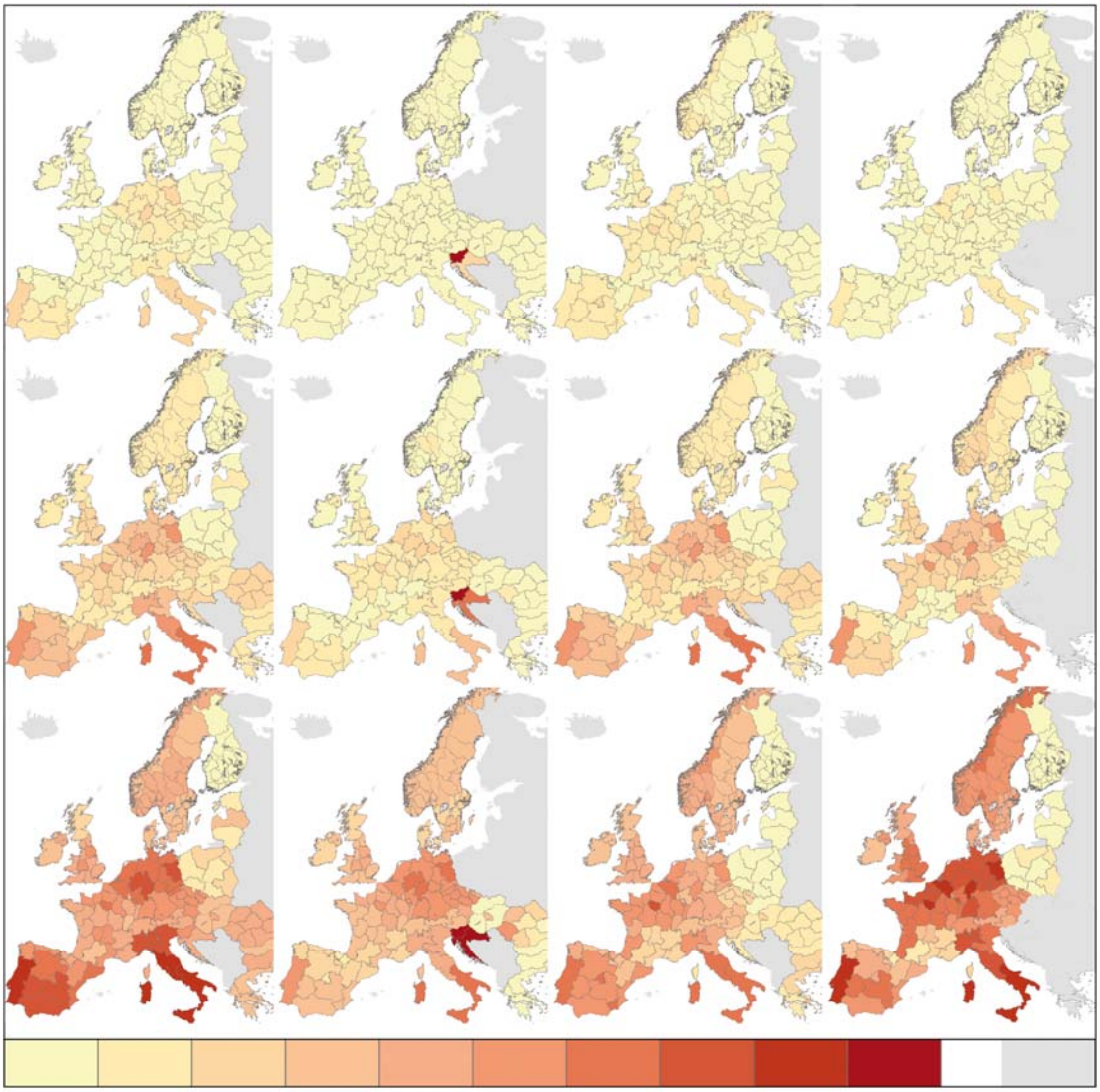
Technical Report No. 27

MAPPING DROUGHT RISK IN EUROPE



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Maps (cover): Drought Risk Maps of Europe for three selected hazard levels

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Abstract

The risk of natural disasters in a very general sense is a combination of hazard and vulnerability. The hazard is commonly described by one or a set of hydrometeorological or hydrological drought indicators. Vulnerability to drought is typically estimated by a combination of relevant, subjectively weighted vulnerability factors. The approach used here takes advantage of reported drought impacts from the EDII database (European Drought Impact report Inventory, Stahl et al. 2012, www.edc.uio.no/droughtdb) and empirically estimates risk as the likelihood of impact occurrence (*LIO*). The approach assumes that drought impacts are symptoms of vulnerability and can therefore serve as a proxy for part of the vulnerability.

Three generations of risk model development and risk map construction were developed within the DROUGHT-R&SPI project. The first generation modelled the *LIO* only by the Standardized Precipitation and Evapotranspiration Index (*SPEI*) over a 12-month calendar-year aggregation period based on a mid-project version of the EDII database (Blauhut et al., 2015). The second generation updates these risk maps based on a later and expanded impact dataset. This version is documented on the respective project flyer prepared for the International Conference on Drought 2015 in Valencia, Spain, and also shown in this DROUGHT-R&SPI Technical Report No. 27. The third generation, also presented in this Technical Report, expanded the modeling approach to the inclusion of multiple variables, i.e. up to two different *SPEI* indices, a shorter and a longer accumulation period, and two vulnerability indices representing sensitivity and adaptive capacity (from De Stefano et al., 2015), which are two common components considered in vulnerability assessments.

The statistical models were fitted to regionally pooled samples of annual impact occurrence in four macro-regions in Europe. To map the risk of drought, *LIO*s were displayed for the four impact categories for which the data has the best pan-European coverage and thus allowed model fits in most regions. The maps show the modeled *LIO* across Europe for impacts on “Agriculture & Livestock Farming”, “Public Water Supply”, ”Energy & Industry” and “Water Quality” for given hazard levels, which correspond to particular drought return periods. The maps show interesting spatial variations of drought risk. For moderate drought, risk is highest in the Mediterranean, in particular for Agriculture and Livestock Farming, and in the densely populated areas of central Europe, in particular for Water Quality and Public Water Supply, a pattern that generally dominates the maps. However, for more severe drought hazard (SPEI values of -2.5 to -2), risk increases everywhere, but with the most differences spatially and for different considered categories. *LIO* of impacts on Energy and Industry only increase for the most severe drought hazard. For the most severe drought, risk is high almost everywhere. The maps show a number of details, which will require some independent validation and comparison with other studies.

The models are based on a number of compromises due to the aim for pan-European comparability. EDII database coverage still has potential for improvement in space and time to reduce uncertainty. For individual regions, the models could be improved by a more specific selection of predictors. Nevertheless, the identified models allow a proof-of-concept for quantitative assessment and visualization of regional differences in first-order drought risk across Europe. The approach can serve as a template for further improvements and integration of existing European efforts, such as the use of the indicators of the European Drought Observatory in the models.

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1. Introduction

Drought risk, in comparison to other natural hazards, still is an underrepresented field of research in Disaster Risk Management. Global investigations often focus on the identification of risk by either only a physical quantification of the hazard or only an identification of underlying vulnerabilities, often expressed by the number of affected people, deaths or the potential to suffer famine. Rarely yet, has the combination of hazard and vulnerability been combined into risk. This report presents the results of a drought risk mapping approach developed within the project DROUGHT-R&SPI.

The multifaceted character of drought as a disastrous hazard with wide ranging impacts even puts wealthy nations at risk. Even though the majority of drought impact research and public recognition focuses on human health and the agricultural sector, drought has more damage potential. Within Europe, all nations have been affected by drought, a fact that the DROUGHT-R&SPI project has illustrated through numerous impact reports assembled in the European Drought Impact report Inventory (EDII) (Stahl et al. 2012, www.geo.uio.no/edc/droughtdb/). For the last three decades, the European Commission estimated the financial impact of drought for over 100 billion Euros of losses to the European Union members (EC 2007b). Drought has affected a variety of environmental and socio-economic systems and has covered about 37% of Europe's surface and more than 100 Million inhabitants (Kossida et al. 2012). To mitigate future drought impacts, an implementation of drought risk management into policy making is therefore desired. Today, merely few countries within Europe do have legal guidance to manage drought events (de Stefano et al., 2015). To improve countries resilience to negative effects of drought and to guarantee comparability among the EU member states, common principles for risk assessment and management are desirable.

The risk of natural disasters in a very general sense is a combination of hazard and vulnerability (IPCC 2007). Commonly, the drought hazard is described by one or a set of drought indicators, mostly based on hydro-meteorological information. Vulnerability to drought is typically estimated by a combination of relevant vulnerability factors. This approach requires explicit information on physical, ecological, institutional and socioeconomic parameters (Jordaan 2012; Sreedhar et al. 2013). A factor-based approach was also applied within DROUGHT-R&SPI to map drought vulnerability across Europe (de Stefano et al., 2015).

Another approach developed within DROUGHT-R&SPI by Blauhut et al. (2015) and Stagge et al. (in revision) used data from the European Drought Impact report Inventory (EDII) as a proxy for vulnerability to drought. Based on statistical modelling of the impact occurrence in the past by the drought hazard indicator SPEI, Blauhut et al. (2015) presented a first generation of sector- specific drought risk maps for selected hazard levels at the scale of European macro regions.

The work presented in this report
a) updates this application with more impact information collected throughout DROUGHT-R&SPI and presents the second generation of these risk maps;
b) further expands the approach by including not only hazard indicators and impact-information proxies but also two indices for the vulnerability components of sensitivity and adaptive capacity as developed by de Stefano et al. (2015) also within DROUGHT-R&SPI and presents the third generation of maps.

The report thus presents two further generations of the initial risk maps by Blauhut et al. (2015). The following sections briefly describe the data, the statistical modelling approach, and the resulting risk maps, and closes with a discussion of the potentials and further research and data needs.

2. Data

2.1. Drought hazard indices

Definitions of drought are almost innumerable; it can be ”both desired and feared” (Steinemann 2014). Due to its relative concept, drought is more difficult to identify than other natural hazards (Logar 2011). Drought is usually characterized by a “creeping” onset, long lasting duration and an independency of seasonality (Wilhite and Vanyarkho 2000; EEA 2009). It is a complex, unpredictable, natural phenomenon and there is no agreement about its precise definition (MED-EUWI 2007; Mishra and Singh 2010). Neither the beginning nor the end can precisely be defined(COM 2007; EEA 2009; Sheffield and Wood 2012). A commonly applied approach is to categorize drought into meteorological, hydrological, agricultural and socio – economic drought (The American Meteorological Society 1997). Broadly defined, meteorological drought, agricultural drought and hydrological drought occur in this particular temporal succession (Zargar, 2011) whereas socioeconomic impacts are noticeable at all stages. Further categorizations such as groundwater drought (Mishra and Singh 2010) and hydrological drought typologies (van Loon and van Lanen, 2012) have been introduced within the last years. Ultimately, drought categorization always depends on the context of research and application (Van Lanen 2012).

For this study the Standardized Precipitation and Evapotranspiration Index SPEI (Vicente-Serrano et al. 2010) were selected as drought hazard indices. This decision was taken aware of the limited interpretability of the more common Standardized Precipitation Index SPI (McKee et al. 1993) in dry regions (Wu et al., 2007) and based on overall results of the project that SPEI appears to be somewhat better linked to impacts across Europe (Stahl et al. 2015). For this study, SPI and SPEI were derived from the E-OBS (version 9) data for the period 1970-2012, which provide estimates of daily precipitation and temperature interpolated from station data to a 0.25° grid (Haylock et al. 2008). The SPI was calculated using the Gamma – distribution; the SPEI was calculated following the recommendations of Stagge et al. (2014), using the Hargreaves method to estimate potential evapotranspiration (Hargreaves 1994) and the Generalized Extreme Value (GEV) distribution for standardization (Stagge et al. 2015). To adapt to the spatial resolution of the impact data, the mean indicator value of all grid cells within each NUTS-combo region was extracted. Furthermore, several indices aggregation timescales (3-, 6-, 9- and 12 month) and month within the year of impact (March, July, September, December) were selected for analysis for the period of 1970-2012.

2.2. Drought impact occurrence

Besides these physically based characterizations of drought, drought can be described by its impacts, e.g. impacts on environment, society and economy. Workpackage 3 in DROUGHT-R&SPI followed this approach to assess the linkage of drought indicators to past drought impact reports (Stahl et al. 2012; Bachmair et al. 2014; Blauhut et al. 2015a,b; Stagge et al. in revision, Stahl et al. 2015) or on quantitative impact data such as forest fire area burned (Gudmundsson et al., 2014) or crop yields (Lenferink et al. 2014; 2015; Gunst et al., 2015). The results showed that in the past, Europe was affected by various different types of drought and a variety of impacts. A comprehensive assessment of past Europe’s major drought events can be found in the European Drought Reference Database (EDR) hosted by the European Drought Center (EDC) (Stagge et al., 2013). The EDR shows hydrometeorological and hydrological drought indicators (Stagge et al., 2015; Tallaksen and Stahl, 2014) as well as reports on the range of drought impacts for each event based on the EDII.

Impacts by drought are as multifaceted as its characteristics and differ region specific. The European Drought Report Inventory (EDII), a unique database established by the EU FP-7 project Drought R&SPI archives a categorized, temporal and spatially referenced collection on drought impact reports (Stahl et al. 2012). Impacts are defined as a negative consequence of drought for environment, society or economy (see EDII- guidelines: http://www.geo.uio.no/edc/droughtdb/). All impact reports refer to:

- An information source
- Spatial occurrence on NUTS-level regions
- Temporal occurrence: year, seasonal or monthly values; assigned to a related major drought event
- One of fifteen impact categories (Figure 1, left) and a number of subtypes (total 105).

More explicit information on the EDII can be found in Stahl et al. (2012 & 2015) and the database itself, accessible at http://www.geo.uio.no/edc/droughtdb/.

While the database continues to grow, this study used the content of March 2015, at which time the EDII database contained over 4800 reported drought impacts. For the applied period of 1970-2012, 2196 reported drought impacts were registered in the EDII database. All reports were reassigned to NUTS-combo regions (Blauhut et al, 2015). Summarized by the four European Macro-regions used in this study (Figure 1), 1419 entries were available for Maritime Europe, 77 for Northeast Europe, 315 for Southeast Europe and 385 for Western-Mediterranean Europe. Whereas the majority of these reported impacts relate to the following well-known major drought events: 1975-1976 West-Central Europe, 1991-95 in the Mediterranean region, 2003 in central Europe, and 2004-2007 on the Iberian Peninsula, with reports from 1976 and 2003 representing the largest share (Stagge et al. 2013, Stahl et al., 2012), an overall increasing trend of drought impact occurrence to the present day is observed.

🟫	A&L	Agriculture & Livestock farming
🟩	Fo	Forestry
🟦	A&F	Aquacultures & Fisheries
🟨	E&I	Energy & Industry
⬛	WT	Waterborne Transportation
🟪	T&R	Tourism & Recreation
🟦	PWS	Public Water Supply
🟦	WQ	Water quality
🟩	FE	Freshwater Ecosystems
🟩	TE	Terrestrial Ecosystems
🟧	SS	Soil System
🟥	Wi	Wildfires
⬜	AQ	Air Quality
🟥	H&S	Human Health & Public Safety
🟪	Co	Conflicts

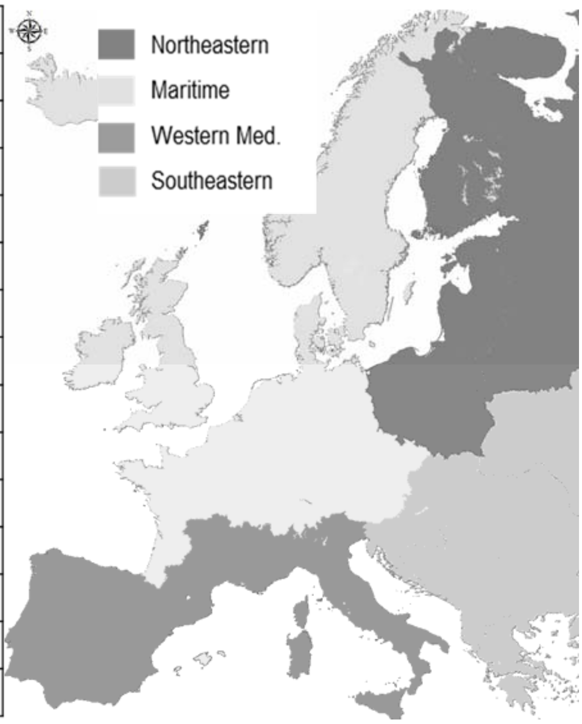

Figure 1 left: Impact categories as defined by Stahl et al. (2012), European macro regions by Blauhut et al. (2015).

Impact reports for all impact categories with a sample size larger than two registered entries were selected for analysis in this study. Following Blauhut et al.(2015), “binary datasets, i.e. “impact” or “no impact”, were created for 1970 – 2012, indicating years with drought impact occurrence in a particular category and in the respective NUTS-combo polygons. For temporal comparability, occurrences of multiyear-drought impacts were assigned to each applicable year. Seasonal and short-term information were generalized to the year of occurrence.

Finally, NUTS-region records were pooled for each macro-region. Figure 2 shows the resulting impact occurrences on an annual basis as they are used for the risk modeling in this study. While Northeastern

Europe has only few entries for four of the five impact categories, Central Europe, the Western-Mediterranean and Southeastern Europe have impact reports for almost all impact categories (Figure 2). In general, the impact categories of ‘Aquacultures & Fisheries’, ‘Terrestrial Ecosystems’, ‘Soil Systems, ‘‘Air Quality’, ‘Human Health and Public Safety’ and ‘Conflicts’ are only scarcely represented. The categories of “Agriculture & Livestock Farming” (A&L),’Public Water Supply’ (PWS) and ‘Water Quality’ (WQ) have the highest pan-European coverage. Impacts on ‘Freshwater Ecosystems’ and ”Energy & Industry”(E&I) are less represented and mainly available in Maritime Europe, southeast Europe and the Western Mediterranean. As already stated in Blauhut et al. (2015), “the Western-Mediterranean region has the majority of entries for two distinct events, the ‘1991-95’ and ’2004-7’ drought.” Southeast Europe has their entries on drought impacts more distributed over several drought events, whereas as drought impacts in Maritime Europe appear to occur more regularly. A conspicuousness is the long duration of drought impacts on forestry for Northeastern Europe.

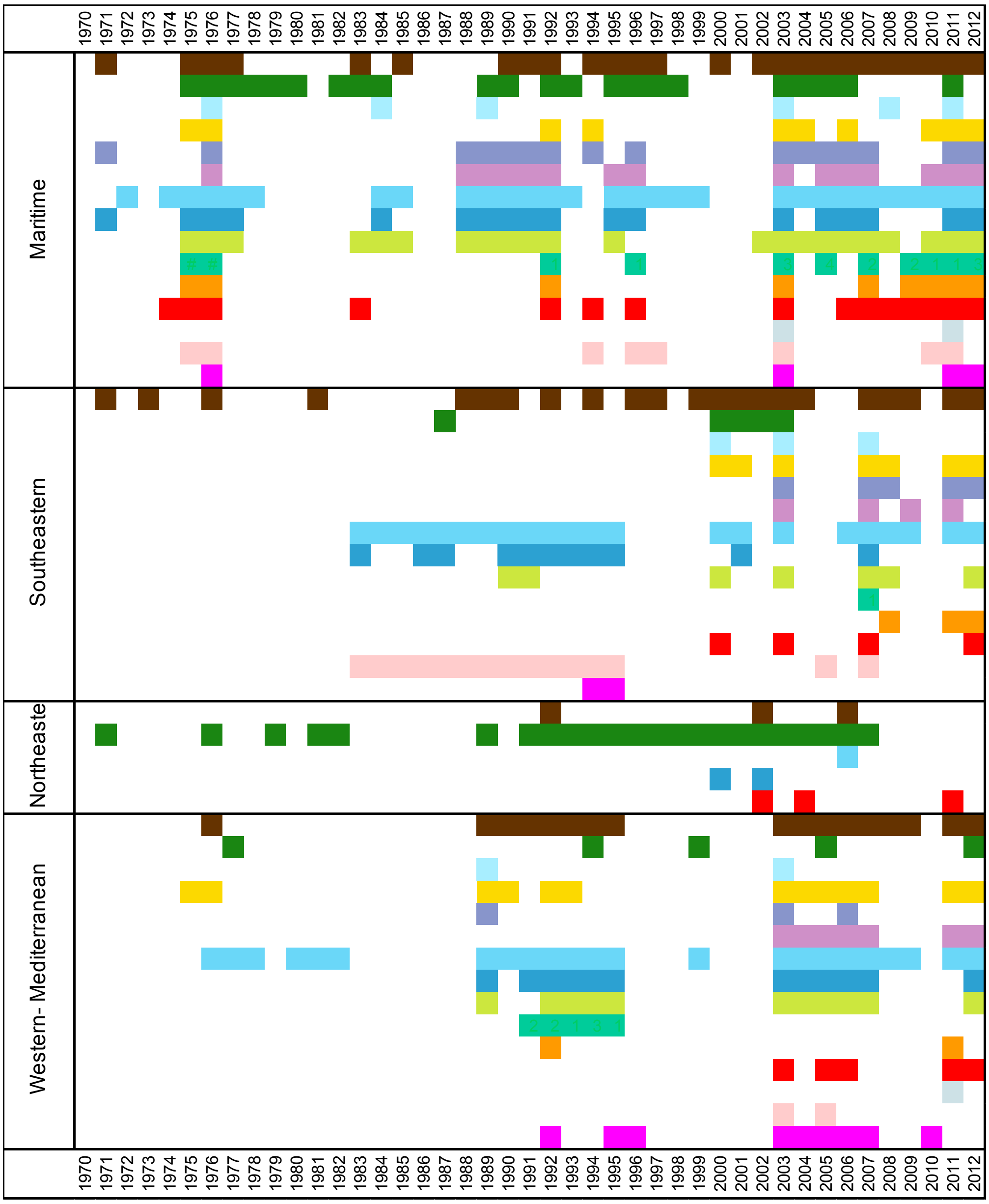

Figure 2 Binary signal of drought impact occurrence by impact categories and macro region (colours of impact categories as in Figure 1).

2.3 Drought vulnerability indices

Another outcome of the Task 3.3: “Sensitive Regions in Europe: drought vulnerabilities, resilience and robustness” in DROUGHT-R&SPI is a vulnerability index at the pan-European scale (De Stefano et al. (2015). To assess vulnerability, they adopted the conceptual model of the IPCC (2001, 2007) and conceptualized vulnerability in terms of factors of exposure, sensitivity and adaptive capacity. Each component was parameterized by a number of measurable variables for which geographically distributed data was available (representing the factors). Factors were chosen based on their influence within the pan European context considering past drought impacts, specific vulnerability situations and expert knowledge from case studies of the Drought R&SPI project.

This study uses the combined indices derived by De Stefano et al. (2015) for the vulnerability components of “sensitivity” and “adaptive capacity”. The vulnerability component “exposure” is not used here as it is based on SPEI and hence would duplicate the hazard indicators used in this study. For sensitivity, the variables used to construct the standardized index include e.g. freshwater abstraction, the water exploitation index, water body status, population density, etc.; for adaptive capacity, the variables used include for example law enforcement, drought management tools, expenditure on education and RT&D, storage capacity of dams & reservoirs, financial resources for drought mitigation, among others. To create the indices, the variables were standardized and weighted. Details can be found in De Stefano et al. (2015).

The resulting maps, i.e. the indices as they are also used in this study are shown in Figure 3. Higher values of sensitivity dominate the Mediterranean due to greater water stress and freshwater abstraction, whereas high values for Northern and Central Europe are due to poor ecological status and high freshwater abstraction rates. Adaptive capacity is highest in the Scandinavian countries due e.g. to economic advantages, and in France and Spain due to high drought awareness and infrastructure; a decreasing trend towards Eastern Europe is noticeable. De Stefano et al. (2015) suggest that some drought prone regions are in fact better adapted to drought.

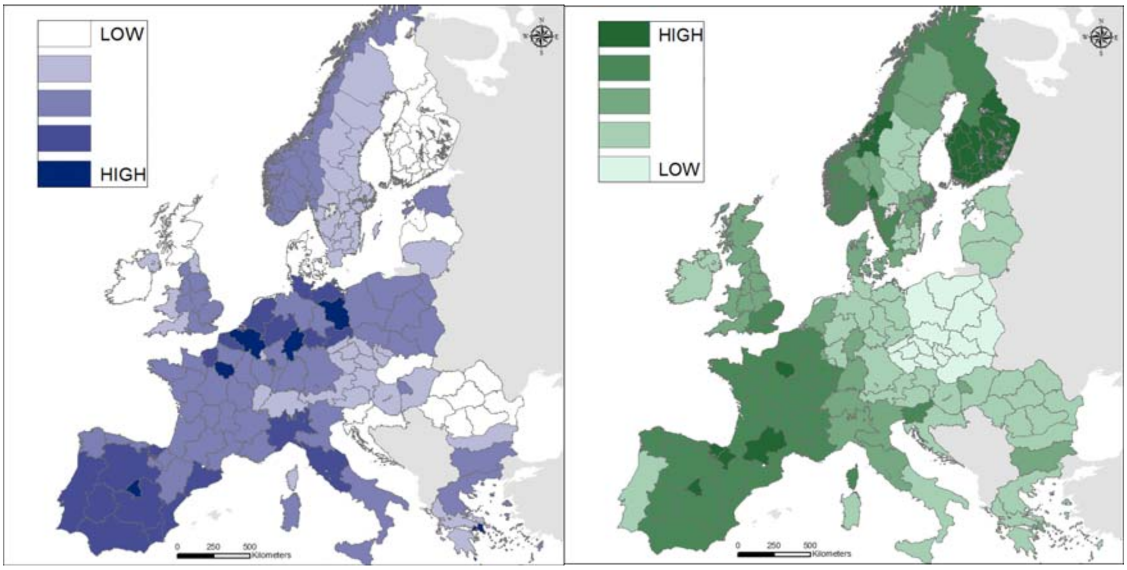

Figure 3 The vulnerability indices of sensitivity (left) and adaptive capacity (right), NUTS-combo scale (from De Stefano et al., 2015).

3. Modelling Drought Risk

The aim of this study is to improve the first drought risk maps of Blauhut et al. (2015) who modelled drought risk as the likelihood of drought impact occurrence based on the drought hazard index *SPEI-12* for December and annual binary impact occurrence. Therefore, this study

a) repeats the same analysis with a much larger impact database (end of project status)
b) considers more than one drought hazard index (*i*), i.e. *SPEI* at different aggregation times as well as the vulnerability indices of sensitivity (*S*) and adaptive capacity (*AC*)

to predict drought impact occurrence by a logistic regression model.

For approach b) a statistical model is fitted to estimate the likelihood of drought impact occurrence *LIO* (drought risk) in each macro region using multivariable logistic regression models (MLRM) as

$$\log\left(\frac{LIO}{1-LIO}\right) = \alpha_0 + \sum_i (\beta_i \cdot SPEI_i) + \beta_{AC} \cdot AC + \beta_S \cdot S$$

where the left hand side of the equation is known as the logit transformation. The model parameters *α* and *β* are estimated using standard regression techniques within the framework of Generalized Linear Models (GLM) (Harrel 2001; Venables & Ripley 2002; Zuur et al. 2009). The macro region specific *LIO* is hence a measure for the probability of drought impact occurrence, which is dependent on the drought hazard indicators $SPEI_{i,}$ (whereas i represents the specific selected *SPEI* and the vulnerability factors of adaptive capacity (*AC*) and sensitivity (*S*). Model performance was assessed by the area under the ROC curve with A_{ROC} >0.5 indicating that decisions of the resulting model will be on average superior to random guessing and A_{ROC} =1.0 indicating a perfect model as described in more detail in the prior studies by Gudmundsson et al. (2014), Blauhut et al. (2015).

To select the specific drought hazard indicators $SPEI_i$ for each region their significance as predictors was tested in a simple binary logistic regression. Figure A2.1 shows the significant predictors (p-value < 0.05) and a model performance with area under ROC (A_{ROC}) > 0.5. As predictors in MLRM should be independent (Zuur et al. 2009), only combinations of *SPEI* indicators were chosen that had a correlation coefficient below 0.5. Table 1 gives an overview of the selected predictors used for modelling.

Table 1 Selected drought hazard indicators for multivariable logistic regression models

	SPE-03 June	**SPE-06 June**	**SPE-06 September**	**SPE-09 December**	**SPE-12 December**	**ADAPTIVE CAPACITY**	**SENSITIVITY**
Maritime	x				x	x	x
Southeastern	x			x		x	x
Northeastern			x			x	x
Western - Mediterranean		x		x		x	x

Following the approach by Blauhut et al. (2015) the fitted models were finally applied to map the pan-European drought risk. For this purpose, for four selected impact categories the macro-region models were applied to estimate and map the *LIO* for five different selected drought hazard levels ($SPEI_{i,}$ =-1, -1.5, -2, -2.5 and -3). For approach b), where two different SPEI indices were included, both were set to the same value. In addition, the actual specific values in each NUTS-combo region for the vulnerability components of *S* and *AC* were used because they do not vary with time (Figure 3). Therefore, they modify the estimated LIO according to the models at a higher resolution and thus make the drought risk more specific.

4. Results

Approach a) LOI modelled as a function of one variable (*SPEI-12*$_{Dec}$)

For Northeastern Europe, the lack of impact data prevented robust model identification. For all other macro regions and four impact categories, *SPEI-12* was a significant predictor and models could be fitted. An example is shown in Figure A2.1. Differences of macro region and impact specific drought risks are evident and relative patterns are relatively stable for different hazard levels. For the most severe drought conditions the maps suggest the highest risk of impact occurrence for A&L in Western Mediterranean Europe followed by WQ in Maritime Europe. *LIOs* for 'Energy&Industry' are highest in Maritime Europe and for 'Public Water Supply' in the Mediterranean.

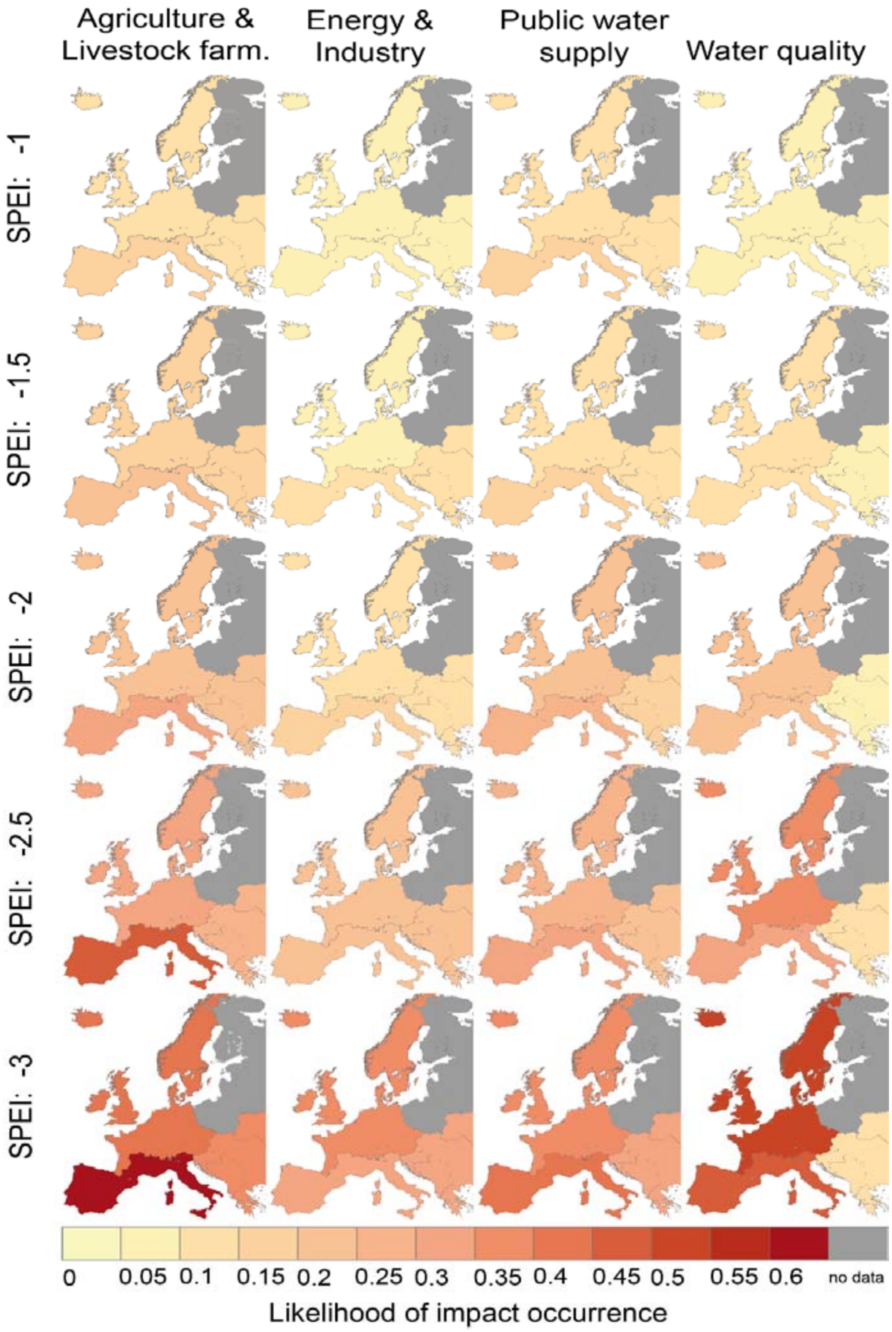

Figure 4 Drought Risk Map for Europe: the likelihood of impact occurrence by impact category for five different hazard levels (approach a) - updated version of Blauhut et al. 2015).

Approach b) LOI modelled as a function of multiple variables (*SPEI* indices and vulnerability*)*

Considering all 15 impact categories, for several, the lack of information on drought impacts on NUTS-combo scale hindered a robust model identification within some macro regions (Table A2.1). Merely Maritime Europe has enough data to identify a multi-variable model for each impact category. Southeastern Europe and the Western – Mediterranean both do not have sufficient data for impacts on 'Soil Systems' and 'Air quality', whereas models for TE, 'Human Health & Public Safety' cannot be modelled in Southeastern Europe. The few impact reports in the EDII for Northern Europe only allow the identification of four models. For almost all MLRM, sufficient model performance ($A_{ROC} > 0.5$) could be identified. Only the impact categories of WQ and 'Wildfire' for Southeastern Europe did not satisfy this model performance criterion. In addition, not all predictors selected based on their individual link to impact occurrence were also significant in the MLRM (Table A2.2). However, for the sake of comparability among the models and to assess the potential of this new approach the models were applied nevertheless.

To facilitate the comparison to the first and second generation of pan- European drought risk maps by Blauhut et al. (2015) and in the previous section (approach a; Figure 4), Figure 5 also displays the four impact categories of A&L, E&I, PWS and WQ. In general, *LIO*s for lowest drought hazard conditions are low and increase with increasing hazard level up to *LIO*s of 90-100% for some regions. Such high values are only reached for E&L in Slovenia and Croatia in this selection of impact categories, but are also reached for other impact categories in some regions, e.g. in Germany for Forestry or in Italy for Tourism and Recreation.

For A&L, *LIO* are already slightly increased for Portugal, northern Germany and Italy (especially southern Italy) for the lowest displayed hazard conditions ($SPEI_i = -1$). This pattern successively increases with increasing hazard severity. Whereas Northeastern Europe shows only minor increases of *LIO (up to 40%)* to increasing hazard severity, Central Europe, Britain and Southeastern Europe (without Italy) show medium to medium high drought risk (40-75%) at highest hazard level. With a chance of ~ 85%, Portugal and southern Italy have the highest *LIO* for A&L.

The impact category E&L shows a different pattern. Besides a LIO of almost 100% in Slovenia for the lowest - and for Slovenia and Croatia for the most severe hazard conditions, *LIO*s generally do not reach likelihoods as high as for A&L. The 'Highest' *LIO*'s (> 50%) were modelled for Germany, the Benelux states, northern France, southern England, Romania and the Iberian Peninsula.

In comparison to the other displayed impact categories, PWS generally has the lowest *LIO*'s overall (max. *LIO* of 70% in France). At a hazard level of $SPEI_{i,} = -2$ higher *LIO*s are modelled for northern Germany, the Iberian Peninsula and Italy. For the most severe hazard conditions, the highest *LIO*'s were found for Italy and Western Europe, especially in regions along the Atlantic. Northeastern and Southeastern Europe only results in comparably low *LIO*s.

The impact category of WQ shows the largest number of regions with the highest LIOs for the most severe hazard severity. The spatial pattern of higher *LIO*s is similar to that of PWS up to a hazard level of SPEI=-2. From $SPEI_{i,} = -2.5$, a generally LIOs increase strongly and reveal some 'hot spots' with Portugal, Île de France, Belgium, Hessen, Brandenburg and southern Italy at highest risk to be impacted by drought (*LIO* > 85%).

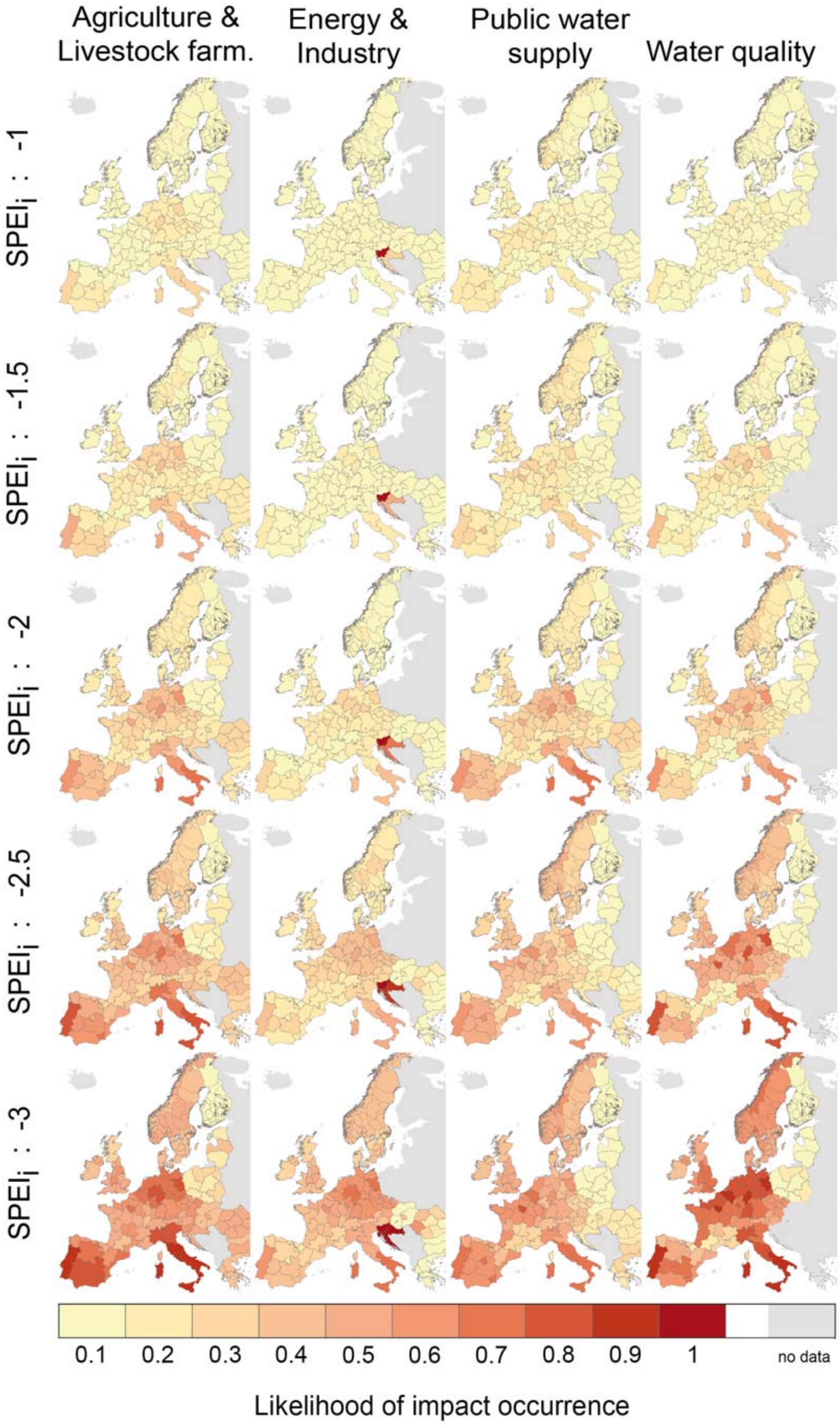

Figure 5 Drought Risk Maps for Europe: the likelihood of impact occurrence by impact category for five different hazard levels (approach b)).

5. Discussion & Conclusion

The presented approach to map drought risk combines hazard and vulnerability, though it differs somewhat from the common approach of considering loss or damage of disasters with a particular return period. As damage or loss data is difficult to obtain for drought, and drought has many impacts that cannot be quantified easily in monetary terms, the occurrence of impacts is a first-order proxy for the exposure to drought and hence part of vulnerability to drought. Based on evidence from the new pan-European impact report inventory, the presented risk maps are based on the empirical modelling of the likelihood of impact occurrence for different assumed SPEI hazard levels (representing different return periods), therefore still following the generally used concept of risk.

The three generations of models that were developed throughout the project duration show rather similar relative patterns of drought risk across Europe. The final risk maps model a wider range of *LIO*s and higher maximum *LIO*s than the simple model with only one predictor, confirming the additional value of using more information for a better distinction of relative risk. In fact, many drought indicators that are used operationally use a combination of a short and long-term aggregation of the water deficit, including the European Drought Observatory (Sepulcre Canto et al. 2012), or the US Drought Monitor (Svoboda, 2002). The final risk maps presented here also add important details to the previous generations, because they consider additional aspects of the vulnerability components “sensitivity and adaptive capacity” at smaller scales. Essentially these modify the baseline likelihood for a macro region. Differences within the macro-regions can be seen, for example in a higher *LIO* for A&L and WQ in Portugal than in parts of Spain or in Southern versus Northern Italy for similar *SPEI* levels. A reverse South-North difference appears to be the case in France and Germany for some impact categories. For A&L a higher risk to suffer from drought in northern Germany is in fact well known. Farming is more intensive farming and soils are sandier. In Spain higher modelled *LIO*s also reflect intensive farming areas. At more severe hazard levels Germany also has a higher *LIO* for E&I than surrounding areas, which corresponds to a higher number of impacts in the past and the fact that water abstractions for energy production are comparably high (Blauhut & Stahl 2015). Finally some hotspots could be identified in terms of particularly high risk modelled. Some of these are plausible but some may be artefacts due to the data singularities. *LIO*s for PWS and WQ are very high for NUTS regions representing large cities, as for example Île de France (Paris) and Berlin. However, in Slovenia a very high modelled *LIO* for E&I was informed by only one database entry. Future studies need to validate such details and compare them to more regional case studies, where available.

Generally, impact likelihood increases for *SPEI* values below -1 for several regions and impact categories, suggesting that the commonly used definition of ‘moderate drought’ used for the *SP*I, also applies to impacts. The increase in risk with increasing severity of the hazard level however differs regionally and by sector. However for all mdoels the uncertainty increases with increasing *LIO*. The models are based on a number of compromises due the aim for pan-European coverage and comparability. The macro regions were a pragmatic choice to create larger pooled samples for the statistical modeling. Rather than pre-defined regions, which are often based on biophysical or climatological regionalization, future work may consider regions based on similar impact profiles i.e. regions better representing similar sectorial relevance and vulnerability. A caveat of the generalized choice of a particular set of predictors for each macro-region is that although the A_{Roc} performance criteria were reached, some of the predictors in the models fitted and applied here were not significant. A specific choice of predictors for smaller regions and separately for each impact category would improve the models and reduce the uncertainty. Stagge et al. (in revision) successfully tested such a more detailed approach at the country level for a few selected countries; In addition, they found an improvement of employing a higher temporal resolution than the annual impact occurrence and hazard indices used here.

The EDII database coverage, which formed the basis for the derived impact occurrence time series that are the models' target variables, also still has potential for improvement in space and time. Main deficits include the lack of precise time stamp for the impact occurrence and often only country scale spatial reference. Despite extensive search for impact information, the derived binary variable has some uncertainty as the state “no impact” may be due to no impact occurrence or to no report found as a result of data availability or local reporting tradition. The distribution of the sources of impact reports as described in Blauhut et al. (2015) are generally diverse in all regions and very likely due to national reporting practice. Whereas Maritime Europe, Northeastern Europe and the Western Mediterranean are dominated by academic and governmental work, reports in Southeastern Europe mainly come from non-governmental reports and the media (newspapers, world wide web). Future work should consider supplementing the text-based impact report data with quantitative impact data.

Nevertheless, the identified risk models allow a proof-of-concept for an alley to a quantitative assessment and visualization of regional differences in first-order drought risk across Europe. The use of the impact report collection and the final step of including the vulnerability components of sensitivity and adaptive capacity also makes this a truly interdisciplinary effort, linking hydrometeorological natural hazard to social and economic sciences approaches. In addition, we have developed and employed a full hybrid approach, i.e. an approach that combines vulnerability factor based indices with data on a wide range of impact reports that serve as a proxy for particular vulnerabilities to drought in the past, into one risk model. Other hybrid-approaches have mostly used vulnerability factors and impact data separately, i.e. to verify overall vulnerability indices by quantitative and/or qualitative past drought impact information, e.g. death rate,(Naumann, Barbosa et al. 2013) or for impact sector specific vulnerability indices (Aggett 2012).

The multi-variable approach employed to construct the final risk maps presented here is flexible enough to incorporate further controls and drivers of drought risks. Future developments may want to consider the inclusion of other indicators, for example the indicators currently used by the European Drought Observatory (e.g. the combined drought indicator based on SPI, Soil Moisture and fAPAR). This extension would allow to link the likelihood of impact occurrence to those indicators that are monitored and modelled in real time for Europe for the purpose of drought monitoring and early warning. Such an application would create a better basis for communication and policy decisions at the EU level.

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Annex 1 – Approach a

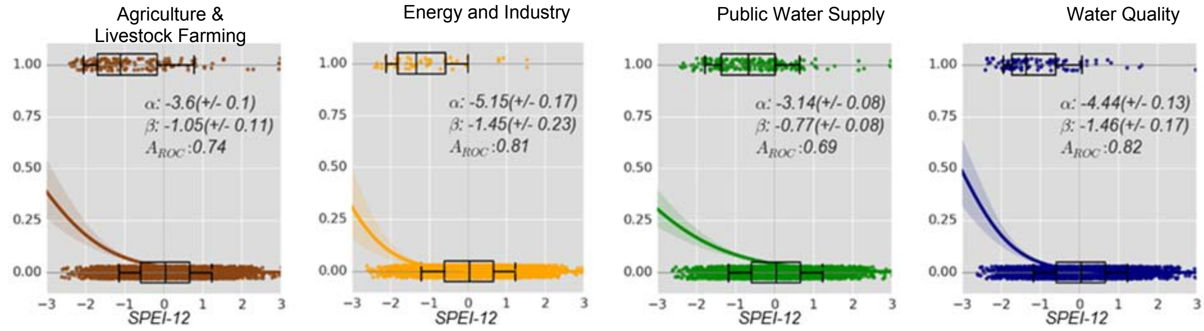

Figure A1.1 Logistic regression models for the second generation riks maps for the example of the maritime region (update of Blauhut et al., 2015). Y-axis shows the LI; Box pots denote the impact occurrence.

Annex 2 – Approach b

Table A2. 1 Significance of drought indices (p-value < 0.05) and Area under ROC > 0.5 for binary logistic regressions with single predictors by impact category and macro region

	Impact category	SPE_03_March	SPE_03_July	SPE_03_September	SPE_06_July	SPE_06_September	SPE_06_December	SPE_09_July	SPE_09_September	SPE_09_December	SPE_12_December	SPI_03_March	SPI_03_July	SPI_03_September	SPI_06_July	SPI_06_September	SPI_06_December	SPI_09_July	SPI_09_September	SPI_09_December	SPI_12_December	Drought_awareness	Drought_management_tools	Drought_recovery_capacity	Economic_resources_and_equity	Education	EXPOSURE	Innovation_capacity	Law_enforcement	Population_density	Public_participation	Socioeconomic_relevance_Agri	Socioeconomic_relevance_Indus	Water_balance	Water_body_status	Water_resources_development	Water_use	Water_use_Agri	Water_use_Indus	SENSITIVITY	SENSITIVITY_AGRI	SENSITIVITY_INDUS	ADAPTIVE_CAPACITY	ADAPTIVE_CAPACITY_INDUS	VULNE_AGRI	VULNE_INDUS	VULNERABILITY
Maritime	A&L	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x		x	x		x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x
	Fo	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x	x	x	x			x	x	x	x	x		x		x	x	x	x	x	x	x	x	x	x
	A&F	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x		x																								
	E&I	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x				x	x			x			x	x	x		x					
	WT	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x		x	x			x	x	x		x		x		x	x	x	x	x				x	x
	T&R	x	x		x	x		x	x	x	x	x	x		x	x		x	x	x	x		x	x					x	x	x	x	x		x					x	x	x					
	PWS	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x		x	x	x		x	x		x	x
	WQ	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x		x		x	x	x	x	x		x		x		x	x	x	x					
	FE	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x		x	x		x	
	TE	x	x	x	x	x	x	x	x	x	x	x	x		x	x		x	x	x	x	x	x	x	x		x	x		x	x	x	x	x	x	x	x		x		x					x	
	SS	x	x		x	x		x	x	x	x	x	x		x	x		x	x	x	x	x	x			x			x	x	x	x	x				x		x	x	x		x	x			
	Wi	x	x	x	x	x	x	x	x	x	x	x	x		x	x		x	x	x	x	x	x							x	x	x	x	x	x	x	x		x								
	AQ	x	x	x	x	x	x	x	x	x	x	x			x	x			x	x	x									x									x			x				x	x
	H&S	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x		x	x	x	x	x							x	x	x					
	Co	x	x	x	x	x		x	x	x	x	x	x		x	x		x	x	x	x			x	x					x									x			x				x	
Southeastern	A&L	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x		x		x		x				x					x						x					
	Fo		x	x	x	x		x	x	x	x		x		x	x		x	x		x																										
	A&F		x		x	x		x	x	x	x		x		x	x		x	x	x	x															x		x			x						
	E&I		x		x	x		x	x	x	x		x		x	x		x	x	x	x													x		x	x	x		x	x	x			x	x	
	WT		x		x	x		x	x	x	x		x		x	x		x	x	x	x															x		x			x						
	T&R		x			x	x		x	x	x		x			x			x	x	x																										
	PWS	x	x		x	x		x	x	x	x	x	x		x	x		x	x	x	x		x		x	x			x		x		x			x			x			x				x	
	WQ	x						x				x						x																													
	FE		x	x	x	x	x	x	x	x	x		x	x	x	x		x	x	x	x																				x				x		
	Wi				x			x	x		x			x	x			x	x		x																										
Northeastern	A&L		x	x	x	x		x	x	x	x		x	x		x			x	x					x			x	x	x						x		x	x				x	x	x	x	x
	Fo			x		x			x	x	x		x	x		x			x	x																											
	PWS																										x				x											x					
	WQ	x	x									x																									x										
	Wi																																														
Western - Mediterranean	A&L	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x				x	x						x									x	x	x	x	x		x
	Fo	x			x	x		x	x		x	x			x	x		x	x		x				x							x															
	A&F			x	x	x	x	x	x	x	x						x	x	x	x	x																										
	E&I	x	x		x	x		x	x	x	x	x	x		x	x		x	x		x						x							x								x	x	x	x	x	x
	WT		x		x	x		x	x	x	x		x		x	x		x	x	x	x				x	x										x											
	T&R	x	x		x	x		x	x	x	x	x	x		x	x		x	x	x	x				x	x	x															x	x	x		x	x
	PWS	x	x	x	x	x		x	x	x	x	x	x		x	x		x	x	x	x									x										x	x				x		x
	WQ	x	x	x	x	x		x	x	x	x	x	x		x	x		x	x	x	x					x	x					x		x			x	x	x			x	x	x	x	x	x
	FE	x	x	x	x	x		x	x	x	x	x	x		x	x		x	x		x				x							x									x				x		x
	TE				x			x	x		x				x			x			x				x							x	x								x	x			x		x
	Wi	x	x	x	x	x		x	x	x	x	x	x		x	x		x	x		x						x						x	x						x	x	x	x	x		x	x
	H&S		x	x	x	x		x	x	x	x		x	x	x	x			x									x																			
	Co	x	x		x	x		x	x	x	x	x	x		x	x		x	x	x	x			x		x	x	x				x								x	x	x	x	x	x	x	x

Table A2. 2 P-values of selected predictors and AROC of the finally selected multivariable logistic regression models by macro region and impact category

	Impact category	ADAPTIVE CAPACITY	SENSITIVITY	SPE-03 June	SPE-06 June	SPE-06 September	SPE-09 December	SPE-12 December	A_{ROC}
Maritime	**A&L**	0.00	0.00	0.00				0.00	0.78
	Fo	0.00	0.00	0.00				0.00	0.86
	A&F	0.38	0.10	0.28				0.00	0.91
	E&I	0.09	0.00	0.00				0.00	0.82
	WT	0.03	0.00	0.00				0.00	0.83
	T&R	0.51	0.00	0.01				0.00	0.81
	PWS	0.00	0.00	0.00				0.00	0.75
	WQ	0.96	0.00	0.00				0.00	0.86
	FE	0.03	0.00	0.00				0.00	0.76
	TE	0.43	0.12	0.08				0.00	0.83
	SS	0.11	0.00	0.01				0.00	0.81
	Wi	0.85	0.33	0.00				0.00	0.83
	AQ	0.12	0.03	0.87				0.01	0.91
	H&S	0.68	0.00	0.05				0.00	0.90
	Co	0.02	0.14	0.00				0.04	0.87
Southeastern	**A&L**	0.50	0.49	0.17			0.01		0.72
	Fo	0.06	0.01	0.17			0.43		0.61
	A&F	0.00	0.00	0.01			0.48		0.84
	E&I	0.01	0.01	0.01			0.64		0.80
	WT	0.27	0.17	0.95			0.09		0.86
	PWS	0.52	0.39	0.28			0.18		0.67
	WQ	0.61	0.18	0.56			0.49		0.27
	FE	0.03	0.00	0.12			0.21		0.79
	Wi	0.61	0.30	0.47			0.18		0.16
Northeastern	**A&L**	0.02	0.23			0.00			0.88
	Fo	0.69	0.39			0.00			0.61
	PWS	0.15	0.89			0.51			0.85
	WQ	0.17	0.62			0.14			0.78
	Wi	0.40	0.12			0.23			0.61
Western- Mediterranean	**A&L**	0.00	0.01		0.00		0.00		0.79
	Fo	0.07	0.35		0.00		0.94		0.74
	A&F	0.83	0.28		0.23		0.05		0.76
	E&I	0.00	0.76		0.00		0.57		0.79
	WT	0.07	0.86		0.01		0.02		0.93
	T&R	0.00	0.12		0.00		0.05		0.92
	PWS	0.00	0.00		0.00		0.02		0.75
	WQ	0.00	0.04		0.00		0.04		0.86
	FE	0.04	0.03		0.00		0.31		0.75
	TE	0.20	0.11		0.14		0.18		0.73
	Wi	0.00	0.04		0.00		0.23		0.90
	H&S	0.66	0.58		0.00		0.63		0.82
	Co	0.00	0.01		0.00		0.03		0.83