnerability of the communities are calculated, yet no quantification of the absolute level of vulnerability is possible.

The quantification of the relative sensitivity was carried out according to the following approach: relative sensitivity values (e.g. mean sensitivity of forest area to windthrow) are multiplied by the relevance of the indicator within the municipality (e.g. share of forest area on municipal area).

The sensitivity indicators will be discussed in the order shown in Table 3 in the following chapters in more detail.

Table 3: Overview of sensitivity indicators and relevant climatic stimuli⁴
The indicators and underlying processes are discussed in detail in the following sections

Sensitivity dimension	Objects/Sectors	Exposure to climatic changes							
		Direct							Indirect
		CHD	CSC	CWP	CSP	CHR	CEV	CSD	CRF
Physical	Sensitivity of settlements to flash floods					+			
	Sensitivity of settlements to pluvial flooding					+			
	Sensitivity of settlements to river floods								+
Social	Sensitivity of humans towards river floods								+
	Sensitivity of humans towards heat	+							
Environmental	Sensitivity of protected areas to drier and warmer climate			-	-		+		
	Sensitivity of soils to potential water erosion					+			
	Sensitivity of lakes to a decrease in water volume			-	-		+		
Economic	Sensitivity of winter tourism to shortening of the winter season		-						
	Sensitivity of forestry to windthrow						+		
	Sensitivity of forests to forest fires	+			-				
	Sensitivity of agriculture to drought			-	-		+		

⁴ Changes in the annual number of heat days (CHD), changes in the annual number of days with snow cover (CSC), changes in annual mean winter precipitation (CWP), changes in annual mean summer precipitation (CSP), changes in the annual number of days with heavy rainfall (CHR), changes in annual mean actual evaporation (CEV), changes in the annual number of storm days (CSD), changes in river floods (CRF)

4. 1 Physical sensitivity

Relative sensitivity of settlement to flash floods

Heavy rainfall events can lead to local flash floods. A flash flood is an event which occurs rapidly, without no or little warning and is usually caused by intense rainfall over a relatively small area (AMS 2000). Compared to other flood events, flash floods cause the highest mortality rates per event (Jonkman 2005).

In NRW, an increase in days with rainfall above 20 mm has been observed from 1950 to 2008, as well as an increase in precipitation amounts for several time periods regarding the duration of the respective rainfall event. In future, the days with heavy rainfall above 70 mm will change ranging from a decrease by 10 % up to an increase of 40 % until the end of the century according to the regional climate models considered (WETTREG, CCLM), yet with large uncertainties (auqa plan GmbH 2009; aqua plan GmbH et al. 2010).

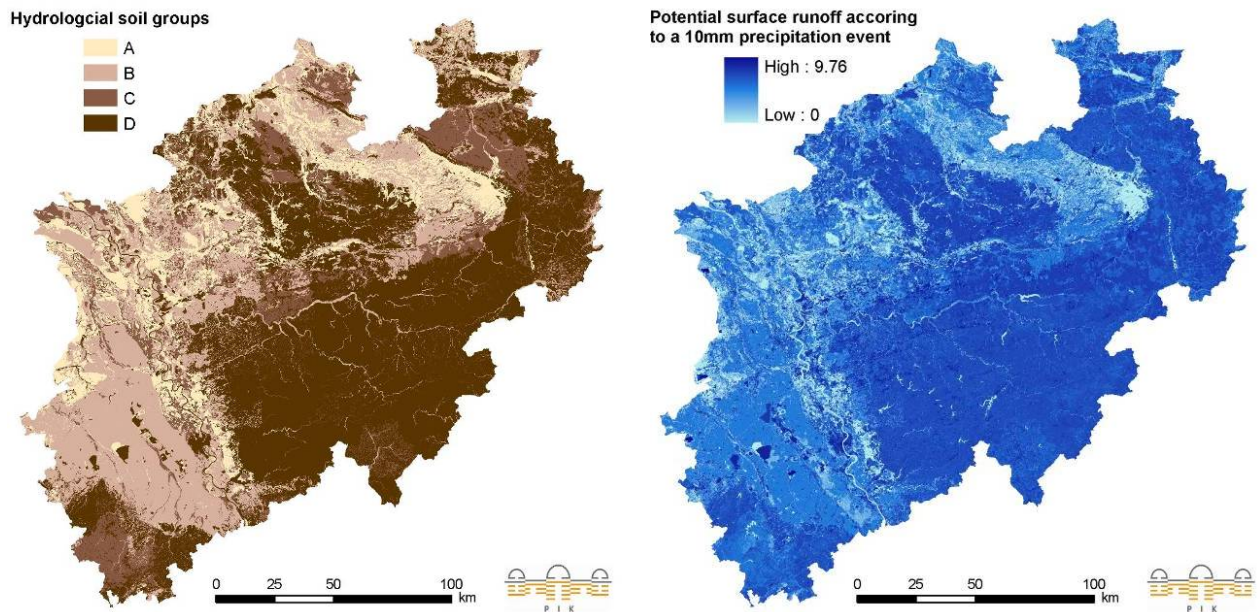
The sensitivity of a catchment to flash floods can be expressed by the steepness of the catchment, the land use type, the soil moisture conditions, the area of the catchment in relation to its runoff course and the likelihood of an unimpeded water flow (Collier 2007). Especially roads leading down into the valley are likely to be affected, as well as areas with filled up or removed drainage systems, which is often the case in settlement areas (Castro et al. 2008).

Around 20 % of flash floods in Germany occurred within the state NRW in the last decades, which in relation to its area lies above the average for Germany. A concentration of flash floods could be found for the Rhine valley. Most of the events in Germany occur between May and September (Castro et al. 2008).

While maps for areas prone to river inundation exist for NRW, no information is available for other areas prone to flash floods, especially in urban areas. Thus, we developed sensitivity maps for flash floods based on topography by applying GIS methodologies.

A combination of flow accumulation (FLAC) analysis with land use data can indicate urban areas at risk (Castro et al. 2008). We therefore determine the flow accumulation based on the potential runoff caused by a rainfall event. Potential runoff is calculated based on soil characteristics and land use of the drainage area by applying the SCS-curve number approach (USDA 1972). Soil types of the regional soil map for NRW (BK50) are assigned Hydrological Soil Types (A = high infiltration capacity and thus low runoff to D= low infiltration capacity and thus high runoff) by applying the criteria concerning minimum hydraulic conductivity, depth of least permeable layers and depth to water table (USDA 2007) (Map 5, Map 5: I left).

Soil groups together with ATKIS land use data are then used as an input for the runoff calculation using the ArcCN tool based on the SCS-approach (Zhan and Huang 2004), assuming a precipitation event of 10 mm in accordance to the selected exposure variable "days with heavy rainfall". The overall runoff pattern is largely dependent on the hydrological soil groups; however, the fine scaled differentiation can be mostly attributed to land use (Map 5, Map 5: I right).



*Map 5: Infiltration characteristics of soils and potential surface runoff
Hydrological soil groups in NRW classified based on the BK50, ranging from low to high runoff potential (A to D) (left) and potential runoff according to a 10 mm precipitation event based on hydrological soil groups and land use (right)*

The flow accumulation per elevation cell is then determined by considering the calculated potential runoff and the flow direction of the water, based on the elevation model of 50 m resolution. Considering the potential time lag of the flow (assuming a 60 min event and taking into account the slope and runoff potential), the peak flow is calculated based on Castro et al. (2008). Settlement and traffic cells affected by a peak flow of $>1\text{m}^3$ were used as an indicator for the sensitivity towards flash floods.

Table 4: Fact Sheet: Relative sensitivity of settlements towards flash floods

Relative sensitivity of settlements towards flash floods
Sensitivity of settlement and traffic areas towards flash floods caused by heavy precipitation events due to accumulation of runoff
Exposure: Increase in the number of days with heavy precipitation
Spatial entity of application: Landscape units
Detailed description: Settlements located in steep river catchments with a short time lag of the runoff water are prone to flash floods, which can be caused by heavy precipitation events (Collier 2007; Castro et al. 2008).

Methodology:

The potential runoff of a 10mm rainfall event is calculated by applying the Curve Number method (USDA 1972; USDA 2007), which accounts for land use and hydrological soil type with the ArcCN tool (Zhan and Huang 2004). The hydrological soil type is assigned by applying the criteria concerning minimum hydraulic conductivity, depth of least permeable layers and depth to water table (USDA 2007).

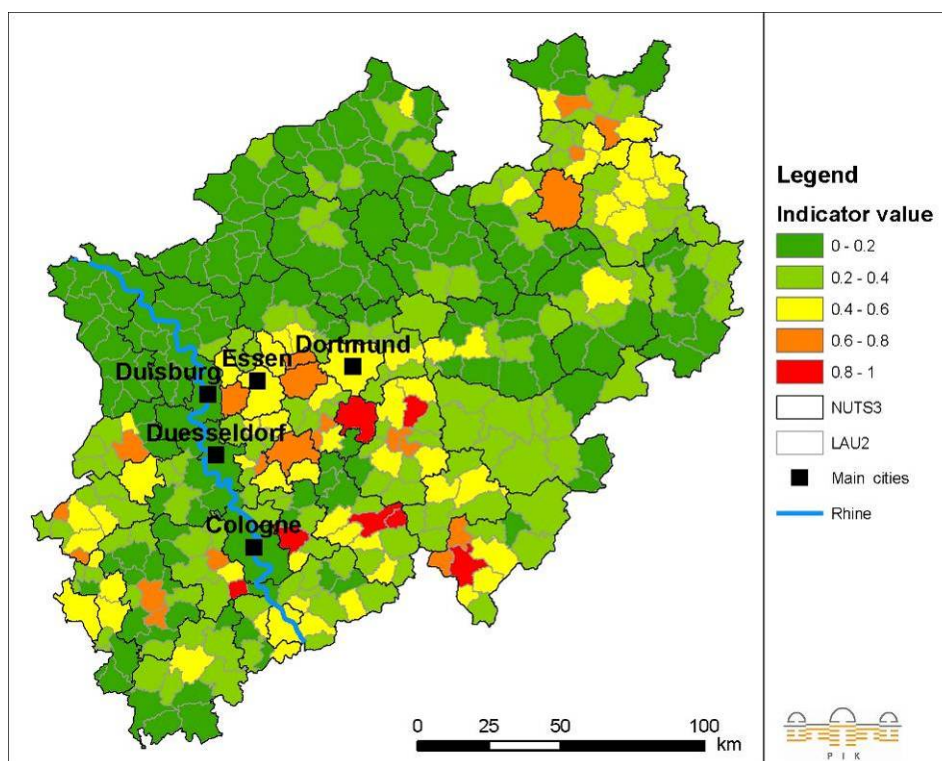
Flow accumulation is then calculated with ArcGIS based on the potential runoff and the flow direction of the elevation model with a resolution of 50 m. Considering the potential time lag of the flow (assuming a 60min event and taking into account the slope and runoff potential), the peak flow is calculated based on Castro et al. (2008).

The share of settlement and traffic cells (classes 4103, 2114, 2113, 2111, 3103 and 9999, gridded to 50 m from the ATKIS25 dataset) affected by a peak flow of $> 1\text{m}^3$ on the total municipal area is then calculated.

Data sources: Topographic data: Digital elevation model 50m (LANUV NRW, 2008), land use data: Authoritative Topographic-Cartographic Information System (ATKIS25, 2000), Federal Environment Agency, DLR-DFD 2009

Key literature sources:

Castro, D., T. Einfalt, S. Frerichs, K. Friedeheim, F. Hatzfeld, A. Kubik, R. Mittelstädt, M. Müller, J. Seltmann & A. Wagner (2008). *Vorhersage und Management von Sturzfluten in urbanen Gebieten (URBAS). Schlussbericht, Hydrotec Ingenieurgesellschaft für Wasser und Umwelt mbH, Aachen, Fachhochschule Aachen, FB Architektur, Deutscher Wetterdienst, Meteorologisches Observatorium Hohenpeißenberg. Aachen, 395 pp.*



Map 6: Indicator map of sensitivity of the relative settlements towards flash floods

Relative sensitivity of settlement to pluvial flooding

Besides areas of intense flow accumulation also landscape sinks, where this flow accumulates and exceeds the retention capacity of the canal system, are threatened (Castro et al. 2008; Grünewald et al. 2009; Hart et al. 2009). This urban flooding process is also called non-riverine flooding, since it does not derive from river discharge water but direct runoff (Chen et al. 2009) and cause mainly drainage problems and thus pose a limited threat to life but mainly economic damages (Jonkman 2005).

It plays an important role in NRW due to its high urban densification and sealed area which impedes infiltration (Held 2000) and occurrence of landscapes sinks or depressions due to former lignite mining without natural surface runoff and often anthropogenic drainage (Drecker et al. 1995; Hydrotec 2004; Grünewald et al. 2009).

We combine the approaches of accumulated surface runoff and landscape sinks: using GIS, we identify sinks within the relief and calculate the amount of runoff, which would be necessary to completely fill each sink, dependent on the respective volume and drainage area and the surrounding topology.

For the potential runoff also land use and soil characteristics are taken into account based on the Curve Number approach described for the indicator “Sensitivity of settlements to flash floods” (see Table 4).

The volume of the sink, which would be potentially flooded, is then divided by the calculated runoff of the respective drainage area, giving an indication of flooding or overflowing of the sink for a potential rainfall event. Thus for sinks with a low ratio, already a small amount of precipitation would cause flooding, due to a low sink volume compared to its total drainage surface area.

Table 5: Fact Sheet: Relative sensitivity of settlements towards pluvial flooding

Relative sensitivity of settlements towards pluvial flooding
Sensitivity of settlements and traffic areas towards pluvial flooding caused by heavy precipitation events within landscape sinks
Exposure: Increase in days with heavy precipitation
Spatial entity of application: Landscape units
Detailed description: Settlements located in landscape sinks with a relatively large drainage area are prone to flooding, which can be caused by heavy precipitation events (Castro et al. 2008; Grünewald et al. 2009; Hart et al. 2009).
Methodology: Landscape sinks within the surrounding relief were identified from the digital elevation model with a resolution of 50m in ArcGIS.
The potential runoff of a 10 mm rainfall event is calculated for each drainage area of the sinks by applying the Curve Number method (USDA 1972; USDA 2007), which accounts for land use and

hydrological soil type with the ArcCN tool (Zhan and Huang 2004).

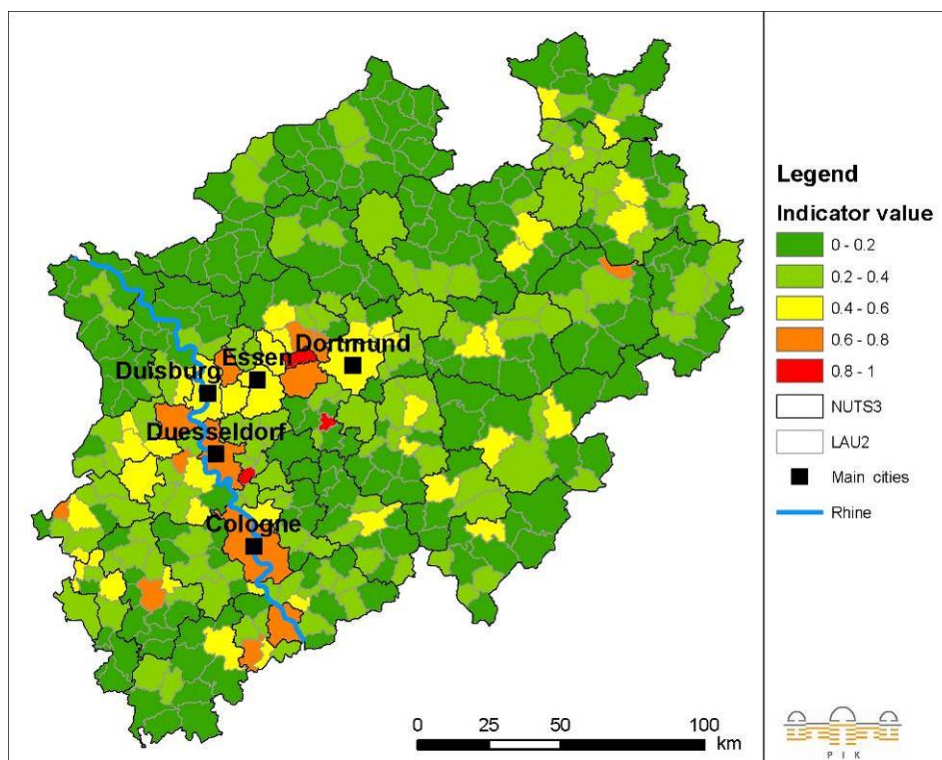
Dividing this potential runoff by the volume of each sink gives an indication of the threat of flooding during a heavy precipitation event.

Since flash floods are mainly a threat for human settlements, only settlements (classes 4103, 2114, 2113, 2111, 3103 and 9999, gridded to 50 m from the ATKIS25 dataset) within these sinks were considered. The value concerning the ratio between drainage area runoff and sink volume was summed for the municipalities and weighted by their area.

Data sources: Topographic data: Digital elevation model 50m (LANUV NRW, 2008), land use data: Authoritative Topographic-Cartographic Information System (ATKIS25, 2000), Federal Environment Agency, DLR-DFD 2009

Key literature sources:

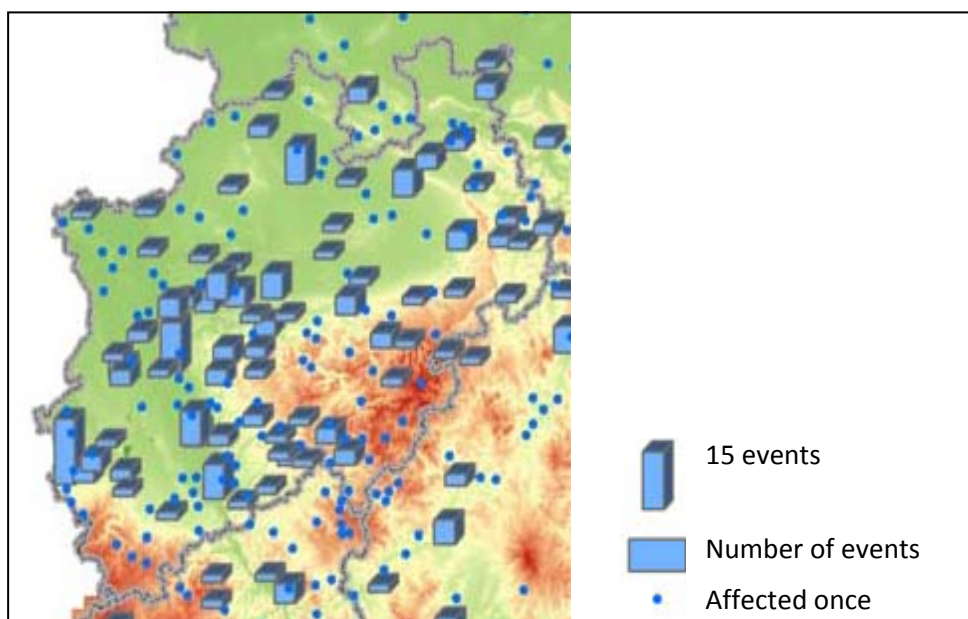
Castro, D., T. Einfalt, S. Frerichs, K. Friedeheim, F. Hatzfeld, A. Kubik, R. Mittelstädt, M. Müller, J. Seltmann & A. Wagner (2008). *Vorhersage und Management von Sturzfluten in urbanen Gebieten (URBAS). Schlussbericht, Hydrotec Ingenieurgesellschaft für Wasser und Umwelt mbH, Aachen, Fachhochschule Aachen, FB Architektur, Deutscher Wetterdienst, Meteorologisches Observatorium Hohenpeißenberg. Aachen, 395 pp.*



Map 7: Indicator map of the relative sensitivity of settlements towards pluvial flooding

Flash flood events with recorded damages in NRW occurred mainly in the lowlands, especially along the river Rhine, in Aachen, in the Ruhr area and around Muenster (Map 8) (Castro et al. 2008). The region along the Rhine and the Ruhr area agree well with the indicator of pluvial flooding (Map 7). Some flash flood events were also observed in the higher altitudes, for

example around Siegen and at the foot of the Sauerland mountains. Also these areas correspond well with identified areas sensitive to flash floods in our analysis.



Map 8: Recorded number of flash floods events with damages in NRW until 31.9.2007 (Castro et al. 2008).

For further validation of the developed indicators concerning heavy precipitation events, results of the developed sensitivity indicator are compared with an exemplary heavy precipitation event, which occurred in the municipality of Dortmund on 26.7.2008. This day, precipitation rates of over 60 mm/h were observed over the western parts of Dortmund and around 200 mm at the climate station of the Dortmund-University within 150 min (Malitz and Rudolf 2008). The latter amount corresponds to more than twice the average rainfall of this month. In addition, Dortmund is geomorphologically characterized by subsidence caused by mining, which contributes to a high sensitivity to flooding.

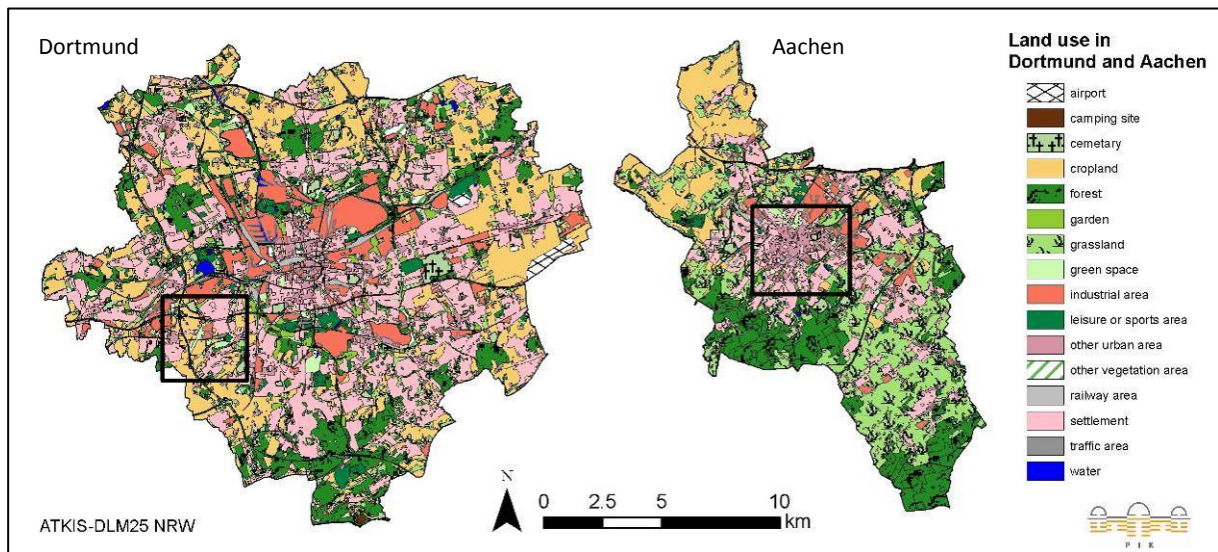
The main damage occurred in the western parts of the city, especially in the districts Marten, Dorstfeld and Schönau, where various streets were inundated by flash floods within a very short timeframe (Grünwald et al. 2009). This part of the city is indicated in Map 9 and will be analyzed further with regard to the indicator for flash flood sensitivity. The flooded streets or street sections within these parts of Dortmund are indicated in Map 10 and Map 11. It can be seen that some of these streets overlap with landscape sinks (Map 10), which were flooded by a heavy precipitation event as observed in 2008. Hereby values below 1 indicate of high probability of flooding of the sink for a precipitation event of 10 mm due to a low sink volume and a high potential runoff from the respective drainage area. As such a precipitation event has a rather small intensity, it can be expected that also sinks with values below 1 are under risk of flooding given events with higher rainfall intensities.

Flooding of other streets, especially in the vicinity of rivers can be attributed to the high potential flow accumulation over the respective areas, as indicated exemplarily by a rainfall event of 10 mm (Map 11).

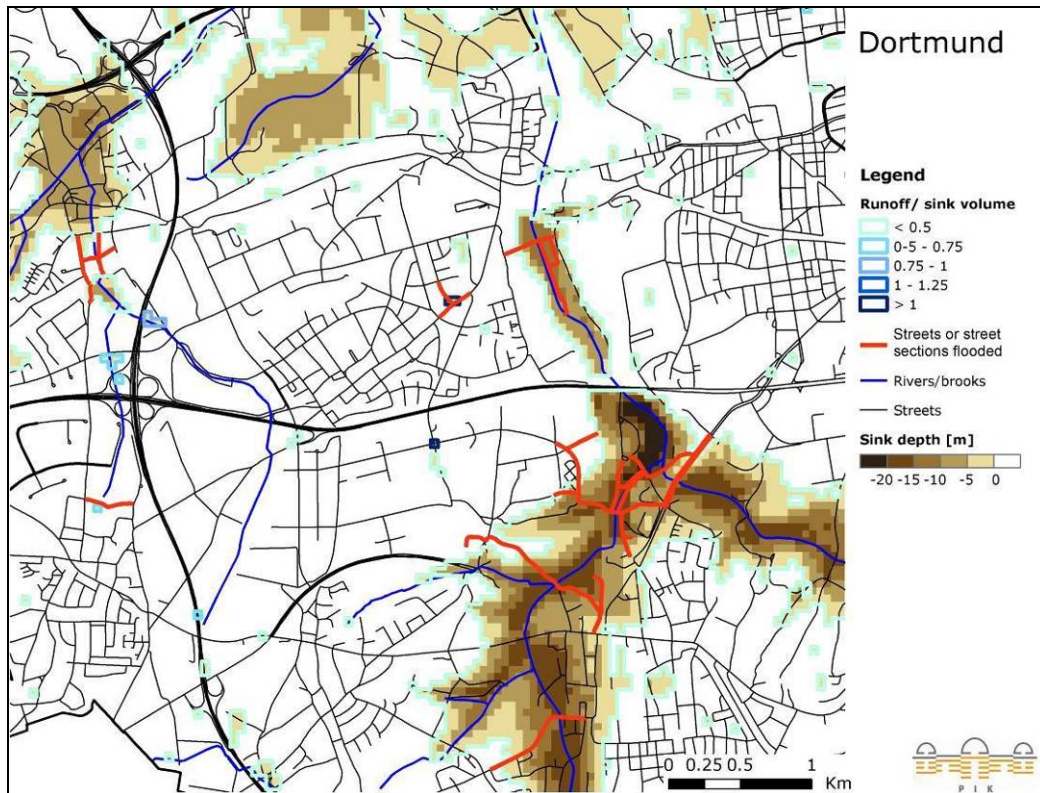
A heavy precipitation event over Aachen, within the centre of the city (Map 9) was recorded on 30.07.2002 with 28 mm of rainfall within 40 minutes (Castro et al. 2008). This caused water damages of several streets, shown in Map 10 and Map 11, based on Castro et al. (2008).

Few streets are located in urban landscape sinks, which might have contributed to the damage (Map 12). Most of the damaged streets are found within areas of high flow accumulation (Map 13). This is especially the case along the course of the river “Wurm”, which has been bypassed subsurfacely within the city centre.

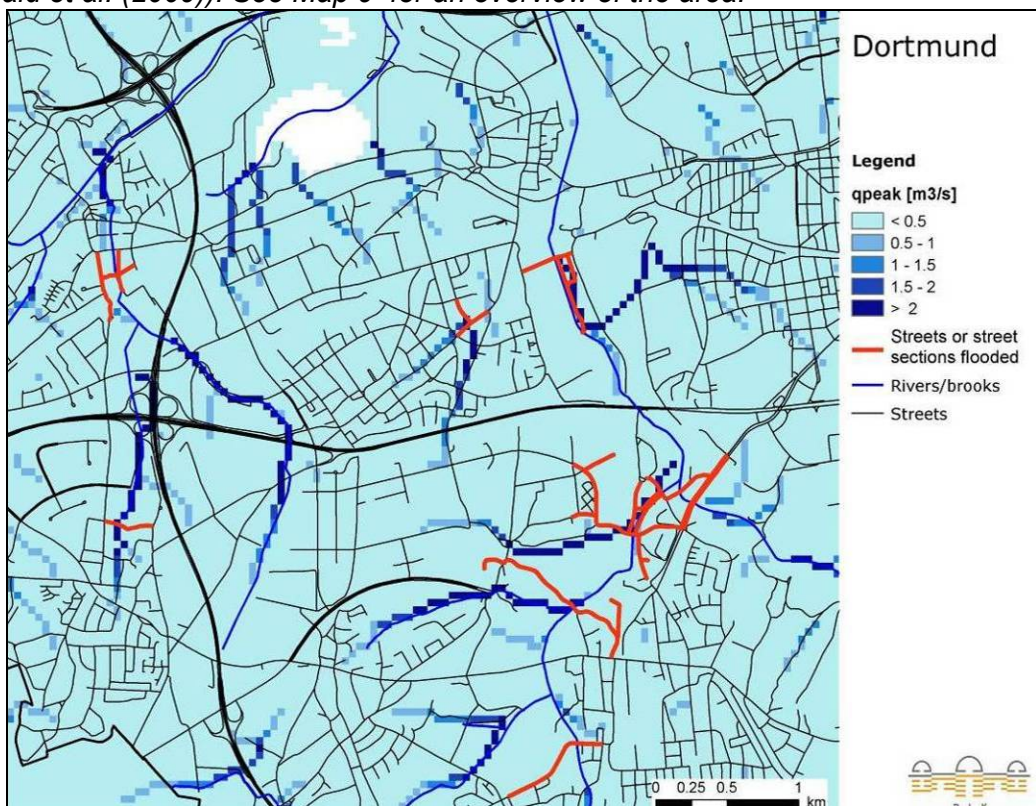
By and large, most of the flooded streets can be explained by either one of the indicators of sensitivity of settlements to flash floods and pluvial flooding. A full picture of their sensitivity would only be possible by integrating data on the capacity of the local canal system, which were not available.



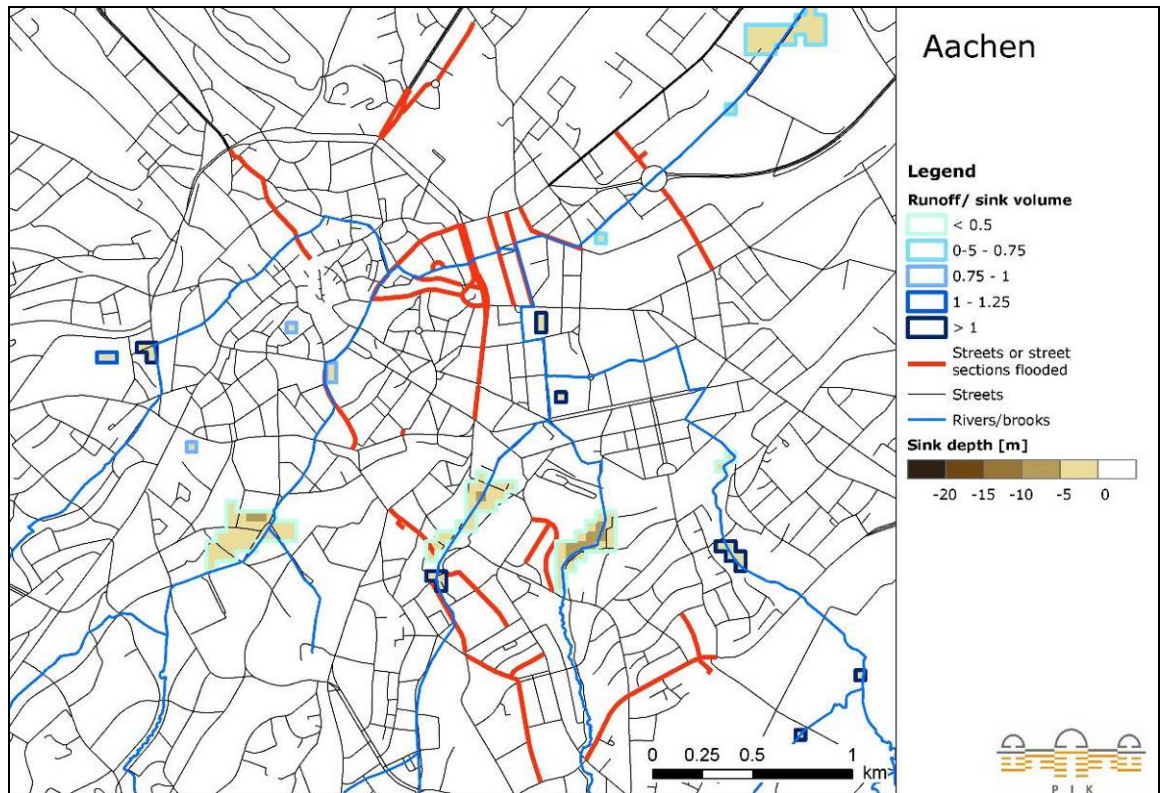
*Map 9: Overview on land cover of Dortmund (left) and Aachen (right)
The marked area is discussed in detail with regard to flash floods (see Map 10 - Map 11)*



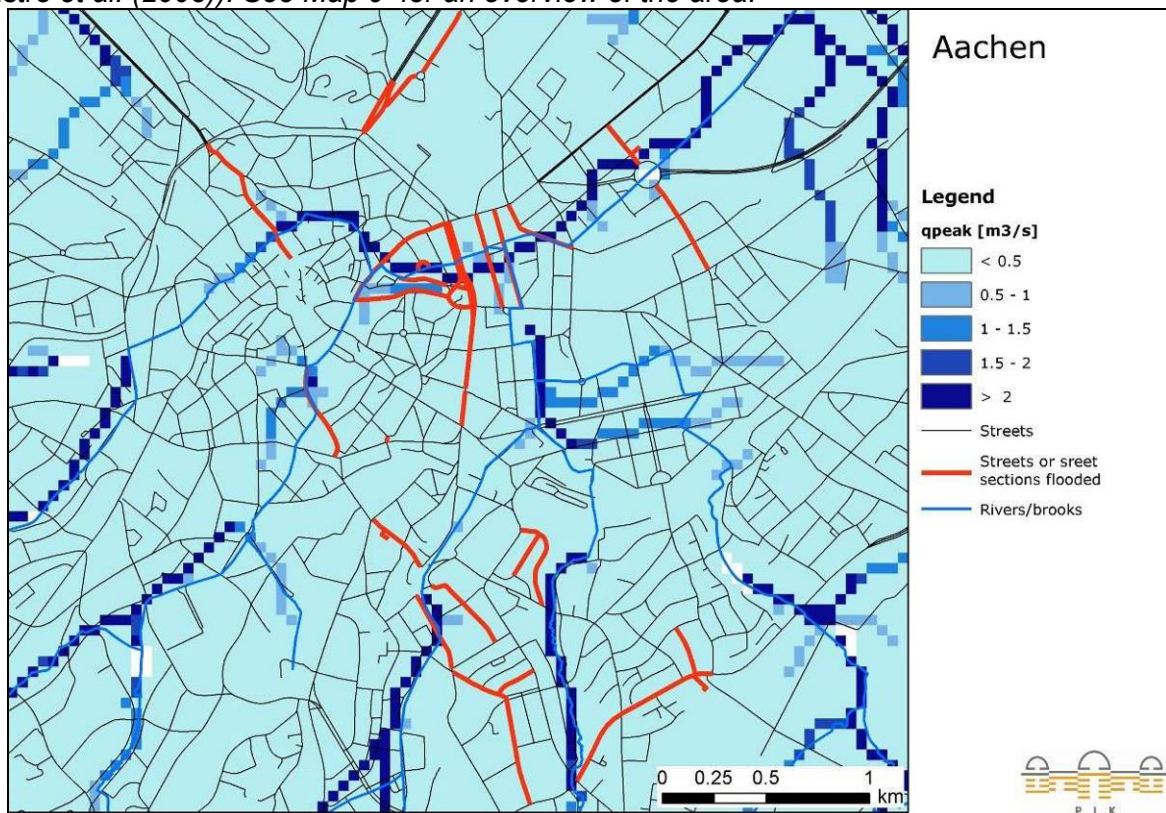
Map 10: Identified landscape sinks in western Dortmund
 Landscape sinks are compared with streets flooded on 26.7.2008 (streets digitalized after to Grünewald et al. (2009)). See Map 9 for an overview of the area.



Map 11: Identified landscape flow accumulation in western Dortmund
 Areas of high flow accumulation are compared with streets flooded on 26.7.2008 (streets digitalized after to Grünewald et al. (2009)). See Map 9 for an overview of the area.



Map 12: Identified landscape sinks in the centre of Aachen
Landscape sinks are compared with streets flooded on 30.07.2002 (streets digitalized after to Castro et al. (2008)). See Map 9 for an overview of the area.



Map 13: Identified flow accumulation in the centre of Aachen
Areas of high flow accumulation are compared with streets flooded on 30.07.2002 (streets digitalized after to Castro et al. (2008)). See Map 9 for an overview of the area.

Relative sensitivity of settlements to river floods

Damages due to major floods in Europe have increased in the last years (Mitchell 2003; Barredo 2007) which can be attributed to the accumulation of population and capital in flood prone areas and to anthropogenic influences of the hydrological cycle (Mitchell 2003). Thus, urban areas are especially threatened by high flood losses due to spatial agglomeration of population, infrastructure and property values (Hooijer et al. 2004; Thielen et al. 2006).

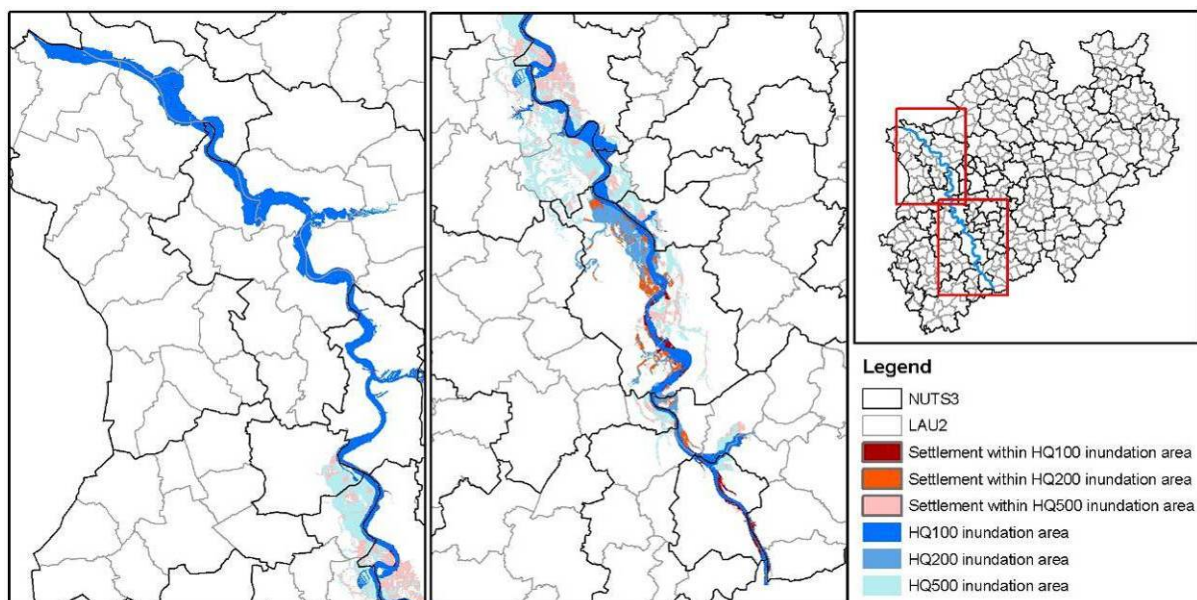
In NRW floods occur regularly, especially severe ones were recently recorded in the years 1993 and 1995 (Disse and Engel 2001) causing damages of more than 1.5 Billion DM (Munich Re 1999). A comparative study of storm, flood and earthquake hazards for the city of Cologne has shown, that most of the economic losses that occur frequently can be attributed to floods (Grunthal et al. 2006).

The sensitivity of settlements towards floods is expressed by the settlement area of an HQ100, HQ200 and HQ500 inundation event of the river Rhine considering current dykes (

Map 14: Settlements within potential inundation areas of the river Rhine

with regard to an HQ100, HQ200 and HQ500 flood event, considering current dykes

). The data is based on inundation maps of the Ministry for Climate Protection, Environment, Agriculture, Nature Conservation and Consumer Protection of NRW, 2003. Inundation areas based on the HQ100 event occur along the whole length of the Rhine, especially in the lower valley. HQ200 and HQ500 inundation areas are concentrated in the central part of the river section of NRW, where they overlap in large parts with settlement areas.



Map 14: Settlements within potential inundation areas of the river Rhine with regard to an HQ100, HQ200 and HQ500 flood event, considering current dykes⁵

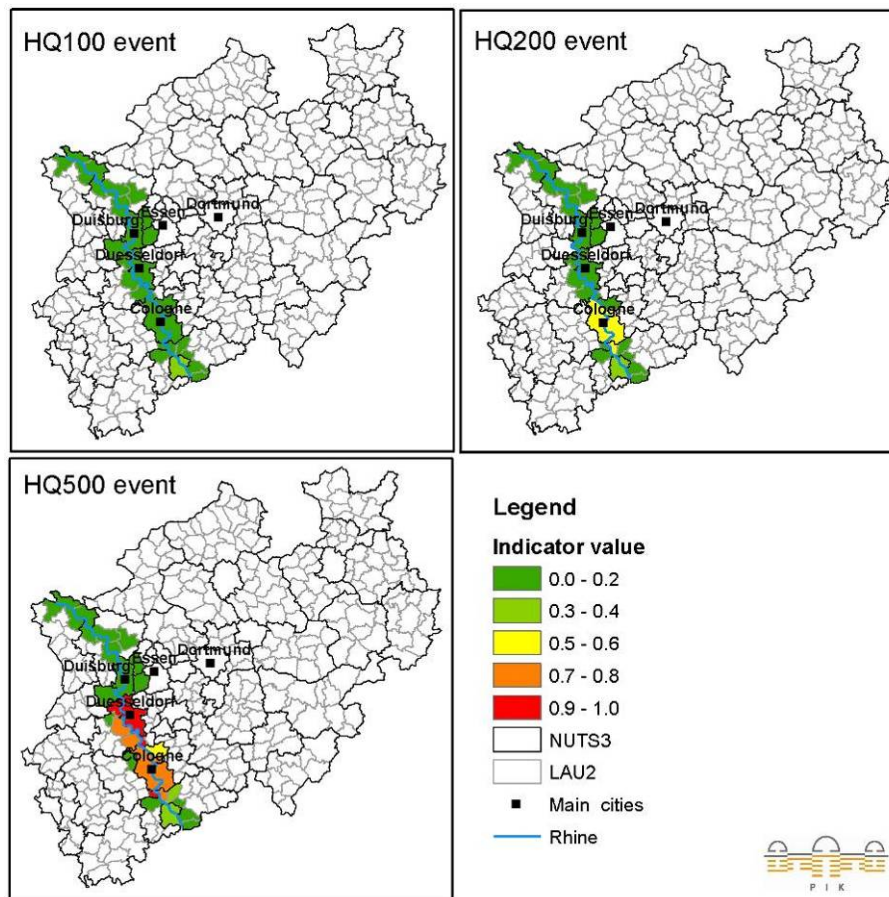
⁵ Data according to the Ministry for Climate Protection, Environment, Agriculture, Nature Conservation and Consumer Protection of NRW, 2003

The indicator of relative sensitivity of settlements towards these flooding events is quantified by the share of settlement area within flood prone areas of an HQ100, HQ200 and HQ500 event compared to the total area of the municipality, normalized to the maximum share for the municipalities.

Table 6: Fact Sheet: Relative sensitivity of settlements towards river floods

Relative sensitivity of settlements towards river floods
Sensitivity of settlement and traffic areas towards river floods caused by extreme river discharges
Exposure: Increase in the occurrence of an HQ100, HQ200 and HQ500 event
Spatial entity of application: Landscape units
Detailed description: Settlements located in river catchments within flood prone areas are especially sensitive to an increase in the inundation events.
<p>Methodology:</p> <p>The share of settlement and traffic cells (classes 4103, 2114, 2113, 2111, 3103 and 9999, gridded to 100 m from the ATKIS25 dataset) within flood prone areas within the municipality is applied as an indicator of sensitivity. The values for all events are normalized by the maximum and minimum share over all events.</p>
Data sources: Land cover data: Authoritative Topographic-Cartographic Information System (ATKIS25, 2000, Federal Environment Agency, DLR-DFD 2009), Flood maps: Ministry for Climate Protection, Environment, Agriculture, Nature Conservation and Consumer Protection of NRW, 2003
<p>Key literature sources:</p> <p>Mitchell, J. K. (2003). "European river floods in a changing world." <i>Risk Analysis</i> 23(3): 567-574.</p> <p>Hooijer, A., F. Klijn, G. B. M. Pedroli & A. G. Van Os (2004). "Towards sustainable flood risk management in the Rhine and Meuse river basins: Synopsis of the findings of IRMA-SPONGE." <i>River Research and Applications</i> 20(3): 343-357.</p> <p>Grunthal, G., A. H. Thieken, J. Schwarz, K. S. Radtke, A. Smolka & B. Merz (2006). "Comparative risk assessments for the city of Cologne - Storms, floods, earthquakes." <i>Natural Hazards</i> 38(1-2): 21-44.</p>

Highest values of relative sensitivity of settlements towards river floods are obtained for the HQ500 event, covering a larger absolute area than the events of lower frequency. While large parts of inundation area according to a HQ100 event are situated in the lower section of the Rhine, this region is less populated and thus shows a less relative sensitivity towards floods. Most sensitive municipalities are found in the densely populated Rhine section, among which are Düsseldorf, Meerbusch, Monheim, Neuss, Dormagen, Niederkassel and Cologne.



Map 15: Indicator map of the relative sensitivity of settlements towards river floods regarding a HQ100, HQ200 and HQ500 event for the river Rhine

4. 2 Social sensitivity

Relative sensitivity of humans to river floods

Floods are considered as one of the most threatening hazards for humans (Jonkman 2005). Flood patterns differ between the regions: at the Rhine, inundation events evolve rather slowly allowing for the preparation of the local population and administration to the inundation event, whereas floods in the steeper and narrower river basins of the mountainous region occur quicker (MUNLV 2009c).

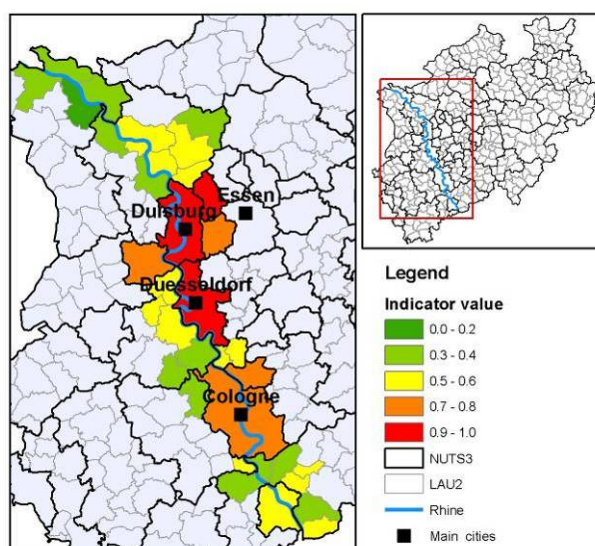
While wide knowledge exists on the change in frequency and magnitude of river discharges, few studies have investigated the use of indicators to describe the social sensitivity to flooding (Haque and Etkin 2007; Fekete 2009; Kubal et al. 2009). Within these studies, economic factors like income of households, unemployment rate, ownership status and structure of the building stock as well as social and demographic factors as the population density, education level, age distribution of the population, mobility of the population, the residence time in the respective area and insurance coverage have been identified as relevant to express the social sensitivity. For the city of Cologne, private precautionary damage prevention by residents' perceptions could be well explained by the factors of previous flood experience, risk of future floods, reliability of public flood protection, the efficacy and costs of self-protective behaviour, their

perceived ability to perform these actions, and non-protective responses (Grothmann and Reusswig 2006).

To describe the sensitivity of humans to flooding, we apply the concept of Fekete (2009), which has been validated for a flood event in Germany in 2002 in terms of people forced to leave their home, seek emergency shelter and their satisfaction with the status of damage regulation.

The index has already been prepared for the NUTS3 regions in Germany by Fekete (2009). To enhance spatial resolution we apply this indicator to the level of municipalities using public data from the Statistical Office NRW. The composite index is based here on the components fragility (share of elderly population), socio-economic conditions (living space per person, unemployment rate, share of graduates with only basic education) and characteristics of the surrounding region (share of 1-2 family homes and population density).

The indicator of sensitivity of humans towards river floods is shown for municipalities comprising settlements in flood prone areas in Map 16. Especially the highly populated Ruhr area of Oberhausen, Duisburg and Düsseldorf exhibit a high sensitivity.



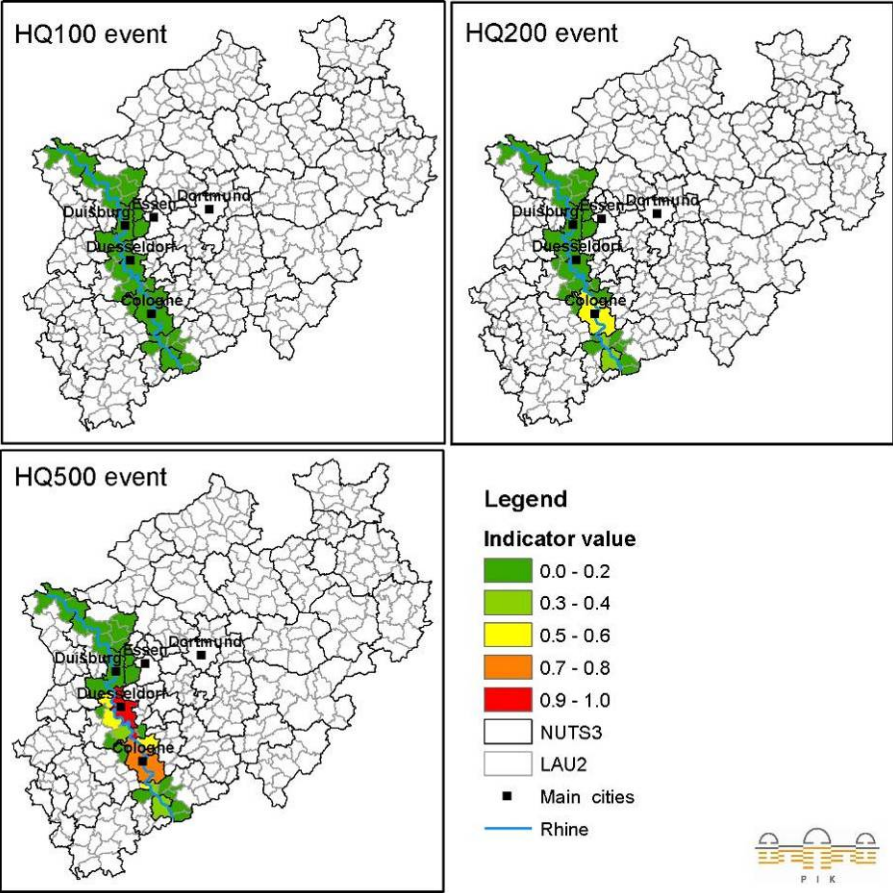
*Map 16: Indicator map of the relative sensitivity of humans towards river floods
Only sensitivity for municipalities comprising settlements in flood prone areas is shown, others
are marked in grey.*

This index is then combined with the share of settlements within flood prone areas according to a HQ100, HQ20 and HQ500 event (following the approach of the indicator “Relative sensitivity of settlements towards river floods”). Thus only municipalities with a large area of settlements (and thus also humans) within inundation areas are assigned high values of relative sensitivity.

Table 7: Fact Sheet: Relative sensitivity of humans to river floods

Relative sensitivity of humans towards river floods
<p>The sensitivity towards river floods comprises aspects of social fragility, socio-economic conditions and the surrounding region. It is combined with the share of settlements in flood prone areas along the Rhine.</p>
<p>Exposure: Increase in the occurrence of an HQ100, HQ200 and HQ500 event</p>
<p>Spatial entity of application: Municipalities</p>
<p>Detailed description: This index is a composite index of three indicators fragility, socio-economic conditions and characteristics of the surrounding region.</p> <p>The index has been developed and validated by Fekete et al. 2009 for a flood event in Germany in 2002 in terms of people forced to leave their home, seek emergency shelter and their satisfaction with the status of damage regulation.</p> <p>This index is then combined with the share of settlements within flood prone area according to a HQ100, HQ200 and HQ500 event of the river Rhine.</p>
<p>Methodology: In general the methodology of Fekete et al. 2009 is applied for municipalities in NRW. As indicators for fragility, the share of population 65 years or older in the year 2007 is used, the indicator socio-economic conditions is expressed by living space per person, unemployment rate, share of graduates with only basic education and the indicator region by the share of 1-2 family homes and population density. Missing data for municipalities were replaced by the mean value of the respective indicator. The resulting index values were normalized over all municipalities.</p> <p>The index value for each municipality is then multiplied by the share of settlements within flood prone areas according to a HQ100, HQ200 and HQ500 event (see</p> <p>Table 6). Values were then normalized to express the relative sensitivity of humans towards river floods of the Rhine.</p>
<p>Data sources: Socioeconomic data: Landesbetrieb „Information und Technik Nordrhein-Westfalen“ 2007, Land cover data: Authoritative Topographic-Cartographic Information System (ATKIS25, 2000, Federal Environment Agency, DLR-DFD 2009), Flood maps: Ministry for Climate Protection, Environment, Agriculture, Nature Conservation and Consumer Protection of NRW, 2003</p>
<p>Key literature sources:</p> <p><i>Fekete, A. (2009): Validation of a social vulnerability index in context to river-floods in Germany. Nat. Hazards Earth Syst. Sci. 9:393–403</i></p> <p><i>Fekete, A. (2009): Assessment of Social Vulnerability for River-Floods in Germany, PhD dissertation, Hohe Landwirtschaftliche Fakultät der Rheinischen Friedrichs-Wilhelm-Universität zu Bonn, UNITED NATIONS UNIVERSITY – Institute for Environment and Human Security (UNU-EHS), Bonn</i></p>

Highest values of relative sensitivity of settlements towards river floods are obtained for the HQ500 event, covering a larger absolute area than the events of lower frequency (Map 17). While large parts of an inundation area according to a HQ100 event are situated in the lower section of the Rhine, this region is less populated and thus shows a less relative sensitivity towards floods. Most sensitive municipalities are found in the densely populated Rhine section, among which are Düsseldorf, Mettmann and Cologne. While Düsseldorf shows the highest sensitivity for the HQ500 event, its sensitivity for the other events of higher frequency is considerably lower. This is probably due to high protection levels of dykes for HQ100 and HQ200 events in this municipality.



Map 17: Indicator map of the relative sensitivity of humans towards river floods regarding a HQ100, HQ200 and HQ500 event for the river Rhine
 Only sensitivity for municipalities comprising settlements in flood prone areas is shown, others are marked in grey

Relative sensitivity of humans to heat

The selection of these key factors and the analysis has been carried out during this project and is described in detail in Lissner et al. (2011).

Climate change has been recognized as one of the most important threats to human health in the future (Costello et al. 2009). Extremely high temperatures are clearly associated with significantly increased mortality and morbidity rates (Semenza et al. 1996; Kosatsky 2005; Vandentorren and Empeur-Bissonnet 2005). The heat wave over Europe in 2003 caused

around 40.000 excess deaths, with mortality rates highest in older age groups (Kosatsky 2005; Vandentorren and Empeur-Bissonnet 2005; Rebetz et al. 2006).

The additional heat load during such an event may overexert the cardiovascular system in particular of elderly people. Consequently, there is a clear correlation between a mortality in population aged 65 or older during and extremely high temperatures (Huynen et al. 2001; Laschewski and Jendritzky 2002; Kovats and Hajat 2008). The proportion of this age group can thus indicate a higher regional sensitivity towards the impacts of heat waves.

Beside higher age, other factors found to contribute to above normal mortality rates including the duration and intensity of a period with heat stress (Huynen et al. 2001; Kysely 2004) or the urban structure (Upmanis and Chen 1999; Eliasson and Upmanis 2000).

For example, urban areas can significantly alter regional climate patterns through the formation of an urban heat island (UHI) (Oke 1982; Kuttler 2008). Due to the specific heat absorption, retention and conduction capacities of urban materials urban temperature can be 5–11 °C higher than temperatures in surrounding areas (Oke 1973; Matzarakis 2001; Hupfer and Kuttler 2005; Stathopoulou and Cartalis 2007; Kuttler 2008). This temperature gradient is especially pronounced just after nightfall (Matzarakis 2001). The proportion of sealed surfaces is thus an important contributing factor favouring the formation of a UHI.

Additionally, the height of buildings can increase the UHI as the surface area for heat retention rises (Hupfer and Kuttler 2005; Matzarakis and Mayer 2008). Concurrently higher buildings limit the sky view factor, which critically determines surface cooling though long wave radiation (Arnfield 2003; Kuttler 2008). Population density can be used as proxy variable to indicate the degree of urbanity and corresponding higher residential houses. This has the additional value of only including those areas into the assessment where many people are at risk.

Thus, the sensitivity of a region to be negatively impacted by heat waves can be delineated by two key factors, namely the potential intensity of the UHI (potential UHI), represented by the sealed surface area and the population density, as well as the proportion of population ≥ 65 years of age. Where all of these key factors occur in conjunction a significantly augmented regional sensitivity has to be expected. Thus, the influencing variables were combined by their minimum values, applying a fuzzy logic algorithm with defined sensitivity thresholds.

Table 8: Fact Sheet: Relative sensitivity of humans to heat

Relative sensitivity of humans towards heat
The sensitivity towards heat waves comprises aspects of social fragility and the potential for an urban heat island.
Exposure: Increase in heat days
Spatial entity of application: Municipalities

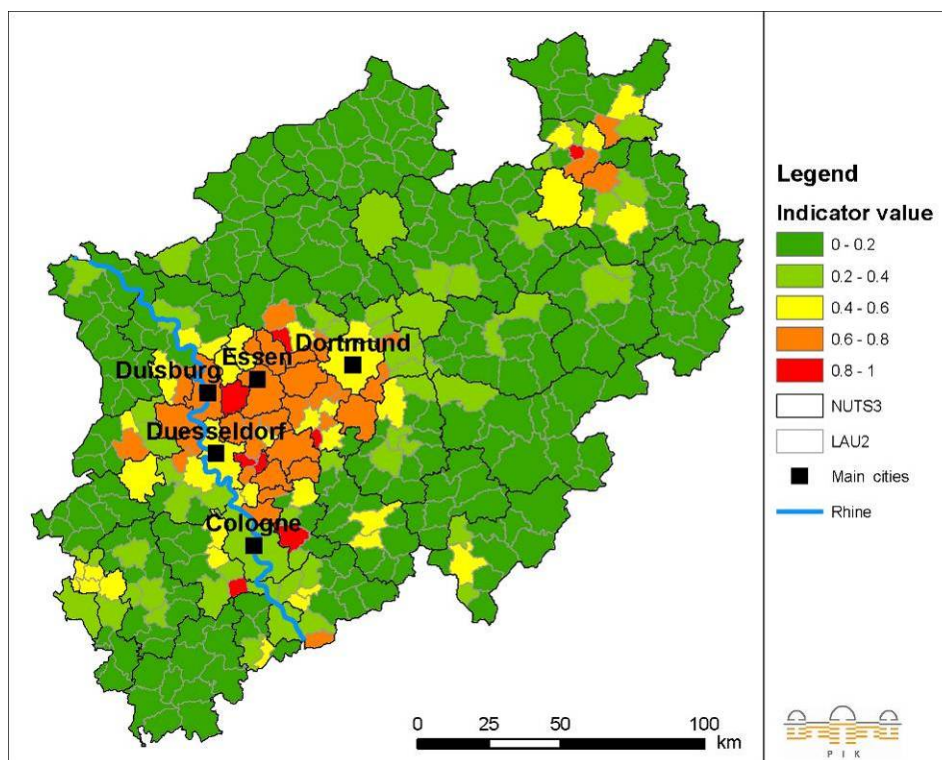
Detailed description: This indicator comprises the social fragility represented by the percentage of elderly population and the potential for an urban heat island, which can exacerbate heat waves locally. Thereby, the urban heat island is expressed by a combination of the population density and the amount of sealed surface.

Methodology: In general the methodology of Lissner et al. (2011) is applied for the sensitivity towards heat waves for municipalities in NRW. This indicator comprises the fragility of population, expressed by the share of elderly population 65 years or older in the year 2007. The potential for an urban heat island (UHI) is represented by the degree of urbanity, expressed by the minimum value of either the population density and the share of sealed surface. A fuzzy logic algorithm is applied to the identified influence variables to address uncertainty regarding the definition of clear threshold values determining the vulnerability. Thresholds for population density were defined at 250 persons/m² and 100 persons /m², for the area of sealed surface at 12.5% and 40% and for the share of elderly population at 19% and 29%. Sensitivity below these lower thresholds is assumed to be very low, above these thresholds to be very high; in between a linear increase in sensitivity is assumed. The fuzzified variables sealed surface and population density were aggregated by means of an AND (minimum) operator, as either a densely populated area or an area of a high sealed surface indicate an urban area which can cause an UHI effect. The potential for an UHI is also aggregated with the share of elderly population by an AND operator but with a compensation factor of 0.6 to account for the fact that both the share of elderly population as well as the UHI potential constituted a sensitivity.

Data sources: Information und Technik Nordrhein-Westfalen (IT.NRW) 2007

Key literature sources:

Lissner, T., Holsten, A., Walther, C., Kropp, J. (2011): A sectoral and standardized vulnerability assessment – the example of heat wave impacts on human health, under review



Map 18: Indicator map of the relative sensitivity of humans towards heat waves

A gradient of vulnerability is apparent from densely populated areas towards those less densely populated (Map 18). Thus the rural mountainous regions display low levels of vulnerability and most parts of the Rhine-Ruhr agglomeration is highly vulnerable. The largest cities, such as Cologne and Dortmund, though very densely populated, have medium to low vulnerability, which can be attributed to its lower share of elderly population.

A spatial aggregation of high to very high vulnerability emerges in the metropolitan Rhein-Ruhr region, as well as in the North-East around the city of Bielefeld. With exception of the city of Münster the northern lowlands exhibit very low levels of vulnerability as well as the mountainous areas in the southwest of the state.

4. 3 Environmental Sensitivity

Relative sensitivity of protected areas towards warmer and drier climate

Impacts of climate change have already been observed for a wide range of ecosystems (z.B. Root et al. 2003). Also Species and habitats are increasingly threatened by land use and climatic changes (Sala et al. 2000; Parmesan and Yohe 2003). Protected areas experience impacts of climate change for example in form of distribution changes of species (Parmesan and Yohe 2003; Thuiller et al. 2005; Pompe et al. 2008), changes in the phenology of species (Badeck et al. 2004b; Menzel et al. 2006; Kropp et al. 2009b; Rybski et al. 2011) or extinction of species (Thomas et al. 2004; Thuiller et al. 2005).

However, climate impacts species and ecosystems in different ways (Berry et al. 2003; Harrison et al. 2003), which leads to complex changes and new species compositions and ecosystems could evolve (Davis et al. 1998).

While various studies simulate impacts of climate change on protected areas (e.g. Araujo et al. 2004; Normand et al. 2007) only few studies focus on the sensitivity itself (Hoffmann 1995; Hossell et al. 2000; Schlumprecht et al. 2005; Holsten 2007; Petermann et al. 2007).

Protected areas aim at providing viable livelihoods especially by conserving biodiversity and are thus especially in the focus of nature conservation strategies (Naughton-Treves et al. 2005; Stoll-Kleemann and Job 2008). For the evaluation of the sensitivity of protected areas to climate change we focus on the Special Areas of Conservation (SAC) according to the EU-Habitats Directive (92/43/EEC) due to data availability. The sensitivity of habitats within areas to climate change has already been analyzed by Petermann et al. (2007), who assigned indicator values of sensitivity of Germany habitats regarding the categories current area borders, ground water dependency, trend in area decrease in the past, ability to regenerate, restriction to high altitudes and neobiota influence. We replaced the further proposed indicator describing qualitative risk by the similar but regionally available information on the conservation status of the respective habitat. The indicator of regeneration capacity represents rather an ecologic adaptive capacity. Therefore, we excluded this characteristic from the sensitivity indicator.

Moreover, we complemented this set of indicators by the sensitivity of the characteristic species of the habitats towards drier and warmer conditions and their stenocious reaction (limitation to a small range of climatic conditions) regarding temperature and moisture. We quantified these characteristics by assigning respective indicators of Ellenberg (1992) to each characteristic plant species.

Table 9: Fact Sheet: Relative sensitivity of Protected Areas towards warmer and drier climate

Relative sensitivity of protected areas towards drier and warmer climate
The sensitivity of Special Areas of Conservation (SAC) according to the EU- Habitats Directive is investigated by assessing the sensitivity of its habitat types within.
Exposure: Increase in air temperature and evapotranspiration as well as decrease in precipitation (in general exposure towards a warmer and drier climate)
Spatial entity of application: Protected areas as “Special Areas of Conservation” (SAC) according to the EU-Habitats Directive (92/43/EEC).
<p>Detailed description:</p> <p>The indicator describes the sensitivity of habitat types within protected area towards the expected climatic changes. It comprises information on sensitivity regarding its current biogeographic conditions, based on sensitivity values of Petermann et al. (2007) and is extended by additional indicators based on the methodology of Holsten (2007).</p>
<p>Methodology: Ten indicators were applied for each terrestrial habitat type within each SAC:</p> <p>Indicator values (1 = less sensitive, 3 = highly sensitive) describing the sensitivity regarding current area borders, ground water dependency, trend in area decrease in the past, restriction to high altitudes and neobiota influence were applied based upon values by Petermann et al. 2007 for habitat types in Germany. The further proposed indicator “qualitative risk” was substituted by the locally available indicator “conservation state”, to indicate already existing pressures imposed on the habitats.</p> <p>This set of indicator was further extended by information regarding the share of cold and wet-tolerant characteristics plants of the habitats, which are expected to be especially sensitive to the expected warmer and drier conditions (Petermann et al. 2007, Schlumprecht et al. 2005). These plants were defined based on their temperature-tolerance (values 2-4) and moisture-tolerance values (values 7-9) based on Ellenberg (1992) and FloraWeb. Indicator values from 1 were assigned for habitat types with a share of less than 33 % of cold or wet tolerant plants, a value of 2 indicates and share between 33 % and 66 % and a value of 3 a share of over 66%.</p> <p>From the same dataset of characteristic plants, the share of stenocious species regarding temperature and moisture conditions (defined here as not indifferent to these conditions) was calculated and</p>

classified analogously to the wet and moisture tolerant plants.

The average of the 10-subindicators was calculated for each habitat type. As only data on the share of area of the habitats within each SAC exist but not on their exact location, the sensitivity of the SAC is first calculated based on the area-weighted sensitivity of its habitats. The sensitivity of the municipality is then expressed by the area-weighted sensitivity of the SACs within, multiplied by their share of area compared to the total municipal area to express the relative sensitivity.

Based on the available data sensitivity values of 454 out 518 SACs were calculated.

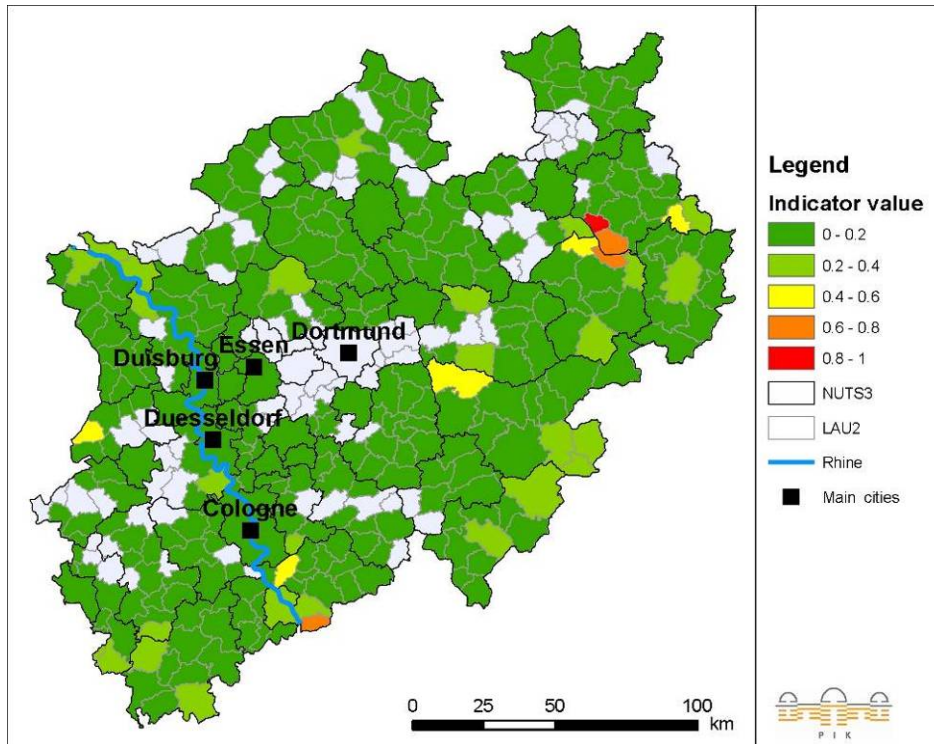
Data sources: Data on SACs: Landesamt für Natur, Umwelt und Verbraucherschutz NRW, 2009, data on typical plant composition of the habitats types in NRW: <http://www.naturschutzinformationen-nrw.de/methoden/de/anleitungen/ffh/lebensraumklassen>, data on temperature tolerance and moisture tolerance of plants: Ellenberg, H. (1992) and <http://www.floraweb.de/>

Key literature sources:

Holsten, A. (2007): "Ökologische Vulnerabilität von Schutzgebieten gegenüber Klimawandel – exemplarisch untersucht für Brandenburg." Institut für Geowissenschaften. Tübingen, Universität Tübingen: 135 S.

Petermann, J., S. Balzer, G. Ellwanger, E. Schröder und A. Ssymank (2007): "Klimawandel - Herausforderung für das europaweite Schutzgebietssystem Natura 2000." In: S. Balzer, M. Dieterich und B. Beinlich: "Natura 2000 und Klimaänderungen." Bonn - Bad Godesberg, Bundesamt für Naturschutz, Naturschutz und Biologische Vielfalt. Vol. 46.

Schlumprecht, H., D. Flemming, P. Schneider, B. Tunger & R. Löser (2005). Folgewirkung der Klimaänderungen für den Naturschutz - Ausgewählte Ökosysteme und Arten, Sächsisches Landesamt für Umwelt und Geologie.



Map 19: Indicator map of relative sensitivity of Protected Areas towards warmer and drier climate.

Only sensitivity for municipalities comprising protected areas with data (SAC) is shown, others are marked in grey.

The relative sensitivity of protected areas shows low values for most of the municipalities (Map 19). This is especially the case in the urban areas, where protected areas represent only a small fraction of the overall municipal area. High relative sensitivities are found in the riverine areas in the southern valley of the Rhine, however, with only a small proportion of protected areas compared to the total municipal area. Municipalities in the Egge Mountains and the municipality of Bad- Honnef with large forest area show a high sensitivity.

Relative sensitivity of lakes towards decrease in water volume

Lakes are valuable ecosystems providing numerous services such as ground water renewal, drinking and cooling water supply, transport and recreation or resting places for migrating species (Arthurton et al. 2007; Bates et al. 2008). The water-level regime and lake level fluctuations are of key importance to structure and functioning of limnic ecosystems, i.e. intra- and inter-annual fluctuations are decisive for extent (space, time) and community characteristics (species composition, species interactions) of the littoral and aquatic-terrestrial transition zone (Riis and Hawes 2002; Coops et al. 2003). Whilst an undisturbed ecosystem might benefit from or cope with water level fluctuations, whose amplitude is highly influenced by regional climate conditions and anthropogenic regulations, extreme fluctuations might exceed species adaptive capacity (Coops et al. 2003; Leira and Cantonati 2008). In addition, fluctuations in water level such as decrease in lake level influence lake physics, chemistry and biosphere, i.e. change in lake morphometry, temperature regime, sedimentation and biogeochemistry (Wetzel 2001;

Furey et al. 2004; Leira and Cantonati 2008), including potential re-suspension of contaminants from sediments if lowering in lake level exposes sediments to oxidation (Skoulikidis et al. 2008). Furthermore, especially small, shallow, groundwater-feed lakes are at risk of siltation (Kalff 2002) which accelerates as water level decreases (Schwoerbel and Brendelberger 2005).

Based on data of two commonly available lake variables an indicator-based approximated estimation of the sensitivity of lakes towards a decrease in lake volume in summer is carried out. Sensitivity is expressed by the ratio of lake surface area to lake volume as lakes of a given volume with a larger surface area available for evaporation potentially exhibit higher water losses by evapotranspiration than lakes with a smaller surface area. Besides, for temperate lakes, lake volume, surface area and mean depth are highly correlated with annual heat budget (Gorham 1964) which is an important characteristic of these ecosystems (Wetzel 2001).

As the decrease in water volume is driven by an imbalance in gains and losses of water (Schwoerbel and Brendelberger 2005), in particular in summer, this imbalance was chosen to be represented by decline in summer precipitation and increase in mean annual evaporation, which mostly changes in the summer months due to a strong warming.

Anthropogenic interventions (i.e. water withdrawal, land use changes or agricultural activities) can also affect the water balance and water quality of lakes (Bates et al. 2008). However, these influences are difficult to quantify and are not considered by this analysis. Thus, the present assessment excluded highly anthropogenic influenced lakes such as reservoirs and focuses on natural lakes and lakes evolved through excavation, which are common especially in the Rhine valley due to gravel mining (LANUV NRW 2007). Thus, a total of 8 natural and 91 excavation lakes are considered with available data on the mean depth and surface area.

Table 10: Fact Sheet: Relative sensitivity of lakes towards a decrease in water volume

Relative sensitivity of lakes towards decrease in water volume
Decrease in lake volume driven by decline in water gains and increase in water losses
Exposure: Decline in summer precipitation sum, increase in mean annual evaporation
Spatial entity of application: Lakes
Detailed description: A decrease in lake volume affects the lake physics, chemistry and in consequence the lake biosphere. These changes are driven by a decline in water gains and increase in water losses, expressed by a decline in summer precipitation sum and increase in mean annual evapotranspiration.
Methodology: The ratio of lake surface area [m ²] to lake volume [m ³] was calculated for each of the 99 lakes and normalised for all lakes within NRW. Thereby a high value indicates a large surface area in comparison to the lake volume present which would allow for a relatively high evaporation and thus support a decrease in summer lake volume during warm and dry summers. Municipalities, which do not

comprise lakes or with a lack of data were assigned the lowest sensitivity.

Data sources: Data on lake characteristics was provided by the Agency for Nature, Environment and Consumer Protection, NRW (LANUV).

Key literature sources:

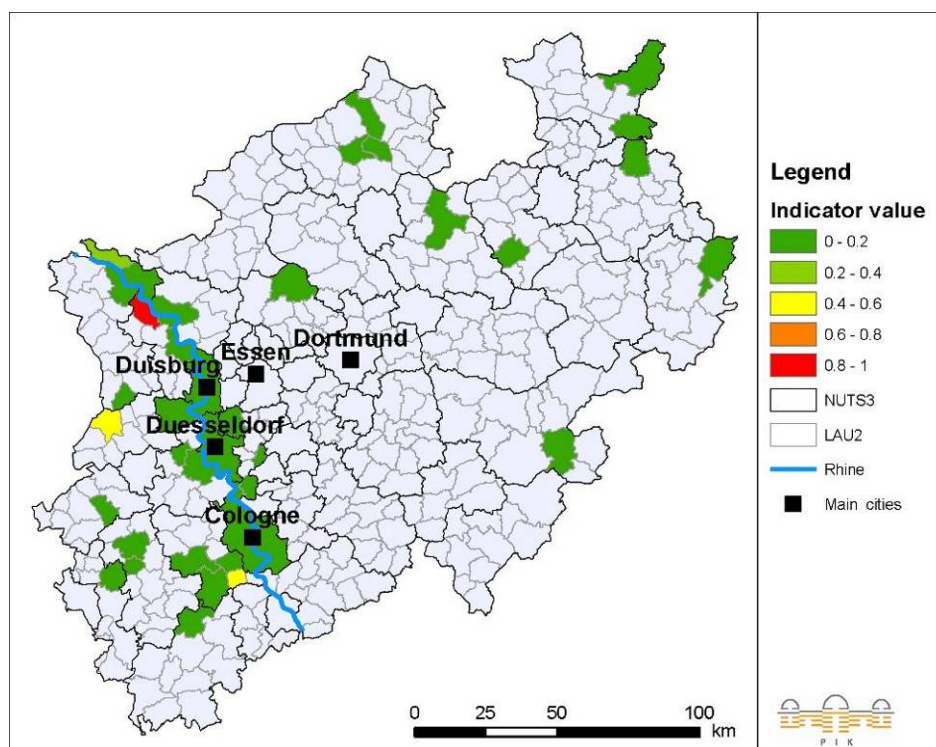
COOPS, H., M. BEKLIOGLU und T. L. CRISMAN (2003): "The role of water-level fluctuations in shallow lake ecosystems- workshop conclusions." *Hydrobiologica* 506-509: 23-27.

FUREY, P. C., R. N. NORDIN und A. MAZUMDER (2004): "Water level drawdown affects physical and biogeochemical properties of littoral sediments of a reservoir and a natural lake." *Lake and Reservoir Management* 20(4): 280-295.

KALFF, J. (2002): "Limnology: Inland water ecosystems." Prentice-Hall, New Jersey. New Jersey. 592 p.

LEIRA, M. und M. CANTONATI (2008): "Effects of water-level fluctuations on lakes: an annotated bibliography." *Hydrobiologia* 613: 171-184.

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Map 20: Indicator map of relative sensitivity of lakes towards a decrease in water volume

The resulting distribution of the sensitivity of lakes towards a decrease in water volume is depicted in Map 20. Most of the municipalities show a low sensitivity, a very high sensitivity is apparent for the municipality Xanthen, which comprises a former arm of the river Rhine characterized by a shallow depth and a large surface area. A medium sensitivity can be found

for the municipalities Brühl and Nettetal. The five considered lakes within the municipality Nettetal are characterized by a low depth as they have originated from fens. The municipality Brühl comprises a large number of rather shallow excavation lakes. The fourth highest sensitivity is apparent for the municipality Emmerich with a former arm of the river Rhine characterized by a shallow depth and a large surface area but a lower share of lake area compared to the above mentioned municipalities.

Relative sensitivity of soils to potential soil water erosion

Soil water erosion is defined as the relocation of soil parts along the soil surface by water. This process can lead to an impairment of quality of local water resources and to soil degradation. The latter entails a reduction in soil mass and water retention capacity and thus reduces the fertility of the soil for agricultural use. Key influencing factors are intense precipitation, slope, soil characteristics and anthropogenic soil cultivation (Scheffer and Schachtschabel 2002). Here, soils are regarded as part of the environmental sphere, thus soil erosion is considered under the environmental sensitivity dimension, although their degradation influences agricultural production in the medium and long run.

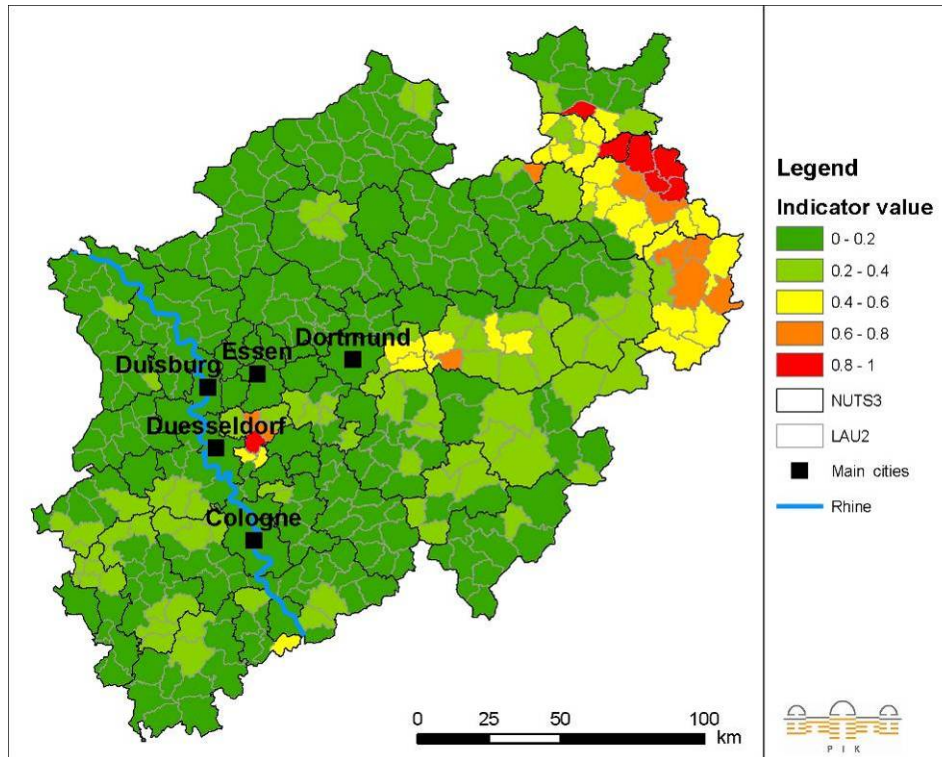
Erosion is especially relevant on agricultural soil due to temporarily uncovered soil surfaces and cultivation. In NRW around 32 % of the area is agriculturally used, thus soil erosion can potentially have a large impact in this state. Climate characteristics, topography and cultivation processes already cause considerable damages through water erosion in NRW (Kehl et al. 2005). Climate change could further influence this impacts through a change in the seasonal precipitation patterns, which has been shown for NRW (Sauerborn et al. 1999) as well as in other regions such as Bavaria (Rippel and Stumpf 2008), Saxony (Michael et al. 2005) or Austria (Scholz et al. 2008).

Soil water erosion is especially dependent on heavy rainfall events (Müller 2003; Boardman 2006) and can be estimated by the Universal Soil Loss Equation (Schwertmann et al. 1990; Renard et al. 1997). It comprises variables of the exposure to rainfall, soil erodibility, slope, slope length, cultivation and soil conservation. The rainfall will be addressed within the exposure part of our analysis. Slope length cannot be sufficiently calculated based on elevation data with a resolution of 50 m, as available in our analysis. Also, anthropogenic factors like cultivation and soil conservation measures cannot be accounted for due to lack of data.

Thus, we apply this formula in a simplified way by considering the sensitivity factors of soil erodibility and slope. We therefore describe the potential and not the actual soil erosion sensitivity, which can be further influenced by agricultural activities.

Table 11: Fact Sheet: Relative sensitivity of soils to soil water erosion

Relative sensitivity of soils to soil water erosion
Soils are exposed to heavy rainfall events causing water erosion. The sensitivity of the soils can be expressed by their texture.
Exposure: Increase in days with heavy rainfall
Spatial entity of application: agricultural soils based on a 50m grid
<p>Detailed description:</p> <p>Heavy precipitation events can lead to soil water erosion especially on agricultural soils. Sensitivity is expressed by a combination of soil erodibility and slope. Thus the potential sensitivity is expressed, disregarding the influence of agricultural and cultivation measures.</p>
<p>Methodology:</p> <p>Soil water sensitivity is described by the factors soil erodibility (K-factor) and slope (S-factor) of the Universal Soil Loss Equation (Schwertmann et al. 1990; Renard et al. 1997). The soil erodibility is derived from the regional soil map (BK50, gridded to 50 m resolution) and slope based on the digital elevation with a resolution of 50 m. The variables are converted to a scale of 0-1 and multiplied according to the equation. Only agricultural soils are considered, since soil erosion is most relevant for these temporarily uncovered and anthropogenically influenced sites. Thus, the product of the K- and F-factor is averaged and normalized over all agricultural soils of NRW.</p>
<p>Data sources:</p> <p>Topographic data: Digital elevation model 50 m (LANUV NRW, 2008), soil data: BK50, Geological Service NRW</p>
<p>Key literature sources:</p> <p>SCHWERTMANN, U., W. VOGL und M. KAINZ (1990): "Bodenerosion durch Wasser. Vorhersage des Abtrags und Bewertung von Gegenmaßnahmen." 2. Ausg. Eugen Ulmer GmbH & Co. Stuttgart.</p> <p>RENARD, K. G., G. R. FOSTER und G. A. WEESIES (1997): "Predicting soil erosion by water. A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE)." Agric. Handbook. Vol. 703. U.S. Dept. of Agriculture. 404p.</p>



Map 21: Indicator map of relative sensitivity of agricultural areas to potential soil water erosion

The distribution of the indicator regarding the sensitivity of agricultural soil to soil erosion shows high values in the mountainous regions, which are however less relevant for agriculture (Map 21). Dominating cambisols, haplic and stagnic luvisols in some areas of the Münsterland are characterized by a higher sensitivity, however, large parts of these are characterized by flat slopes and less erodible podzolic soils which lead to an overall low sensitivity. Loess areas along the foothills of the low mountain ranges indicate a medium to high sensitivity.

4. 4 Economic Sensitivity

Economic sensitivity will be quantified for sectors relevant within NRW and especially influenced by climate. NRW can be regarded as an energy state, producing one third of the overall electricity of Germany (Energie Agentur NRW 2007). The energy sector is therefore highly important for NRW, and consequently, climate impacts (e.g. decreasing water supply for cooling demand of power plants) play an important role. However, assessments regarding concrete impacts need data on water withdrawal, the consideration of the EU water directive and the employment of sophisticated approaches to be calculated for each power plant (e.g. Förster and Lilliestam 2008). Data on this covering the whole state of NRW were not available for this project. Thus, the dimension of economic sensitivity will focus on short term and direct influences of climate on the sectors forestry (in terms of timber production), agriculture and winter tourism.

Relative sensitivity of forests to windthrow

The sensitivity of forest to storms has been analyzed within this project and is described in Klaus et al. (2011) in more detail.

In Germany, 53% of economical losses related to natural disasters in the last decades can be attributed to storms (Munich Re 1999), which generally occur with a return period of around ten years (Hofherr 2007). They can be considered as the most important short-term acting natural stressors for forests, to significantly influence their structure (Fischer 2003).

Causing the highest insured losses in Central Europe since at least 1990 (Munich Re 2007) and blowing down 62 Mil. trees (Fink et al. 2009) on 18.01.2007, Kyrill ranks among the most devastating storms of the last decades. One third of the European and half of the German forest loss was recorded in NRW (MUNLV 2010a).

Based on spatial data of damaged areas of this storm event (Spelsberg 2008), an integrative measure of sensitivity of forest areas to storm was developed, by statistically comparing the occurrence of storm damage with local characteristics of the forest areas.

Forest characteristics (deciduous, mixed, evergreen, natural forest, distance to forest edge), soil characteristics (suitability for decentralized seepage, porosity, cation exchange capacity, depth to groundwater table, soil moisture level, soil erodibility, soil quality, grain size⁶) and topography (slope, altitude, curvature, aspect, hillshade with regard to westerly directions) were considered as sensitivity factors.

The ordinal variables were transferred to metric ones and normalized together with the metric variables. Ordinal variables were considered as binary variables (forest types and aspect). All variables were aggregated to a cell size of 50 m, based on the available resolution of topographic data.

The probability of the occurrence of each of these variables in a damaged area by "Kyrill" was then calculated based on a logistic regression⁷. The model was then fitted to the data using backward variable selection (Pampel 2000). Starting with a complete model, predictors were removed one by one in case of meeting Akaike's information criterion (AIC) (Akaike 1998), which was the case for two variables, deciduous forest and northern slope, since they explain an insignificant variance. According to the Wald-test, regression coefficients of the remaining 19 variables were significant on a level <0,05 except the depth to the groundwater table.

The remaining parameters explain only $D^2 = 11\%$ (goodness of fit indicator as the ratio of residual variance to null variance, see Peng et al. (2002)) of the deviance of the model. Similar results were found by Schütz et al. (2006) for the prediction of Lothar damages in Swiss spruce stands and Jalkanen and Mattila (2000) with respect to stands in northern Finland.

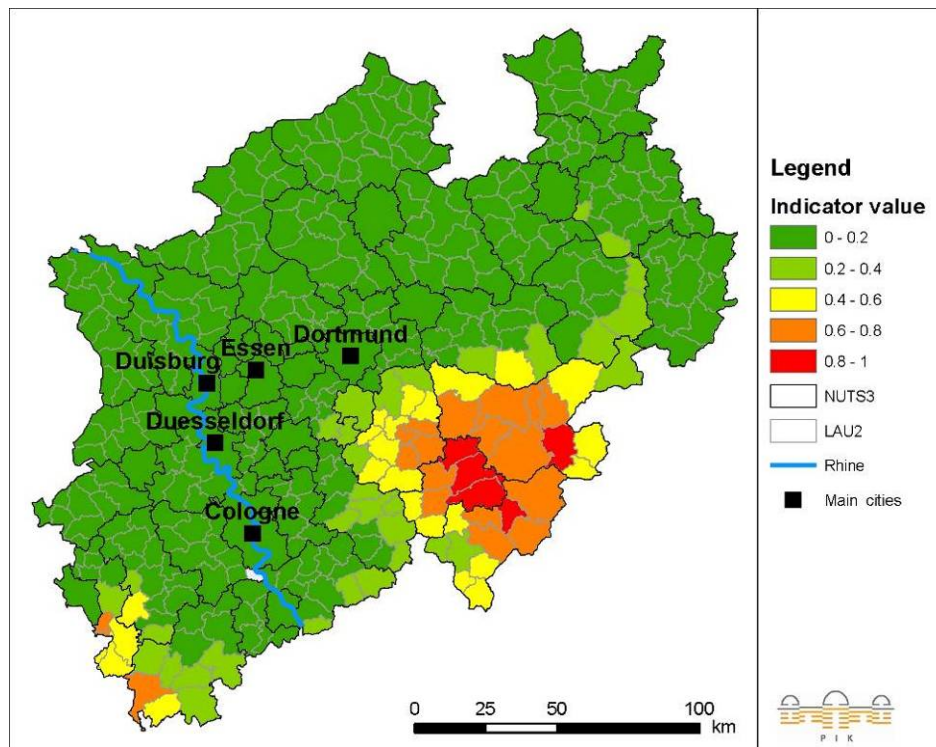
⁶ Additionally capillary action, field capacity, available water capacity and water permeability were analyzed but not included in the model, since they show a high correlation with the variables soil moisture level, cation exchange capacity, depth to ground water table and grain size.

⁷ For computational reasons a randomly selected sample of 460.000 cells was analyzed, representing 20 % of the total cells.

In order to evaluate the power of the model to reproduce the area damaged by Kyrill, the continuous probability outcome of the regression analysis p , ranging from 0 to 1 was transformed to a binary number, by defining a threshold t from which on a certain cell is coded damaged and otherwise undamaged. This yields an AUC value (Sing 2009) of 0.763, which can be considered as a fair agreement between model output and the recorded wind damage caused by Kyrill when using an optimal threshold value. It was empirically found to be maximized for $t = 0.07$, with an overall model accuracy of 0.71. Thus, apart from the poor goodness of the model, overall classification accuracy of the model for this threshold is satisfactory. The resulting model outcome represents the windthrow probability based on an event similar to the storm event Kyrill.

Table 12: Fact Sheet: Relative sensitivity of forests to windthrow

Relative sensitivity of forest to windthrow
The sensitivity of forest to windthrow depends on the characteristics of the forest stand, soil conditions and topography.
Exposure: Increase in storm days
Spatial entity of application: Grid cells of 50m, based on DEM
Detailed description: This index is a composite of forest characteristics (deciduous, mixed, evergreen, natural forest, distance to forest edge), soil characteristics (suitability for decentralized seepage, porosity, cation exchange capacity, depth to groundwater table, soil moisture level, soil erodibility, soil quality, grain size) and topography (slope, altitude, curvature, aspect, hillshade with regard to westerly directions). These variables have been aggregated by means of a logistic regression model validated for the storm event Kyrill (Klaus et al. 2011), which caused severe forest damage in the year 2007 in NRW (MUNLV 2010a).
Methodology: A logistic regression model has been applied to relevant variables of forest, soil and topography characteristic in order to capture the sensitivity to windthrow based on observed storm damage of the Storm event Kyrill in NRW 2007. Overall model accuracy is satisfactory with a value of 0.71. The resulting model outcome represents the windthrow probability based on an event similar to the storm Kyrill. High resolutions data on the 50m grid was then averaged over the municipalities.
Data sources: Topographic data: Digital elevation model 50 m (LANUV NRW, 2008), land use data: Authoritative Topographic-Cartographic Information System (ATKIS25, 2000), Federal Environment Agency, DLR-DFD 2009, natural forest sites and sites damaged by Kyrill: State Office for Forestry NRW, soil data: BK50, Geological Service NRW
Key literature sources: Klaus, M.,A. Holsten,P. Hostert & J. P. Kropp (2011). "An integrated methodology to assess windthrow impacts on forest stands under climate change." <i>Forest Ecology and Management</i> , 261/11, 1799-1810



Map 22: Indicator map of the relative sensitivity of forests to windthrow
 Only sensitivity for municipalities comprising forest area is shown, others are marked in grey.

Values based on the 50m grid range from 0 – 50 % storm damage probability for a severe storm event similar to the event “Kyrill”. Storm damages are highly probable in Sauerland and Eifel with values of over 5%. According to the mean value of all cells within each municipality, the municipality Neuenrade in northwestern Sauerland ($p = 0.095$) is most sensitive. A large number of cells in Neuenrade is predicted to have a storm damage probability of over 10 %. The lowest mean sensitivity ($p = 0.003$) is found in Gladbeck in the Lower Rhine region with probabilities of not more than 1.7%. When combining this sensitivity with the share of forest area on the total municipal area, the municipality Kirchhundem shows the highest values (Map 22), followed by nearby municipalities in the Sauerland mountains. Low values are found over most of NRW especially in the lowlands. This is due to a low share of forests and a mostly low sensitivity, which can be accounted for by fewer needle leaved forest area with a higher sensitivity to windthrow.

Relative sensitivity of forests to forest fires

Compared to other German states, forest fire risk is relatively low in NRW. However, fire events have occurred in small numbers each year in the past (Figure 8 a). During extremely hot summers, fire damage increased considerably, which can be seen for the years 1996, 1998 and 2003. Recorded fires and the area burnt are highest in spring and late summer (Figure 8 b). Whereas the former can be explained by a minimum of precipitation throughout the year, the high number of fires in later summer could be attributed to high temperatures and increased human activity in forests. The overall monthly pattern of the numbers of fires in NRW can be reproduced well by a climatic forest fire risk, considering temperature, humidity, wind speed,

precipitation and snow cover (Kropp et al. 2009b). Forest fires in the German state of Brandenburg also show a similar annual pattern to several applied climate forest fire indices (Badeck et al. 2004a).

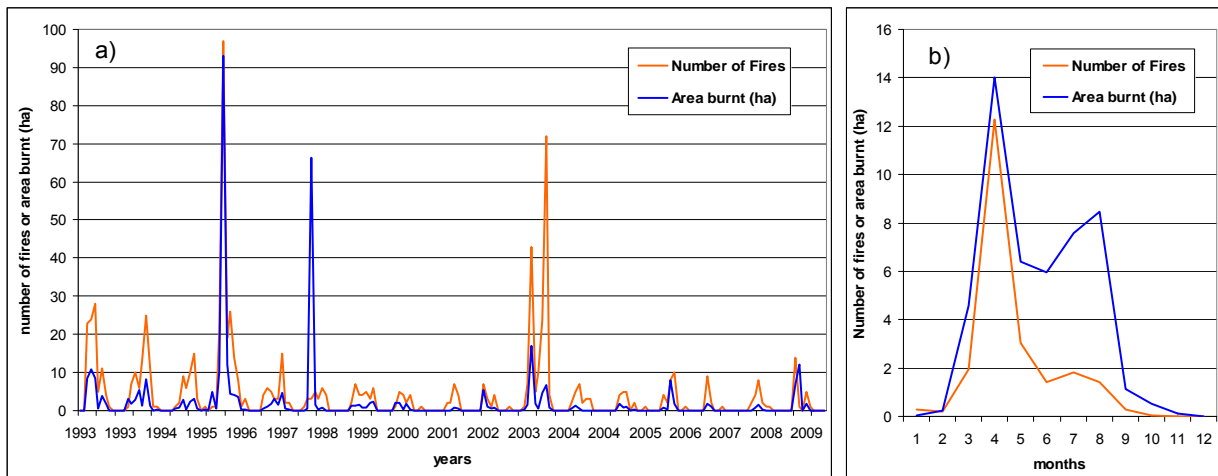


Figure 8: Observed forest fire statistics in NRW with regard to the number of fires and the area burnt in state and private forests from 1993-2009 a) as a trend of monthly data and b) averaged over the months (Federal Agency for Agriculture and Food (BLE))

Under climate change, climatic conditions are expected to strongly increase the potential fire risk in NRW with a prolonging of the fire season until later in the year (Kropp et al. 2009b).

Sensitivity to forest fires is strongly influenced by forest types: while in NRW the average annual area burnt amounts to 9.3 ha between 1993-2009 for broad leaved forests, these values are much higher for needle leaved forests with 13.5 ha (according to data of the Federal Agency for Agriculture and Food (BLE)). Considering the distribution of forest types given in the forestry report for NRW (LFV NRW 2007), burnt area is 1.55 higher for needle leaved forest than for broad leaved forests. Unfortunately, no spatially explicit data below state level exists for NRW. Thus spatial autocorrelation of vegetation and soil characteristics cannot be ruled out. However, simulations of forest fire for the state of Brandenburg, Germany, showed less fire occurrence under broad leaved than needle leaved forests given the same soil conditions (Thonicke and Cramer 2006).

A key influencing factor of forest fire is the fuel moisture, which can be divided into dead fuel biomass influenced mainly by atmospheric variables, and living fuel biomass, which also depends on the soil moisture conditions of the soil (Nelson 2001). The influence of soil characteristics on forest fire dynamics is for example apparent from the boreal forests, where wet surface soil moisture conditions limit the extent of burned area (Bartsch et al. 2009). In this region, soil moisture anomalies appear to act as an on/off switch instead of a linear factor influencing the fire frequency regime, however provide no clear indication about this threshold. They also found that the size of area burnt is not directly linked to soil moisture, but more influenced by fuel availability as a sensitivity factor. Yet, larger fires occurred only under moisture conditions slightly above the average or lower. Unfortunately no spatially explicit data on fuel biomass for forest in NRW is available; however soil moisture characteristics can be applied from regional soil maps.

Besides vegetational and pedologic factors also humans influence forest fires. This has been most studied in Mediterranean countries, where population density and forest accessibility are generally associated with higher fire risk (Chuvieco et al. 2010; Costa et al. 2010). Forest fires caused by humans in Switzerland were also found to strongly depend on human accessibility, which can be described by the distance of forest to settlements (Reineking et al. 2010). Since in NRW over 98 % of the forest fires from 1993-2009 are caused by humans (negligence and arson, only considering fires with known causes, according to data of the Federal Agency for Agriculture and Food (BLE)), this indicator seems appropriate.

Studies have shown that no single factor can explain forest fire occurrence, but a multitude of factors concerning climatic, environmental and human determinants play a role (Cardille et al. 2001; Syphard et al. 2008; Costa et al. 2010; Reineking et al. 2010). Thus, a combination of the factors forest type (mixed or deciduous), soil moisture conditions (expressed by the potential available field capacity) and accessibility (expressed by the distance to the nearest settlement) is applied for NRW.

Table 13: Fact Sheet: Relative sensitivity of forests to forest fires

Relative sensitivity of forest to forest fires
The sensitivity of forest to forest fires expressed by forest type, soil moisture conditions and forest accessibility.
Exposure: Decrease in summer precipitation, increase in heat days
Spatial entity of application: Forest stands
Detailed description: The sensitivity of forest to forest fires is expressed by a multitude of factors describing the forest type (mixed or deciduous), soil moisture conditions (expressed by the potential available field capacity) and accessibility (expressed by the distance to the nearest settlement).
<p>Methodology: The sensitivity concerning the forest type is calculated by considering the observed forest fires in NRW from 1993-2009, where burnt area is 1.55 higher for needle leaved forest than for broad leaved. This ratio is taken into account for the sensitivity, by assigning needle leaved forest the highest value, and broadleaved forests, the value of 0.64 accordingly (class 4107) of the ATKIS dataset). Values are then averaged over the forest area of the municipalities. Sensitivity concerning the soil moisture characteristics is considered by the normalized mean value of potential available field capacity of the soils under forests (class 4107 of the ATKIS dataset) within a municipality.</p> <p>Sensitivity with regard to the human influence is taken into account by the distance of the forest (classes 311,312,313 of the CORINE dataset) to the nearest settlement (classes 111,112 of the CORINE dataset), averaged over the municipalities. This dataset was preferred over the regional ATKIS dataset to account for distances to objects outside of the state.</p> <p>All three indicators are averaged with equal weight. This value is then multiplied by the share of forest area within the municipality to obtain the relative sensitivity.</p>
Data sources: land use data: Authoritative Topographic-Cartographic Information System (ATKIS25, 2000), Federal Environment Agency, DLR-DFD 2009, CORINE Land Cover (CLC2006); Federal

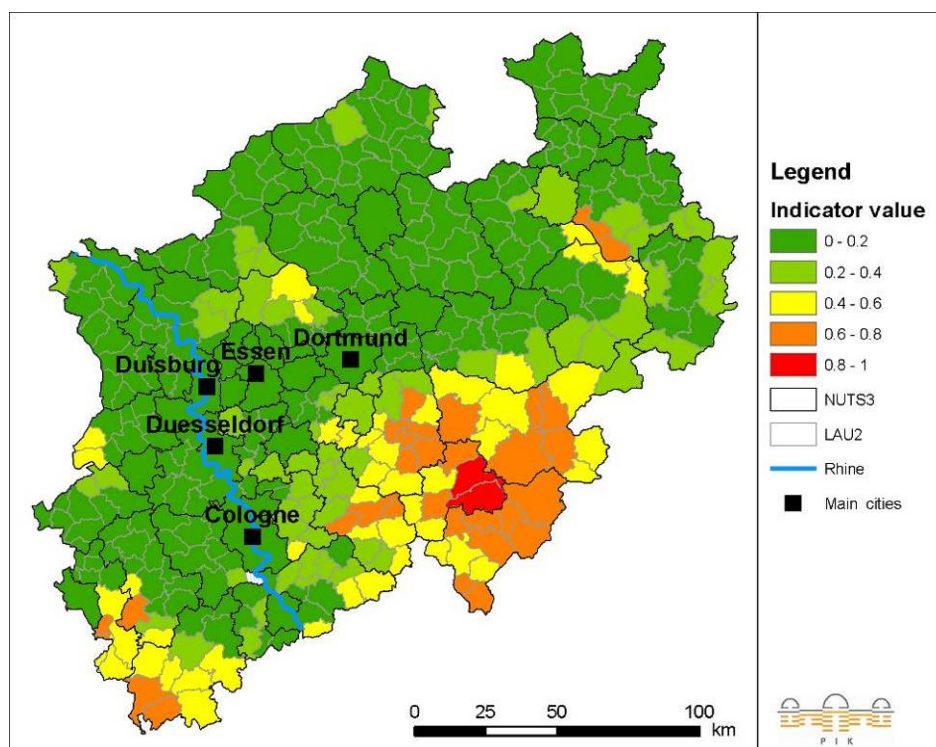
Environment Agency, DLR-DFD 2009.

soil data: BK50, Geological Service NRW

Key literature sources:

Reineking, B., P. Weibel, M. Conedera & H. Bugmann (2010). "Environmental determinants of lightning- v. human-induced forest fire ignitions differ in a temperate mountain region of Switzerland." *International Journal of Wildland Fire* 19(5): 541-557.

Bartsch, A., H. Balzter & C. George (2009). "The influence of regional surface soil moisture anomalies on forest fires in Siberia observed from satellites." *Environmental Research Letters* 4(4): 1-5.



*Map 23: Indicator map of the relative sensitivity of forests to forest fires
Only sensitivity for municipalities comprising forest area is shown, others are marked in grey*

The distribution of the relative sensitivity of forests to forest fires shows low values in the densely populated valleys, which is mainly due to the low share of forests in these municipalities (Map 23). The mountainous regions however comprise larger areas of needle leaved forest and soil of medium to low potential available field capacity and are thus assigned high sensitivity. The most sensitive municipalities are Kirchhundem and Lennestadt, which are also most sensitive regarding windthrow. Overall, the distribution is similar to the sensitivity with regard to windthrow, but additionally two regions are characterized with high values: the Hohe Mark and Egge mountains with large areas of needle leaved forests, a close distance to settlements and relatively dry soils.

Relative sensitivity of winter tourism towards to a shortening of the winter season

The study region NRW comprises one of the largest winter sport region north of the Alps; the Winter sport region Sauerland/Siegerland-Wittgenstein (in the following called Sauerland) with over 150 ski lifts and around 280 ha ski runs (IFT Roth et al. 2001; 2008) and a total of over 450000 arrivals in the season 2009/2010 (Tourismus NRW e.V. 2010).

To ensure a profitable season, over 250 snow machines provide snow conditions for alpine tourism (Wintersport-Arena Sauerland 2009). The winter sport resorts in Sauerland have a high regional economic relevance with a gross annual turnover (including secondary economic effects) of around 100 mio € and around 8000 workers associated to this sectors in the winter months (IFT 2008). Smaller resorts are located in the Eifel mountains.

Skiing resorts are highly dependent on climatic conditions and thus especially sensitive to the expected climatic changes, as has been shown for the Alps (Abegg et al. 2007; Uhlmann et al. 2009) and low mountain ranges in Germany (Sauter et al. 2009; Steiger 2010).

In recent years, the annual number of natural snow days has already decreased considerably in Sauerland, however could be compensated to some extend by artificial snow production. In the winter 2007/08 only 22 natural snow days were recorded. These snow conditions could be complemented by artificial snow to achieve a winter season of 70-100 days (Wintersport-Arena Sauerland 2008). However, also the conditions for artificial snow making are expected to be impaired under climate change to the rising temperatures (Steiger and Mayer 2008; Olefs et al. 2010). This is also the case for the Sauerland region, where the snow production potential, as a key factor for the operation, is expected to decrease considerably in the next decades, based on the regional climate models CCLM and STAR (see Figure 9). This decrease is apparent for both higher and lower elevated stations.

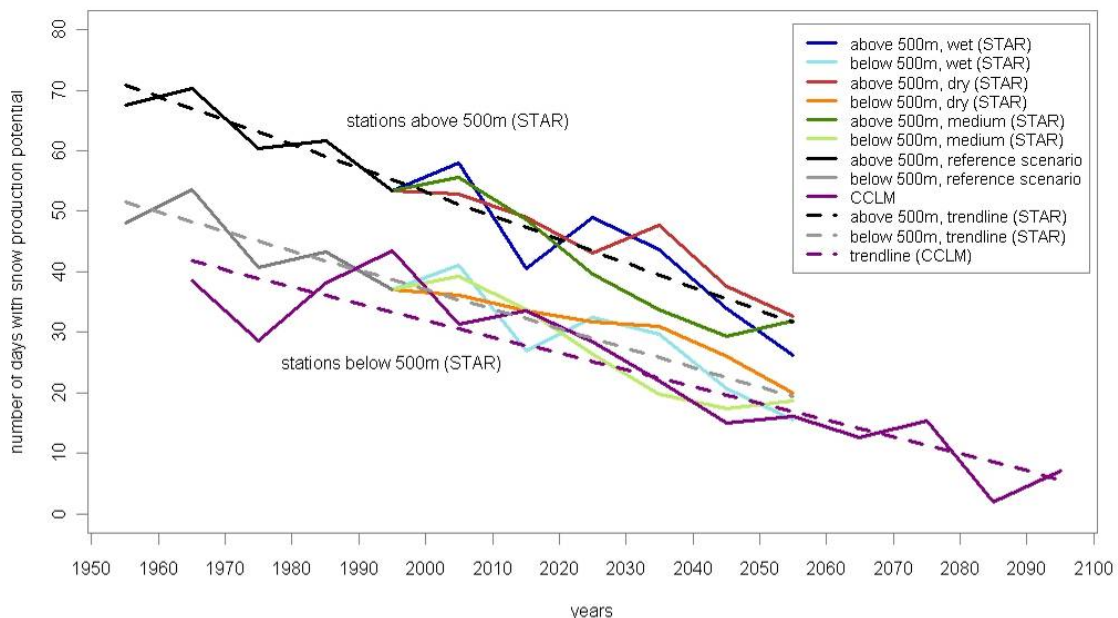


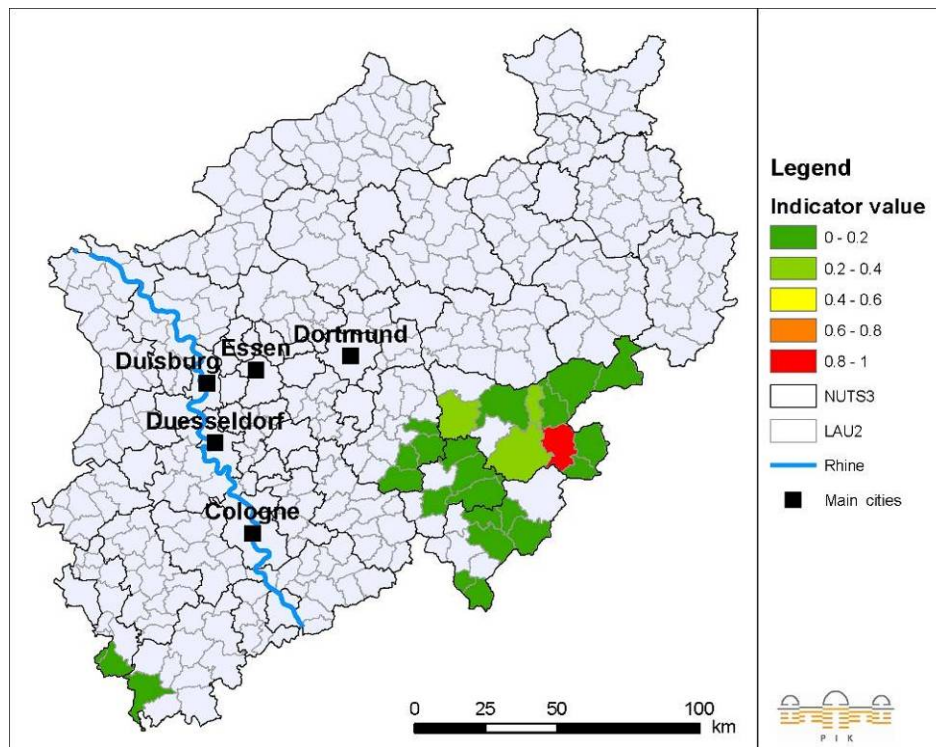
Figure 9: Change in snow production potential for the winter tourism area of Sauerland in NRW based on the climate models STAR (for stations above and below 500m) and CCLM until 2060 or 2100 respectively, under scenario A1B. A day with a snow production potential is here defined by the minimum daily wet bulb-temperature of -4°C or lower. Values are averages of 5 year time periods (Kropp et al. 2009b).

With a maximum altitude of the skiing area within NRW of 824 m (Roth et al. 2002a), this sector can be regarded as especially sensitive to a decrease in snow cover days until the end of this century.

Winter sport conditions are above all influenced by the altitude of the resort, which is represented by a stronger decrease in the number of days with snow cover. To quantify the sensitivity of the tourism sector towards a decrease in the winter season, the total slope length has been considered for resorts in Sauerland (Roth et al. 2001) and Eifel (Gemeinde Hellenthal 2010; Stadtverwaltung Monschau 2010). Roth et al. (2001) identified core winter sport areas in the Sauerland region based on advantageous snow conditions and available infrastructure, which are recommended as focal regions for further investments. Thus, sensitivity of the winter tourism areas within this core region is assumed to be half the value compared to surrounding regions.

Table 14: Fact Sheet: Relative sensitivity of winter tourism towards to a shortening of the winter season

<i>Relative sensitivity of winter tourism towards to a shortening of the winter season</i>
The sensitivity of the winter tourism sector towards a shortening of the winter season is expressed by the total length of ski runs within the municipality.
Exposure: Decrease in days with snow cover
Spatial entity of application: municipalities
Detailed description: The sensitivity of winter tourism to climate change is considered to be especially high for resorts in low mountain ranges. In NRW all ski resorts are located in such area of relatively low altitude, the Sauerland and Eifel mountains. Thus the size of the skiing area is regarded as a proxy for the sensitivity here.
Methodology: The size of the skiing area is expressed by the length of ski runs within the municipality. Data on ski length is available for municipalities in the main skiing areas of Sauerland and Eifel. Due to more advantageous conditions, ski resorts within the core area identified by Roth et al. (2001) are considered to be half as sensitive as areas in the surroundings. These values are then weighted by the area of the respective municipality to express the relative sensitivity.
Data sources: Data on the length of ski runs for the Sauerland mountains: Roth et al. 2001, data for the Eifel mountains: Gemeinde Hellenthal 2010; Monschau 2010. For Monschau only the number of lifts was available. The length of ski runs was thus estimated by the average length of ski runs for the remaining resorts.
Key literature sources: ABEGG, B., S. JETTÉ-NANTEL, F. CRICK und A. DE MONTFALCON (2007): "Climate Change in the European Alps: Adapting Winter Tourism and Natural Hazards Management." S. AGRAWALA (Hrsg.). OECD.



*Map 24: Indicator map of the relative sensitivity of winter sport to a shortening of the winter season
Only sensitivity for municipalities comprising data on slope length is shown, others are marked in grey.*

According to the available data, 26 municipalities (24 in Sauerland and 2 in Eifel) offer alpine ski activities. The highest sensitivity was calculated for Winterberg (Map 24) with 59 lifts and a total of 19884 m ski runs. This municipality is followed by Bestwig, Schmallenberg and Sundern, however with much smaller value of sensitivity. Thus, normalized values shown in Map 24 reflect only the spatial pattern of the most vulnerable areas.

Relative sensitivity of agriculture to droughts

Around half of the area of NRW is used for agriculture, two thirds of this area underlies crop production and a quarter is grassland. The main crop types are cereals, followed by maize (LWK NRW 2008a). The total water use of the agricultural sector amounted to around 12 mio³ in 1998. This water is mainly used for irrigation and is derived largely from ground and spring water. Compared to the water consumption of households and industry, the amount for irrigation is by and large negligible (MUNLV 2009b).

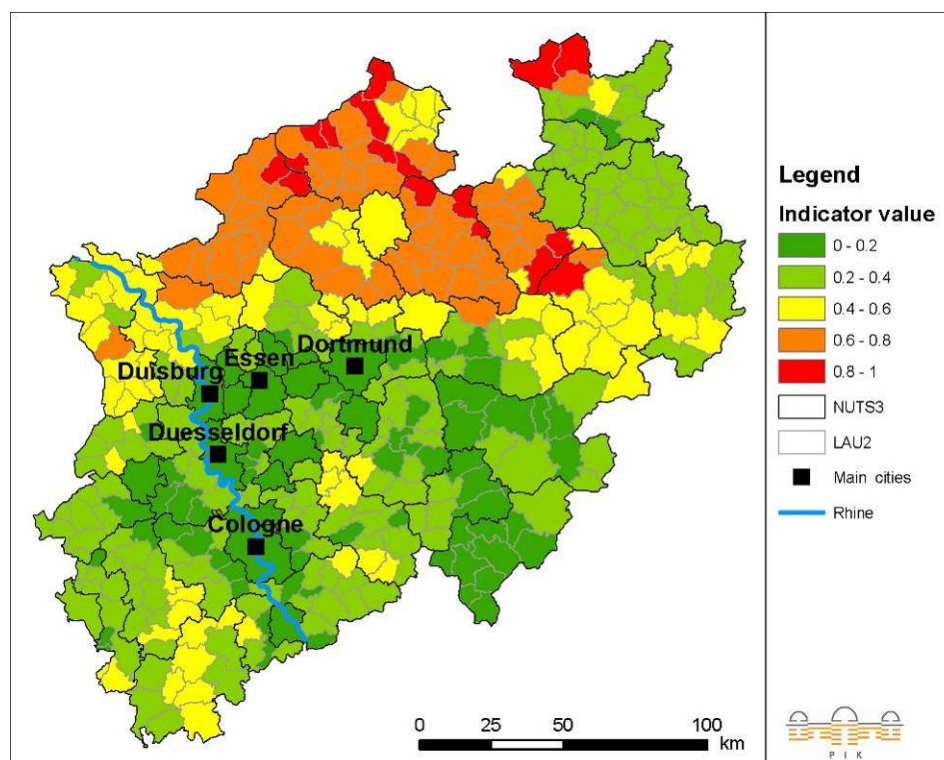
The overall gross value of agriculture, forestry and fishery and makes up only 0.6 % of the total, with a share of employees of 1.5 % (LWK NRW 2008b). However, agriculture is highly dependent on climatic conditions and thus sensitive towards climatic changes. The sensitivity is influenced by soil conditions and agricultural plant types. As planting cycles are rather short and thus flexible on a temporal scale (as opposed to forestry), sensitivity will be described in the following by soil characteristics.

When relating prices with climatic conditions, land rents of agricultural soils are expected to decrease or increase slightly until 2040 in NRW, (Lippert et al. 2009). A further statistical analysis of agricultural yield and climate parameters indicates no production changes for winter wheat and slight increases for maize production (Kropp et al. 2009b). However, water scarcity, which is by and large currently not a constraint in Germany, could not be addressed within the applied methods. The relevance of water availability for agricultural production is apparent from studies focusing on East Germany with drier conditions. Here, future water deficit is expected to increase leading to drought risk and production limitations (Schindler et al. 2007). Yield production of maize could decrease due to summer drought, whereas increases in wheat production due to more humid conditions in this season are possible. Soils most affected by yield decreases were characterized by low water retention capacities (Wechsung et al. 2008).

While numerous studies apply crop models to simulate agricultural yield under climate change (e.g. Wechsung et al. 2008; Ferrara et al. 2010) or correlate characteristics of the agricultural sector with climatic factors (Wechsung et al. 2008; Lippert et al. 2009), few studies consider the factors sensitivity and exposure separately for Germany. An approach has been carried out for Eastern Germany with regard to future drought risk (Schindler et al. 2007). Thereby, sensitivity was expressed by the amount of plant-available water based on soil parameters. The soil moisture regime is considered as one of the main determinants of constraining plant growth (Mueller et al. 2010). We therefore express the sensitivity of agricultural soil in NRW to drought by the average potential available soil water.

Table 15: Fact Sheet: Relative sensitivity of agriculture to drought

<i>Relative sensitivity of agriculture to drought</i>
The sensitivity of agriculture to drought is expressed by the average potential available soil water of soils under agricultural use
Exposure: Increase in evaporation
Spatial entity of application: municipalities
Detailed description: The sensitivity is expressed by the plant available water as a characteristic especially relevant for agricultural production. Plant available soil water is calculated by potential available field capacity given by soil map data.
Methodology: Potential available field capacity is averaged over agricultural soils for each municipality (ATKIS classes arable land 4101, pasture 4102, fallow land 4110). Lowest field capacities were assigned highest sensitivity. These values were then multiplied by the share of agricultural land of the municipality to derive the relative sensitivity.
Data sources: land use data: Authoritative Topographic-Cartographic Information System (ATKIS25, 2000), Federal Environment Agency, DLR-DFD 2009, soil data: BK50, Geological Service NRW
Key literature sources: Schindler, U.,J. Steidl,L. Muller,F. Eulenstein & J. Thiere (2007). "Drought risk to agricultural land in



Map 25: Indicator map of the relative sensitivity of agriculture to drought

The spatial distribution of the relative sensitivity of agriculture to drought (Map 25: Indicator map of the relative sensitivity of agriculture to drought

) shows highest values in large parts of the Westphalian Bay and the northern part of the Minden landscape. This region is dominated by podsollic soils with low available water capacities. Moreover, agriculture is the prevailing land use in this area. The mountainous as well as urban areas comprise a smaller share of agricultural land and are thus assigned a lower sensitivity. A higher share of agricultural land use in the western Rhine valley is accompanied by relatively high potential soil water availability, rendering this region a low sensitivity.

5. Adaptive capacity with regard to climate change

Adaptive capacity in relation to climate change impacts is defined as “the ability of a system to adjust to climate change and variability to moderate potential damages to take advantage of opportunities, or to cope with the consequences” (IPCC 2007b). Exposure and sensitivity together with the adaptive capacity then determine the overall vulnerability of a system.

Consistently with the European wide analysis, the adaptive capacity will be considered in a generic manner, which includes general factors such as education, income or health (Adger et al. 2007). However, processes determining the vulnerability of a system, especially the adaptive

capacity, work at different scales (Adger and Vincent 2005). Various studies have attempted to quantify indicators of adaptive capacity at the national or county level (e.g. Brooks et al. 2005; Cutter et al. 2010). The development of adaptive capacity indicators on the regional level for Germany is currently an active field of research (Werg et al. 2011).

Adaptive capacity indicators identified on the European level based on Schröter et al. (2004) will be applied for this case study (see section 3.4 of the scientific report). However, this concept has to be adjusted to the quite fine scaled level of the 396 municipalities in NRW as the common spatial level of this case study. These municipalities have a mean size of 86 km² and often comprise only one small to medium sized city. Therefore indicators values which do not differ spatially at this scale (e.g. implementation level of national or state adaptation strategies) or indicators with underlying processes acting on levels outside of municipalities (e.g. technological resource availability or traffic infrastructure) are not suitable for this case study.

The quantification of adaptive capacity on municipal level of NRW will therefore concentrate on the economic resources (indicating the dimension action) and knowledge/awareness (indicating the dimension awareness). Thereby the economic dimension is described by the personal (household level) as well as municipal financial situation. While most municipalities have a balanced budget, 17 are currently or in the upcoming years overindebted and are thus under the supervision of public authorities.

The knowledge of citizens is expressed by the educational school level. Unfortunately no data exists on the awareness of people in NRW concerning climate change related adaptive capacity. Therefore proxy indicators of the initiative of the community (mainly driven by personal motivations) with respect to climate change or sustainability issues are applied here. The indicators are described in Table 16 and Table 17. As no projections of these indicators until the considered time horizon of the year 2100 exist, adaptive capacity is applied is expressed by its current status.

Table 16: Indicators of adaptive capacity on municipal level

	Determinant	Proxy	level	Data source
Economic Resources	Financial resources of municipality	Status of financial budget of municipality 0= truly balanced (39), 1= virtually balanced (281), 2= approved reduction in common reserves without obligation of budget consolidation concept (38), 3 = approved budget consolidation concept (13), 4 = budget consolidation concept not approved (50), 5 = overindebted (17) ⁸	LAU2	MIK NRW ⁹ , 2009

⁸ The municipalities of Bochum, Moschau, Laer, Horstmar and Stolberg with missing values for this dataset, were excluded from this subindicator.

	Financial resources of private households	Available income of private households	LAU2	IT.NRW ¹⁰ , 2009
Knowledge and awareness	Participation in climate change and sustainability initiatives on municipal level	Composite indicator, see Table 17	LAU2	see table below
	Education level	% of population of principal residence with highest school education level (Secondary school or higher)	NUTS3	IT.NRW, 2007

Table 17: Indicators for participation in climate change and sustainability initiatives on municipal level

Proxy	level	Data source
Participation in the network of “Municipal Climate Concepts” (“Netzwerk Kommunale Klimakonzepte”) for the development of integrated mitigation and adaptation concepts with potential funding of the Environmental Ministry NRW: All participants (38)= 1, municipalities chosen for further funding (5) =2, winners (2) = 3	LAU2	Ministry for Climate Protection, Environment, Agriculture, Nature Conservation and Consumer Protection of NRW ¹¹
Participation in the European Energy award with state funding All participants (63) = 1, municipalities with award (29) = 2, municipalities with gold award (6) = 3	LAU2	EnergyAgency.NRW ¹²
Agenda 21 initiative of the municipality Participation (238) =1	LAU2	Agenda 21 Forum ¹³

The two indicators for economic resources and knowledge and awareness respectively have been weighted equally. Also the indicator of Economic Resources has been aggregated with equal weight with the indicator of Knowledge and awareness to the final indicator of relative

⁹ Ministry of Municipal and Internal Affairs NRW (<http://www.mik.nrw.de>)

¹⁰ State office for Information and Technology NRW (<http://www.it.nrw.de>)

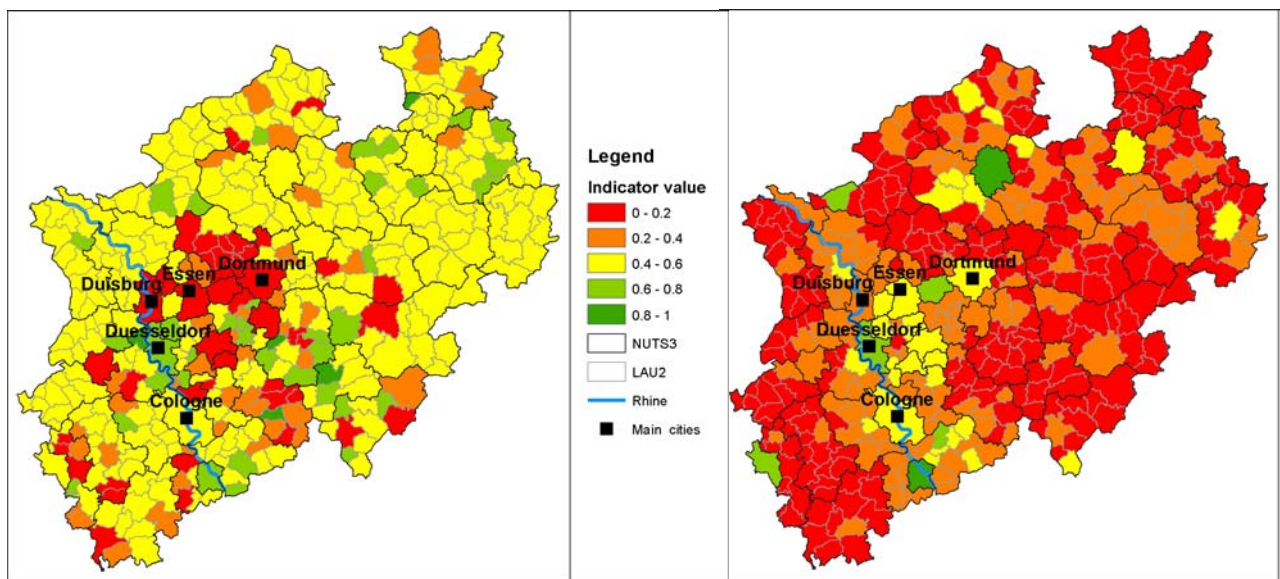
¹¹ http://www.umwelt.nrw.de/umwelt/klimakommune_nrw/index.php

¹² http://www.energieagentur.nrw.de/_database/_data/datainfoopool/karte_eea_2009.pdf

¹³ http://www.agenda21-treffpunkt.de/lokal/stadt/abc_stadt/nrw.htm#Anchor-49575

adaptive capacity. In this process, all indicators were normalised by the minimum and maximum value within NRW. Thus, an equal influence of economic resources and knowledge and awareness on the human adaptive capacity is assumed. Moreover, the pan-European weighting factors derived from the Delphi analysis for the adaptive capacity dimensions are not applied as they relate to the European level rather than the regional case study level and comprise only a small number of samples. Also, equal weighting enhances transparency for the interpretation of the results.

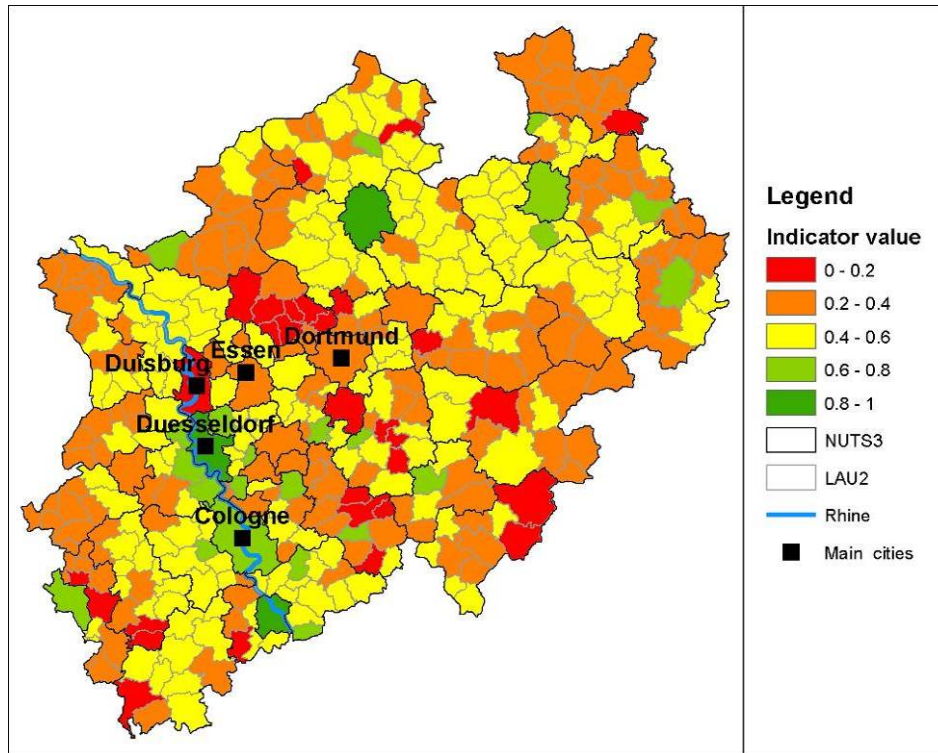
The maps of the subindicators of the relative adaptive capacity with regard to economic resources and knowledge and awareness are shown in Map 26. It becomes clear that the many of the municipalities in the former industrial Ruhr area are characterised by low economic resources. Düsseldorf, as the capital city of NRW however shows relatively high economic resources. The indicator of knowledge and awareness reveals a distribution towards relatively low values. Thus, the majority of the municipalities exhibits low values. The municipalities, which comprise universities such as Münster or Aachen are characterized by high education levels. In Bonn 45 % of the population has a school degree of secondary school or higher, which is explainable by a remaining high density of public institutions in this city.



Map 26: Indicator map of relative adaptive capacity with regard to economic resources (left) and knowledge and awareness (right)

The overall relative adaptive capacity (Map 27) shows high values in the municipalities along the Rhine, such as Düsseldorf, Cologne or Bonn, with the exception of Duisburg with very low economic resources. Bonn and Münster reach the highest values.

This contrasts to the findings from the pan-European analysis, showing a higher adaptive capacity rather in the Western part of NRW, which might derive from higher values in technological resources, which was not considered on the case study level.



Map 27: Aggregated indicator map of relative generic adaptive capacity with regard to economic resources and knowledge and awareness. Low values (red) indicate a low adaptive capacity, high values (green) a high adaptive capacity.

6. Aggregation methodology for the vulnerability assessment

Vulnerability, as the final target measure, is defined as a function of impact and adaptive capacity. Thereby the impact of a sector is determined by the respective exposure and sensitivity.

Before and after the aggregation all values are normalized to the data space of NRW. To consider positive as well as negative changes, exposure variables are normalized between -1 and 1, whereby no changes are represented by 0. The values -1 or 1 reflect the most extreme normalized value in the direction with the most extreme absolute values (see also Figure 3). In consequence, normalized values of exposure range between -1 and 1, according to the direction of change, whereas sensitivity as a dimensionless characteristic of the system ranges between 0 and 1 (Figure 10).

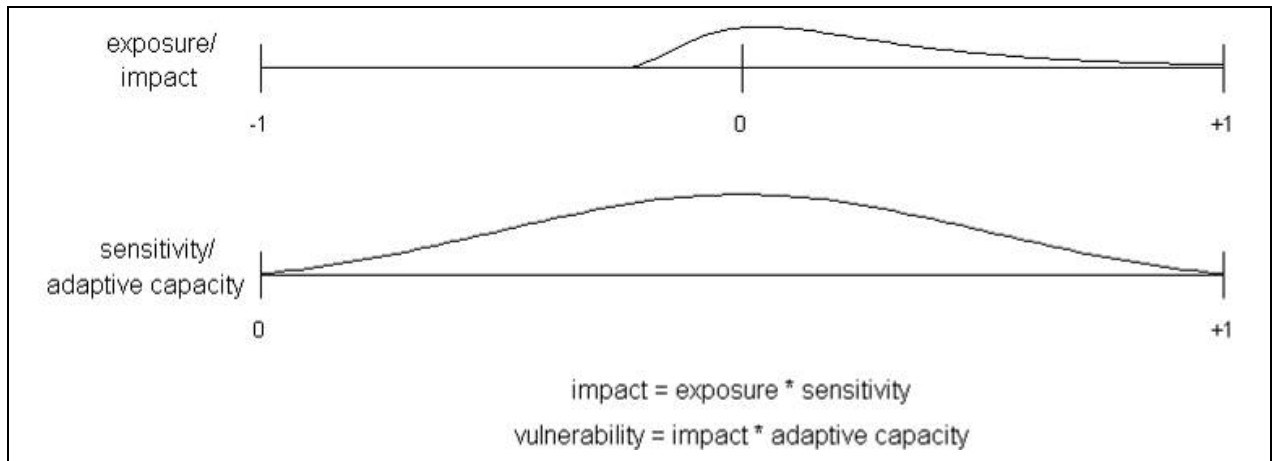


Figure 10: Schematic distribution of normalized exposure and sensitivity indicator values and calculation of impact and vulnerability

Two aggregation methods are common in vulnerability assessments: the arithmetic mean of the influencing factors (e.g. by applying equal weights) or the multiplication. The latter implies that the inputs are perfectly substitutable and that the resulting average values in overall are decreased, without considering further normalization. Also, the weighting of the input factor is not homogeneously distributed, but lower values have a much higher influence on the product. Calculating the arithmetic mean, implies that the inputs are perfectly substitutable and truly equal weights are applied, which is common studies with normative arguments (Hinkel 2011).

We chose a multiplication of the vulnerability components. Thereby the value of zero is maintained in the aggregation process. In other words, zero exposure cannot be compensated by a high sensitivity and will subsequently lead to zero impacts. The sensitivity and the respective exposure values for a specific sector are then multiplied to provide the impact (ranging from -1 to +1 consequently), as illustrated in Figure 11. Zero impacts are marked in grey colour, which can originate from either zero sensitivity of the system or no climatic changes relevant for the specific system. Positive changes are shown in green (high sensitivity and high negative exposure), negative ones in red (high sensitivity and high positive exposure).

The consideration of positive effects of climate change, through a reduction in exposure is based on the assumption that impact processes between exposure and sensitivity work equally in both ways (positive and negative effects). This is a strong assumption, considering the multitude of sectors analysed. The potential positive effects of climate change for some municipalities should thus be interpreted with caution.

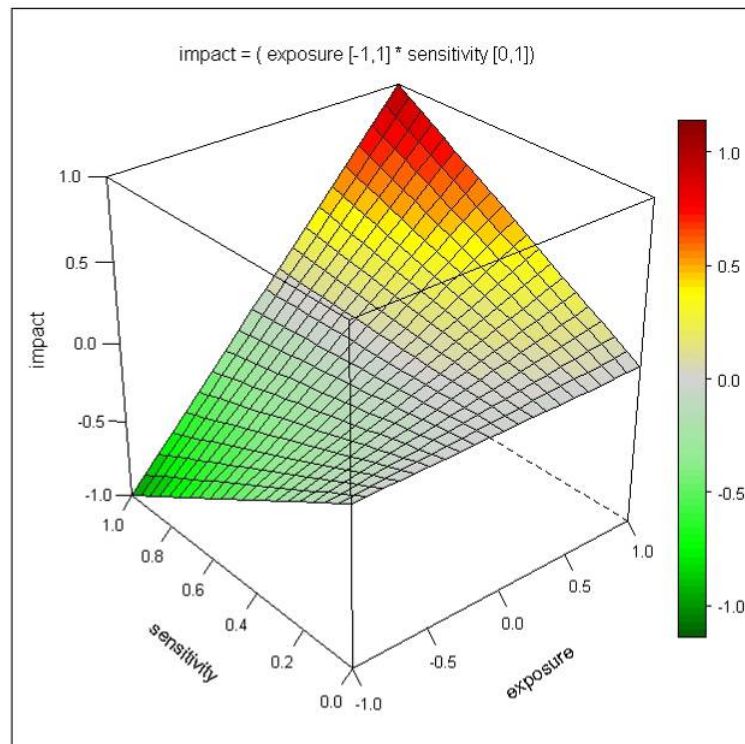


Figure 11: Schematic quantification of impacts as a function of exposure and sensitivity

This multiplication for sensitivity and exposure is carried out individually for the 12 sectors (summarised in Table 3). For direct exposure variables, data from CCLM is used as described in section 3.1 of the scientific report as well as indirect exposure variables for river inundation.

The specific sectors are then aggregated to the following four dimensions: physical, social, environmental and economic. Thereby the values are averaged and equal weight is assigned to each indicator within a dimension as well as to the four dimensions. The pan-European weighting factors derived from the Delphi analysis for the sensitivity dimensions are not applied as they relate to the European level rather than the regional case study level and comprise only a small number of samples. Moreover, equal weighting enhances transparency for the interpretation of the results.

Indicators with missing values for the sensitivity (e.g. no winter tourism activity) are classified as not sensitive in the following calculations. For the indicators “settlements sensitive to river inundation” and “humans sensitive to river inundation”, the impacts concerning the three considered inundation events are first summed and normalised to prior to the aggregation to the dimensions “physical” and “social”, respectively.

For the aggregation of each indicator within a dimension as well as for the four dimensions the non-normalized values are averaged. Thus, if in one dimension high exposure and high sensitivity do not coincide spatially (i.e. within at least one municipality), the resulting lower impact is considered within the aggregation of impacts.

The aggregated impact (ranging from -1 to 1) is then multiplied by the generic adaptive capacity (ranging from 0 to 1) to express the vulnerability of the system. However, vulnerability is defined as a measure of “the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change” (IPCC 2007b). Thus positive changes are not considered in

this definition. Therefore vulnerability is restricted here to positive values ranging from 0 to 1, whereby positive values are classified as not vulnerable (value 0).

The various steps of normalizing the data to the overall data space found within NRW, eventually lead to resulting relative values. In other words, no absolute statements concerning e.g. the final vulnerability (e.g. “municipality X is vulnerable”) are possible. However, relative statements for the study area can be made, (e.g. “Municipality X has a much higher vulnerability than municipality Y”). This consequently leads to differentiated results within the case study, which may not be discernable from the results of the pan European analysis as these values have been normalized to the European data space.

7. Results of the aggregated impacts

The results of the sector-specific and aggregated impacts are shown in Map 28. The physical impact is strongest in the foothills of the mountains and in the Rhine valley, whereas positive impacts prevail in the low lying areas. These are projected to experience reduction in heavy rainfall days according to the CCLM model, which influences the impacts with regard to flash floods and pluvial flooding.

This heterogenous pattern of physical impacts contrasts the findings the pan-European analysis, yielding marginal impacts over most regions of the state. This is mainly due to small projected changes in the flooded area (see section 3.2 for discussion on the hydrological model uncertainty).

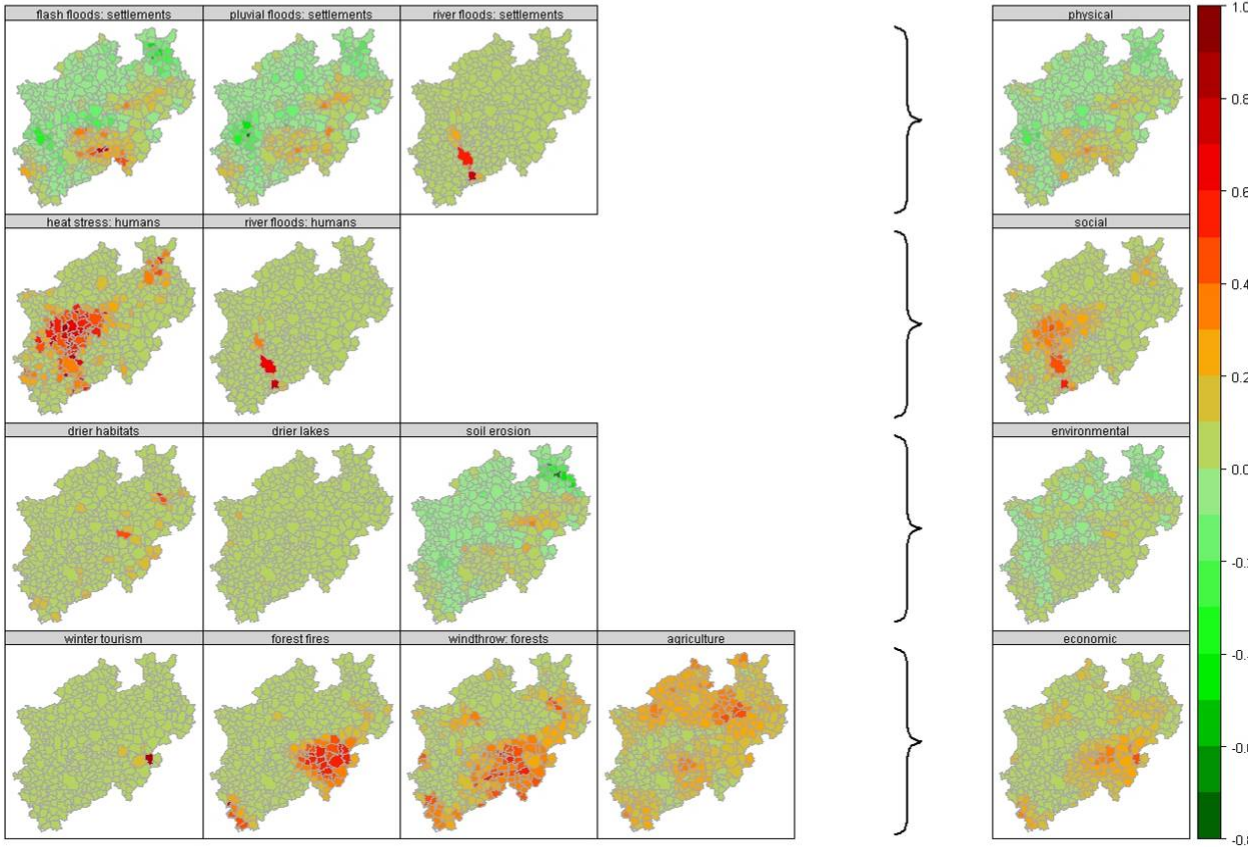
Social impacts are highest in the Rhine valley, which is both affected by increases in river floods and heat days. Here population density is also highest, which increases the impacts of both considered indicators. Also, in contrast to these case study results, the social impacts show marginal values on the pan-European scale for NRW. One reason is the consideration of sea level rise on this level, which is irrelevant for NRW. Also the small projected changes in flooded area lead to the classification of low impacts.

Environmental impacts show lower values than the other dimensions over large parts of the state. This can be explained by the low relative sensitivity of the habitats within the protected areas and the lakes, mainly due to the small share of area of these entities within the municipalities. While a strong spatial differentiation is apparent for the sensitivity of soils to erosion, the corresponding exposure variable “days with heavy rainfall” is projected to decrease in many areas. Thus, the impact with regard to soil erosion is diminished.

The environmental impacts in NRW from the pan-European assessment show lower values in the mountainous area of Sauerland and higher ones in the North. However, this assessment was based on different indicators.

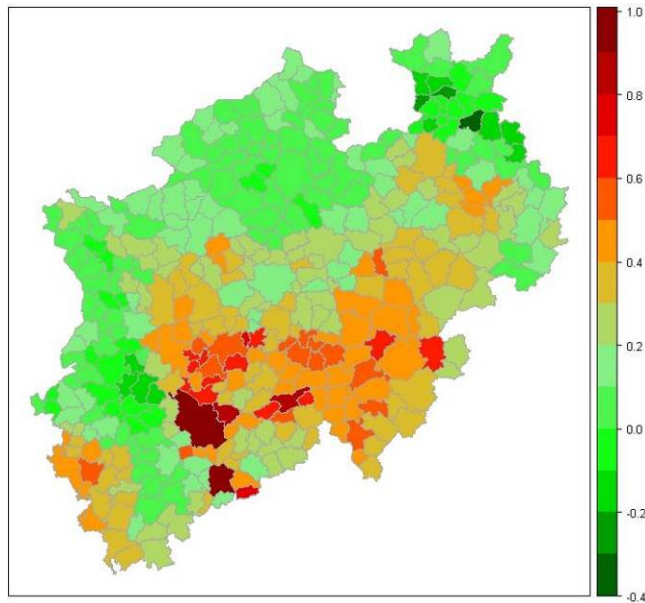
Economic impacts are characterised by a rather heterogeneous picture with regard to the sectoral impacts. For forestry, strong impacts are apparent in the mountainous areas. These comprise both a large share of forest in the municipalities as well as a dominance of needle-

leaved trees, which are especially sensitive with regard to windthrow and forest fires. Agriculture however, shows the strongest relative impacts in the Westphalian Bay with larger agricultural areas and soil characterised by a low water retention capacity. Winter tourism is most affected in the higher elevated areas of Sauerland with the strongest dependency on this sector. Economics impacts on the pan-European level show a spatially disperse pattern, mainly due to the results of the impacts on the energy sector, which have not been considered on the case study level.



Map 28: Maps of relative sectoral impacts and relative impacts aggregated to the dimensions physical, social, environmental and economic in 2100, based on climate data of the CCLM model under scenario A1B. Both negative and positive impacts are shown. Underlying sensitivity and exposure variables have been normalized to the data space of NRW.

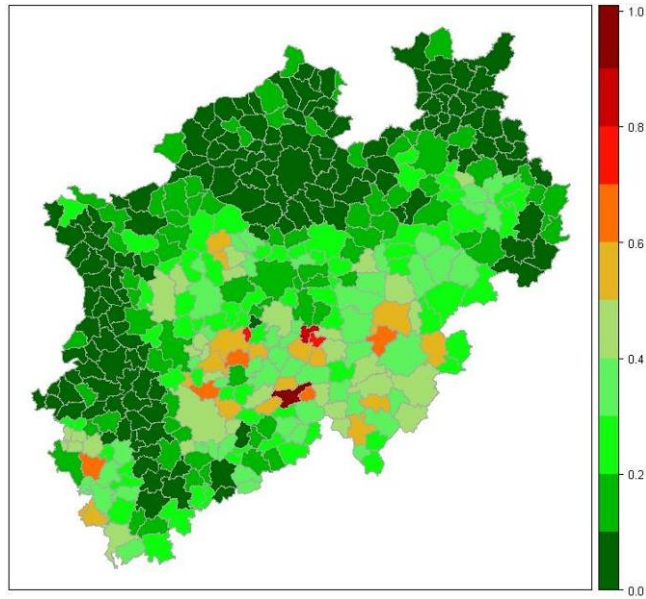
The overall relative impacts range from lower negative values, indicating improving conditions to stronger positive values, indicating adverse effects of climate change over most of the state. Positive impacts are mainly due to a decrease in heavy rainfall days in some areas. Adverse impacts are strongest for the upper Rhine valley, the densely populated Ruhr area and the mountainous areas.



Map 29: Aggregated relative impacts with regard to climate change in 2100, based on climate data of the CCLM model under scenario A1B. Both negative and positive impacts are shown. The overall impact values have been normalized to the data space of NRW.

8. Results of the overall vulnerability to climate change

The overall relative vulnerability to climate change shows low values for large parts of the lowlands. For the other parts, however, the pattern is more heterogeneous than for the aggregated impacts. This is mainly caused by the spatially distributed values of the adaptive capacity. By and large, most vulnerable municipalities are found along the upper Rhine valley, the Ruhr area in the mountainous areas as well as at the foothills of the mountains. The results from the pan-European assessment, however, show a spatially quite homogenous pattern of vulnerability with slightly higher values in the northern region.



Map 30: Relative Vulnerability of municipalities to climate change in 2100, based on climate data of the CCLM model under scenario A1B. The overall vulnerability values have been normalized to the data space of NRW.

Based on the changes in the considered seven climate variables, three regions of similar climate change characteristics - not current climate - have been identified by means of a cluster analysis (see section 3.1). These climate change regions are shown in Figure 12 (left). The first cluster comprises large parts of the Westphalian Bay and the Lower Rhine region. The second cluster “Low mountain range” is covering the higher altitudes of the study area, like the low mountain ranges “Eifel” and “Sauerland”. The third cluster “Cologne Bay” encompasses the southern part of the Rhine-Valley.

The relative values of vulnerability and its components impacts and adaptive capacity are shown in the radar chart in Figure 12 (right) based on the minimum and maximum values for the three regions.

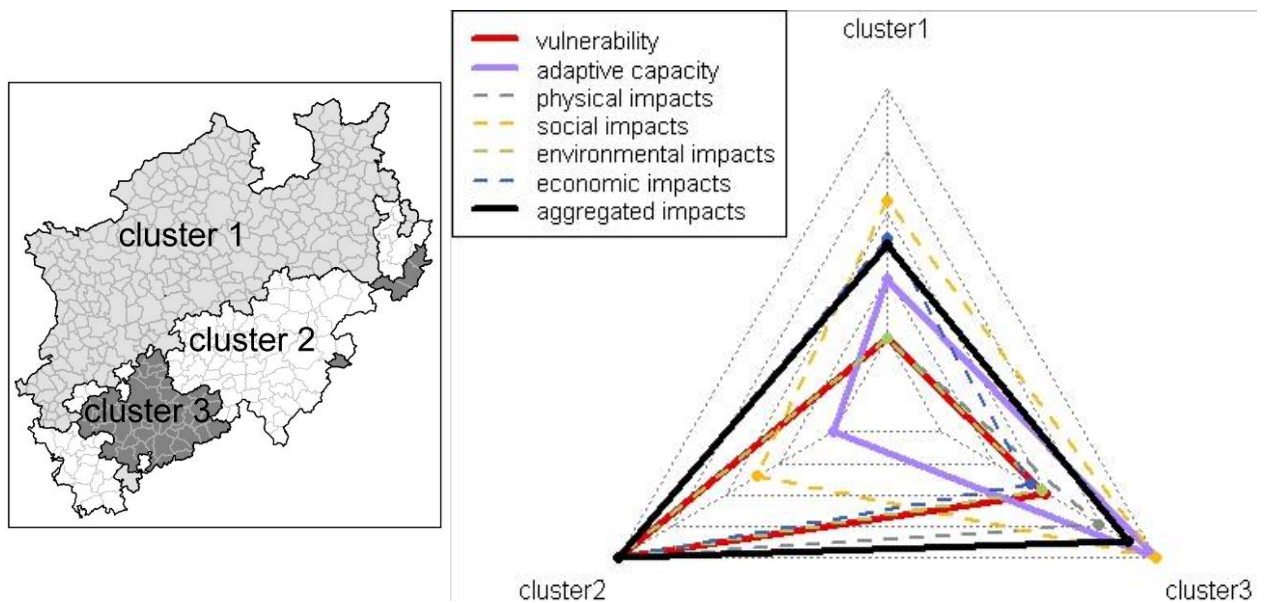


Figure 12: Relative vulnerability of three climate change regions in NRW
 Values are normalized to the maximum and minimum values for the three regions for visibility purposes. Regions are delineated based on a cluster analysis identifying regions experiencing a similar change in the considered climate variables until the year 2100 based on the climate model CCLM under scenario A1B (see section 3.1)

The overall vulnerability is highest in the second cluster “Low mountain range”, mainly due to a strong reduction in snow cover affecting the local skiing industry and an increase in storms leading to a higher threat of windthrow. The strong impacts are accompanied by a low relative adaptive capacity regarding economic resources and knowledge and awareness conditions. However, the region is also characterized by low potential social impacts as it is not affected by flooding of the river Rhine and less affected by heat waves due to higher elevations and a lower population density.

The lowest vulnerability of the regions is found in the first cluster “Westphalian Bay - Lower Rhine region”. Here, lower physical and environmental impacts can be expected under the model CCLM. However, social impacts are relatively high due to a higher share of urban area within flood prone areas of the river Rhine and due to a strong increase in heat days affecting the population. The economic impacts are medium compared to the other clusters, which is mainly due to some potential impacts of windthrow on forest in the region of “Hohe Mark” and “Egge mountains” and potential negative effects of droughts on agricultural areas in the “Münsterland”. Together with a relatively low adaptive capacity, this results in the lowest vulnerability value regarding the three clusters.

The cluster three “Eifel and Sauerland” exhibits overall a medium values of vulnerability compared to the other two regions. Especially economic and social impacts are higher in this region. This can be explained by a high share of population and urban area in flood-prone areas along the river Rhine and an expected strong increase in heat days affecting this densely populated region. However, the relative adaptive capacity is high regarding the economic resources of the region and the level of knowledge and awareness. This is especially the case for the city of Bonn.

9. Governance and response strategies

A start towards the planning and implementation of adaptation measure for NRW was made with the adaptation strategy for the state, published in April 2009 by the Ministry for Climate Protection, Environment, Agriculture, Nature Conservation and Consumer Protection (MUNLV 2009a). It is partly based on results from a multi-sectoral vulnerability study carried out at the Potsdam Institute for Climate Impact Research (PIK) at the same time (Kropp et al. 2009a; Klaus et al. 2011; Lissner et al. 2011; Rybski et al. 2011). However, this scientific report only formulated suggestions; the concrete implementation is an issue of political institutions. The political adaptation strategy of the state addresses the fields agriculture and soil, biodiversity and nature conservation, water resources, tourism, health, cities and urban agglomerations and safety of power plants.

All these sectors, with the exception of plant safety were subject to analysis of the prior vulnerability study. Plant safety could not be considered due to lack of data, especially concerning the numerous coal power plants. Thus, a stronger collaboration with energy companies is needed to gain a more detailed understanding of this highly relevant sector of NRW.

In the adaptation strategy a focus is set on urban areas of this densely populated state. Adaptation measures with regard to heat stress, heavy rainfall events and drought are further exemplified in a special report for cities and urban agglomerations (MUNLV 2010c). Heat wave and heavy rainfall impacts will be assessed in detail for the city of Cologne and concretized by means of municipal adaptation measures in the upcoming years (Ptak et al. 2010). This focus on urban areas is to some extent in line with the results of this project, which show higher potential impacts in these areas. However, adaptive capacity with regard to knowledge and awareness and economic resources is generally higher in the urban municipalities, leading to a lower vulnerability. It has also been shown, that high potential impacts occur in the mountainous regions as well as along the foothill of the mountains. These municipalities should thus be investigated further with regard to their adaptation potential.

Impacts on water the water sector and possible adaptation options are also analyzed in a further report concerning surface and ground water resources (MUNLV 2010d). Various impacts and adaptation measures are discussed concerning drinking water, water reservoirs and drainage. Inundation risk is adressed in the report, but no clear increase in flood risk is expected for river basins in NRW for the near future. However, new studies project considerable increases in flood risk for the river Rhine (De Keizer et al. 2010; Hurkmans et al. 2010; Te Linde et al. 2010). Therefore, a large gradient of risk perception is apparent between the NRW and the Netherlands. While for the former, the norms for the design of river dykes correspond to a discharge with a return period of around 200 years, in the Netherlands, usually 500-1250 years apply (Linde et al. 2010; Linde et al. 2011). In fact, the current situation of lower protection levels in NRW leads to a reduced risk in the Netherlands. In consequence a high uncertainty regarding flood damage within the Netherlands is related to the future protection level in Germany. Given these new scientific findings and the discrepancy in risk level concerning inundation, current adaptation to flooding should be re-evaluated in NRW. A comparison of flood protection measures for the river Rhine has shown that only a drastic dike heightening

could effectively prevent flooding under climate change until 2050. Additionally, retention polder or reforested areas can reduce the risk locally. For the Cologne, a bypass around the city also showed an effective reduction in peak water levels, however this would only have local effects (Linde et al. 2010). Also, damage reduction measures and spatial planning could reduce flood impacts. More research however, is necessary in this field.

A mitigation concept for NRW was first set up in 2001 (MWMEV 2001), which is based on the national mitigation strategy. Therein, the national aim of reducing emissions by 25% until 2005 compared to 1990 is followed. However, only a reduction of 6% was achieved by 2005, as quantified in the following mitigation strategy in the year 2008 (MWME 2008). New reduction targets of 33% until 2020 were then defined, in line with the national emission targets. As next steps, a mitigation policy is planned providing the legal framework, followed by a mitigation plan defining clear measures.

To enhance local and regional action, within the initiative “Klimakommune Plus”, municipalities in NRW are supported financially regarding adaptation and mitigation concepts (MUNLV 2010b). The municipalities Bochum and Saarbeck were awarded in 2009. Both aim at reducing emissions by energetic renovations of the building stock. Bochum further strongly promotes bicycle traffic, while Saarbeck envisions energy autarchy in 2030 through the compensation of fossil fuels with renewable energy sources, such as solar, wind and biomass.

Further financial support is also granted for municipalities participating at the European Energy award (EnergieAgentur.NRW 2007). This is a quality management system, which allows to monitor and quantify energy resources within municipalities in order to identify most efficient emission reduction potentials. By now, over 100 municipalities in NRW are participating in this award.

The above described “bottom-up” concepts strengthen local initiatives and action to mitigate climate change. In addition, “top-down” concepts with clear targets and short to long term time lines should be defined. NRW can be regarded as an energy state, producing one third of the overall electricity of Germany (Energie Agentur NRW 2007). In total, 98 % of the electricity produced in NRW derives from fossil fuels, largely from coal (88 %). Thus, a focus should be set on the large amount of emissions stemming from power plants, which are particularly concentrated in NRW. However, still today new coal power plants are being erected and planned.

Overall, regarding mitigation and adaptation strategies, climate change should be considered as a cross-sectional issue. This is apparent also from the large range of sectors considered in this study and their interlinkages.

Additionally to this cross-sectoral integration, climate change aspects need to be integrated vertically in the political context. This is especially the case since a cooperation of the German government with the states of a high degree of autonomy is crucial in the implementation of policies and strategies. Analysis of the development of sustainability strategies for North Rhine-Westphalia have shown that an elaborated process at the state level is a requirement for the integration into the national level (Happaerts 2008).

10. Applicability of the methodology of the pan-European analysis

The pan-European concept of vulnerability framework has been jointly developed together with this case study concept. The overall methodological frame could thus be well applied to the regional scale of NRW in a quantified way. In many fields, this case study could step beyond the pan-European analysis, due to better data sources and further developed methodologies. Thereby, for some sectors, a spatially more detailed analysis was possible (e.g. flash floods), while for others, sensitivity indicators could be refined concerning their content related explanatory power (e.g. sensitivity of nature conservation areas). Moreover by applying a new set of exposure indicators and regional data of sensitivity, additional impacts could be considered, such as windthrow impacts in forest due to storms.

The spatially very detailed resolution of municipalities applied in this case study however, also entails a limitation concerning the considered indicators (e.g. data constraints on the regional level concerning cultural assets). Also within municipalities, processes acting on different spatial scales have to be considered as compared to a broader scale. Therefore the adaptive capacity analysis concentrated on the dimensions awareness and action.

The overall methodology however, is in line with the pan-European analysis, such that the results are comparable, but the more fine-grained case study approach results in a more differentiated picture for the case study areas as it comes out of the pan-European assessment. Another factor which influences the results is the normalization of data: the relative differences between the municipalities of the case study areas are quite small compared with the differences among the whole continent; even those municipalities which are marked in red on the case study map are only moderately vulnerable from a pan-European perspective. Thus, the pan-European vulnerability map shows a more homogenous picture for North Rhine-Westphalia. This clearly underlines the scale-dependency of any vulnerability assessment. Or in other words, the situation in another country (e.g. Mediterranean) could be more severe than in NRW.

11. Uncertainty and limitations of the results

This vulnerability assessment represents a coherent methodology to assess the effects of climate change on the local scale to initiate concerted adaptation. However, climate change vulnerability assessments are constrained by large uncertainties. In fact, these studies are often fraught with higher uncertainties than studies from related fields such as natural hazards or sectoral assessments due to a multitude of stimuli and consequences, the high complexity of the system and the large time horizon (Patt et al. 2005).

A considerable part of uncertainty is derived from the climate change projection, where we are mainly facing by two kinds of uncertainties: i) forcing uncertainty (e.g. which forcing scenario to choose) and ii) model uncertainty (e.g. which General Circulation Model to choose). In addition uncertainty arises which is related to the downscaling procedure.

In an exemplary way of operationalizing a regional vulnerability assessment this study is based upon a single climate model, CCLM. This has to be kept in mind when interpreting the presented results. When comparing mean annual temperature and mean annual precipitation values of the model CCLM with observed averages a bias of the model for this region towards colder and wetter conditions becomes apparent (Figure 13). For simulated values under scenario A1B, the model also follows this trend compared to the statistical model STAR under dry, medium and wet assumptions.

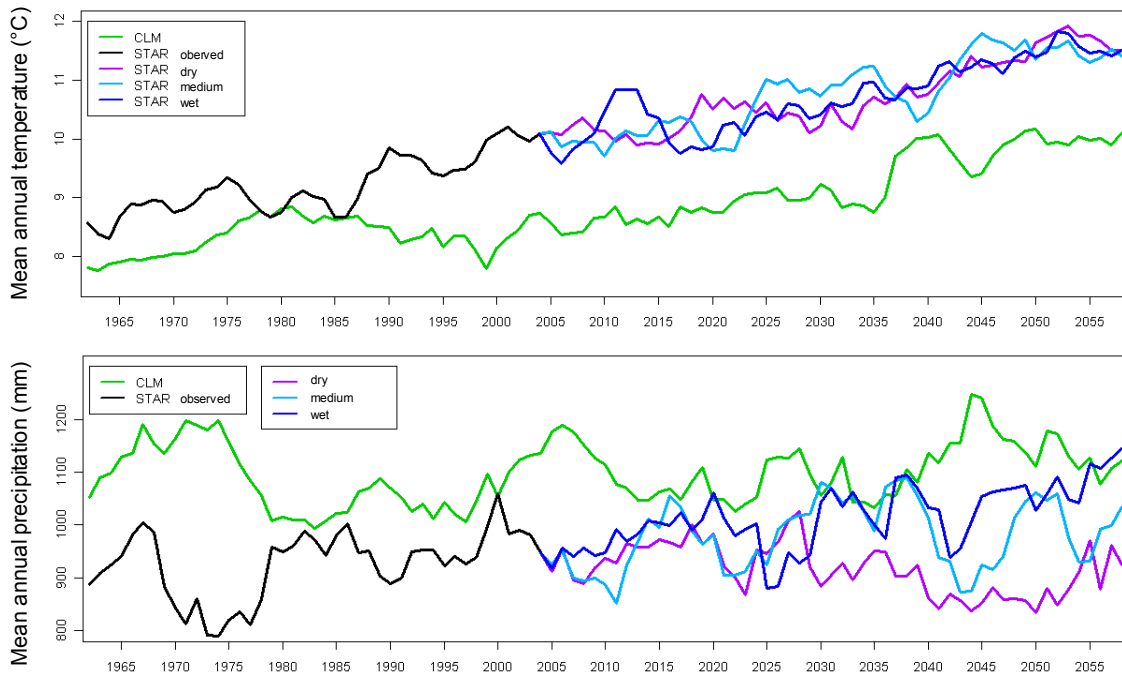


Figure 13: Changes in annual mean temperature and precipitation
Mean annual temperature (top) and mean annual precipitation (bottom) from 1961-2060 averaged over NRW for the regional statistical model STAR (under dry, medium and wet conditions) and the regional dynamical model CCLM under the scenario A1B. Values for the model star until 2006 are observed (black line). All values are averaged over a continuous 5-year range. (Kropp et al. 2009b)

Regarding extreme conditions, the number of heat wave days of 3.4 simulated by the model CCLM under scenario A1B averaged over NRW for the period of 1961-1990 lie above the observed value of 1.2. However, both models indicate a similar increase in heat wave days until 2031-2060 (Lissner et al. 2011). Nevertheless, the changes of heat wave days simulated by the dynamical model CCLM and the statistical STAR between these periods show a different spatial pattern. While CCLM projects a higher overall increase, especially in the Ruhr area, the model STAR simulated stronger increases in the northern part of NRW (Figure 14).

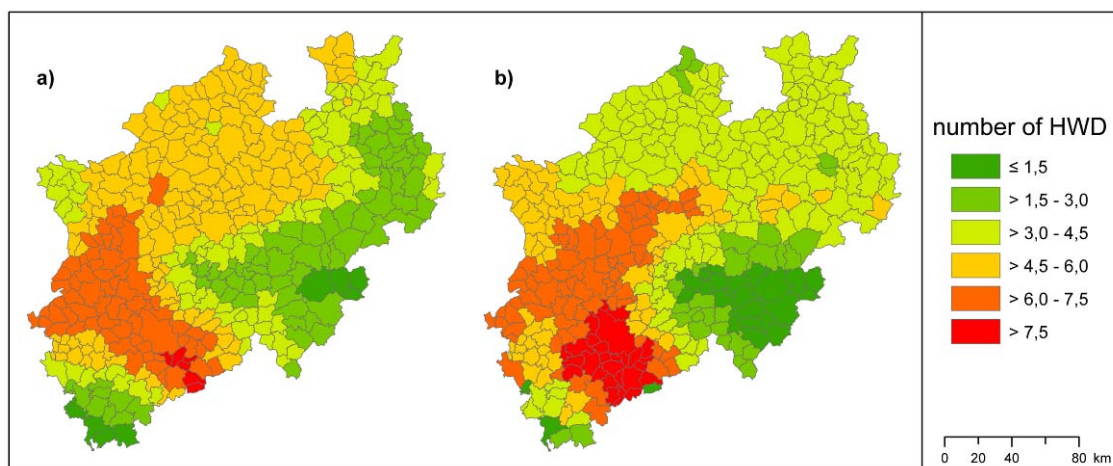


Figure 14: Changes in heat wave days
Increases in mean yearly number of heatwave days (HWD)¹⁴ between 1961-1990 and 2031-2060 for the regional climate models a) STAR and b) CCLM under scenario A1B. (Lissner et al. 2011)

The past observed conditions of heavy precipitation are well represented by the model CCLM as well as the statistical model WETTREG for the cities of Cologne and Wuppertal in NRW for the period of 1961-1990 (Figure 15). However, the simulated multiplication rate of these extreme days until 2031-2060 under scenario A1B varies considerably between the regional models. While CCLM projects an increase in heavy precipitation days for Cologne of 1.18, REMO simulated hardly any changes (1.08) and STAR a stronger increase by the factor of 1.27. The model WETTREG even projects a decrease in heavy precipitation days. It can thus be noted, that simulations of these extreme days are subject to a strong uncertainty, where in some cases the direction of change is even unclear.

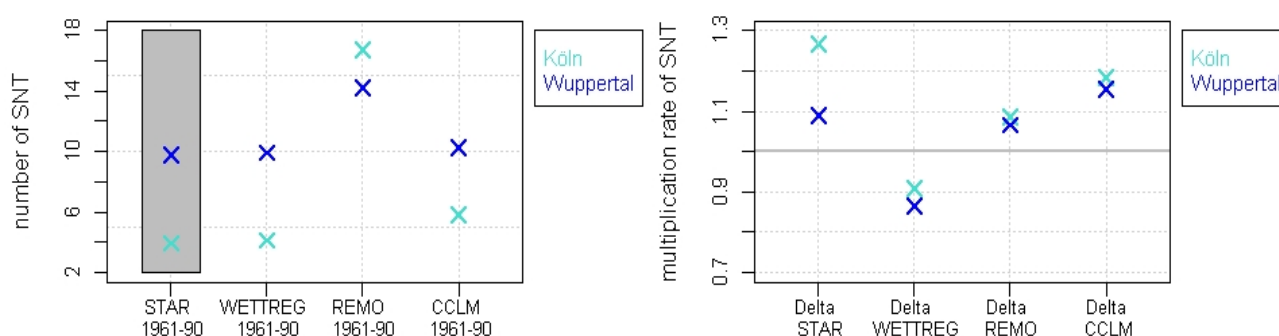


Figure 15: Changes in days with heavy precipitation
Mean annual number of days with heavy precipitation above 20 mm in 1961-1990 (left) for the cities of Köln and Wuppertal in NRW from observation (highlighted in grey) and model simulations for the statistical models WETTREG and STAR and the dynamical models REMO and CCLM and multiplication rates until 2031-2060 under the scenario A1B (right). A multiplication rate of zero represents no changes. Not that the data from 1961-1990 of the model STAR represents observed values¹⁵.

¹⁴ A heat wave is here defined as a period of at least three consecutive days with $T_{max} \geq 30$ °C. All days constituting a heat wave are referred to as heat wave days.

¹⁵ For the grid based models 4-11 cells were averaged, for the station based model 7-9 station were averaged for each municipality.

A strong bias of climate models is also apparent when comparing extreme values of the daily maximum wind speed averaged over NRW simulated by the models CCLM and REMO between the period 2071-2000 and 2031-2060 under scenario A1B (Figure 16). It can be seen that the difference between the model is in fact larger the climate change signal. However, comparing the relative values, shown as the changes in the 99.5th percentile, both models project a comparable increase in these extreme storm conditions (Klaus et al. 2011).

In summary, the difference between climate model outputs is large, especially for climate extremes. However, it is explainable that statistical models could output extremes better than dynamic ones, as they keep the moments of the past and assume additionally a trend. However, also for such an approach it is not completely sure that the future is well-represented.

The results of this study, based on a single model, should thus be regarded as an exemplary approach to operationalize a regional and comparable vulnerability assessment. For the profound interpretation of the results and hence the recommendation of specific adaptation measures to stakeholders, a set of climate models and scenarios would have to be considered.

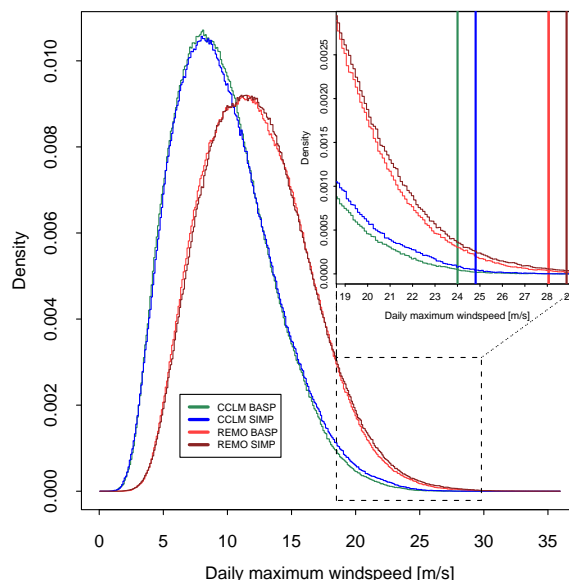


Figure 16: Changes in daily maximum wind speeds

Histogram of the daily maximum wind speed simulated by REMO and CCLM (mean over all model runs) for the periods 2071-2000 (BASP) and 2031-2060 (SIMP) averaged over NRW (class width = 0.1ms^{-1}). The upper tail of the distribution is depicted in more detail by the inset. The vertical lines highlight the 99.95th percentile values for each curve. (Klaus et al. 2011)

Besides these uncertainties stemming from the simulated exposure data, large uncertainties also lie in the lack of information on future sensitivity. For none of the considered sensitivity indicators projections until 2100 are available on this detailed spatial level. Thus, sensitivity was integrated as the current situation. However, this may overestimate the vulnerability in some areas where changes towards a reduced sensitivity (e.g. conversion of species composition in forests) have already been initiated. For specific indicators, such as the demographic change, information exists until the mid of this century on the level of NUTS3 regions. A study assessing the impacts of heat waves, which additionally to climate change took into account

these expected demographic changes, showed that although heat waves are projected to increase strongly in Cologne, this effect is partly alleviated by a reduction in sensitivity due to a lower share of elderly population in future (Lissner et al. 2011).

Also, the inclusion of adaptive capacity in a vulnerability assessment involves uncertainties, especially since often the direction of change and the causal chains between the variables are debated (Adger and Vincent 2005). According to the IPCC assessments, adaptive capacity is determined by the 'characteristics of communities, countries, and regions that influence their propensity or ability to adapt' (Smit et al. 2001). Adger and Vincent (2005) therefore argue that adaptive capacity contains generic features, such as available resources to face the exposure. Therefore, in this study, we integrated adaptive capacity in a general way, expressing the current general capacity overarching the considered sectors. This approach has also been followed in the European wide assessment of vulnerability of ecosystem services to climate change, ATEAM (Schröter et al. 2005a). Yet, they concluded that this generic way leads to very complex results, which are then difficult to communicate to stakeholders (Patt et al. 2005). Also it proved to be less useful to stakeholders, as they had the impression that they could evaluate their adaptive capacity better themselves (Hinkel 2011). Schröter et al. (2005b) suggest differential adaptive capacity measures, which take into account the heterogeneous pattern across individuals. Future studies could thus specify specific indicators for adaptive capacity based on the characteristic of the sectors or systems considered.

Finally, the aggregation process is a key feature of uncertainty in any vulnerability assessment. Concerning the aggregation of the components of vulnerability - exposure, sensitivity and adaptive capacity - we applied a multiplication procedure. This implies that a low value of one variable cannot be compensated by a higher one of another variable. This seems reasonable for the aggregation of exposure and sensitivity, since thereby zero changes in climate will always lead to zero impacts. However, for the aggregation of adaptive capacity and the impacts, this relation is not so clear. Moreover, the four dimensions of impacts (physical, social, environmental and physical) and the two dimensions of adaptive capacity (economic resources and knowledge and awareness) had to be aggregated. As this is a strongly normative decision, and regional judgments from stakeholders were not available, equal weights have been applied. This approach is common for normative arguments in such assessments (Hinkel 2011), however, the inclusion of weighting factors could change the final vulnerability results considerably.

12. Summary and transferability of results

We presented an approach which allows for a comparative and integrated assessment of climate change impacts, while enabling a sector-specific perspective of risk analysis. We demonstrate the approach through a multisectoral, regional case study in the German federal state of North Rhine-Westphalia. This region exhibits a strong spatial heterogeneity, while being of special relevance for the German economy generating about a quarter of the German GDP.

Sensitivity is quantified for the physical, social, environmental and economic dimension by means of tailor made approaches for specific sectors. These comprise sensitivity of settlements,

humans, and environmental resources such as protected areas, soils and lakes and economic branches such as forestry, agriculture and tourism. For some sectors, existing approaches have been incorporated into analysis, for others new methodologies have been developed. Examples are an indicator based approach for the health sector, describing the sensitivity of humans to heat waves by the urban heat island potential of the surrounding region and the demographic structure based on a detailed literature analysis. Relevant sensitivity factors of windthrow of forest stands were identified by a comparison of pedologic, silvicultural and topologic conditions with a past storm event, which was accompanied by high timber losses.

Exposure is defined as normalised changes between relevant and sector specific climate variables between the past and future. It is exemplarily based on a regional climate model and related directly to the respective sensitivity sectors. Additional to these direct climate stimuli also indirect climatic exposure such as river flooding is considered. Aggregation of the sector specific impacts, comprising both sensitivity and exposure, lead to integrated impact measures on administrative level.

Our results show some sector-specific differences of impact-severity, yet spatial hot spots are clearly identifiable. The results give some clear indications towards suitable intervention options in specific sectors.

This integrated and coherent overall methodology is in general transferable to other regions. However, the selection of impacts chains should be adapted to the specific regional relevance. It has to be stressed, that the results of this case study express relative vulnerabilities. Given a better data source, for some sectors, absolute vulnerabilities or impacts can be determined. This has been achieved for the windthrow risk in forests, where sensitivity was related to actual past damages occurring during a severe winter storm. These approaches support the transferability of the methodology and results to other regions.

12. Literature

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