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Towards pan-European drought risk maps: quantifying the link between drought indices and reported drought impacts

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Abstract

Drought in Europe is a hazard with a wide range of transboundary, environmental and socio-economic impacts on various sectors including agriculture, energy production, public water supply and water quality. Despite the apparent importance of this natural hazard, observed pan-European drought impacts have not yet been quantitatively related to the most important climatological drivers to map drought risk on a continental scale. This contribution approaches the issue by quantitatively assessing the likelihood of drought impact occurrence as a function of the standardized precipitation evapotranspiration index for four European macro regions using logistic regression. The resulting models allow mapping the sector-specific likelihood of drought impact occurrence for specific index levels. For the most severe drought conditions the maps suggest the highest risk of impact occurrence for 'Water Quality' in Maritime Europe, followed by 'Agriculture & Livestock Farming' in Western Mediterranean Europe and 'Energy & Industry' in Maritime Europe. Merely impacts on 'Public Water Supply' result in overall lower risk estimates. The work suggests that modeling and mapping for North- and Southeastern Europe requires further enhancement to the impact database in these regions. Such maps may become an essential component of drought risk management to foster resilience for this hazard at large scale.

Introduction

Drought is a natural hazard known to be very difficult to grasp and its general characteristics, creeping onset, long lasting duration, large spatial extent and cross-boundary effects have hindered scientists and practitioners to precisely define the hazard (Wilhite *et al* 2007, EEA 2009). Independent of its definition, drought can cause a variety of direct and indirect, negative (and sometimes positive) impacts. Even though the majority of drought impact research and public recognition focuses on the agricultural sector, drought has more damage potential. Its multifaceted character affects a variety of environmental and socio-economic systems that can be classified into a number of different categories (Stahl *et al* 2012).

For the last three decades, the European Commission estimated that drought has caused over 100

billion Euros of losses to the European Union members (EC 2007b), has covered about 37% of Europe's surface, and has affected more than 100 million inhabitants (Kossida *et al* 2012). Despite some controversy over global drought trends (Dai 2012, Sheffield *et al* 2012) there is medium confidence that Southern Europe has experienced more intense and longer droughts (IPCC 2012). Furthermore, there is medium confidence that drought will intensify for the Mediterranean and Central European region due to climate change (IPCC 2012). Hence, increasing resilience to this hazard through an appropriate drought risk assessment at different scales is a valid concern and important to address. In Europe, an assessment at the pan-European scale, i.e. to support EU level policy development and cross boundary communication is still pending.

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 and for Europe the standardized precipitation and evapotranspiration index (SPEI) (Vicente-Serrano *et al* 2010a) has become popular in recent years (Potop 2011, López-Moreno *et al* 2013, Spinoni *et al* 2013). But, even though more than 100 drought indicators are known (Zargar *et al* 2011) and have been compared in a number of studies, clear guidance on their usage is still lacking. One reason for this is that most indices describe general anomalies of meteorological conditions, but only few drought indices were developed with or have been tested against observed drought impact data. Vulnerability to drought is typically estimated by a combination of relevant, subjectively weighted vulnerability factors (Kumar 2008, Jordaan 2012, Fu *et al* 2013, Sreedhar *et al* 2013). This approach requires explicit but difficult to obtain information on physical, ecological and socioeconomic parameters. Although drought impacts are symptoms of vulnerability (Knutson *et al* 1998), the majority of current approaches do not consider past drought impact reports to estimate vulnerability, and only a few studies have validated their approaches using historical drought impact observations (Aggett 2012, Naumann *et al* 2013, Karavitis *et al* 2014).

The presented work takes advantage of a new database of reported drought impacts in Europe to derive a first-order estimate of pan-European drought risk. The employed approach estimates the regional likelihood of drought impact occurrence (LIO) as a function of a drought index using a statistical model. The objective of the effort is to provide insights to sector specific differences in drought risk on a pan-European scale. As mapping is the appropriate method to communicate complex spatial and temporal information (WHO 2014), the study focused on an approach that allows mapping the LIO specific hazard levels.

Data and methods

Spatial domain and resolution

Historical drought impacts are commonly reported for local administrative entities. However, all European countries are heterogeneous in their administrative units regarding spatial extent and size. To overcome this challenge, the European Union has created a standardized hierarchical geocode that refers to country-specific administration units, the Nomenclature of Units for Territorial Statistics (NUTS) (European Commission 2005). Non-physical data in Europe is mostly referenced to these NUTS regions at three different levels (NUTS-1 to NUTS-3). However, even these NUTS-regions are spatially not comparable in size. Hence, for this study we composed spatial units ('NUTS-combo level', supplements 1, figure S1) as a combination of NUTS level polygons in different countries that approximately match a reference size of

Belgium as an optimal tradeoff between spatial resolution and coverage. Further, to account for the large climatic differences in the region under investigation, we used a classification that divides Europe into climatologically comparable macro regions (figure 2, left) adapted from the European and Mediterranean Plant Protection Organization (Bouma 2005). For our purposes we associated the Eastern Mediterranean countries to Southeastern Europe due the spatial extents of major droughts events in the past.

Drought impact reports

Reports on drought impacts in Europe are numerous and available in various sources and formats. Within the EU FP-7 project Drought R&SPI (eu-drought.org) a unique standardized and categorized collection of drought impact reports was archived in the European Drought Impact Report Inventory (EDII) (Stahl *et al* 2012). An impact is hereby defined as a negative consequence of drought for environment, society or economy. Reports on drought impacts are spatially referenced either to their respective NUTS region or to locations such as rivers and lakes. Reports with only vague locational information are assigned to the next higher administrative level to ensure correct reference. Due to this generalization impacts may appear to cover a larger area than they actually did. As a temporal orientation, entries have a date stamp in form of either an exact date, a season or the year of occurrence. All impact reports are categorized into one of fifteen impact categories (sectors) and into a more detailed specification of impact types. Full documentations and the data themselves are accessible at <http://www.geo.uio.no/edc/droughtdb/>.

While the database continues to grow, this study used the content of July 2014, at which time the EDII database contained over 2500 reported drought impacts. As a compromise between data availability and currentness of data, the period of 1970–2012 was selected. For this time frame 1509 reported drought impacts were registered in the EDII database for the NUTS-combo regions that comprise Maritime Europe: 56 were available for Northeast Europe, 464 for Southeast Europe and 347 for Western-Mediterranean Europe. 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 (Stahl *et al* 2012, Stagge *et al* 2013).

Impact reports in four sectors (referenced as 'impact category' within the EDII database) with a sufficient sample size in terms of quantity and spatial and temporal distribution were selected for analysis in this study. These sectors are: (1) 'Agriculture & Livestock Farming', (2) 'Energy & Industry', (3) 'Public Water Supply' and (4) 'Water Quality'. Entries in these

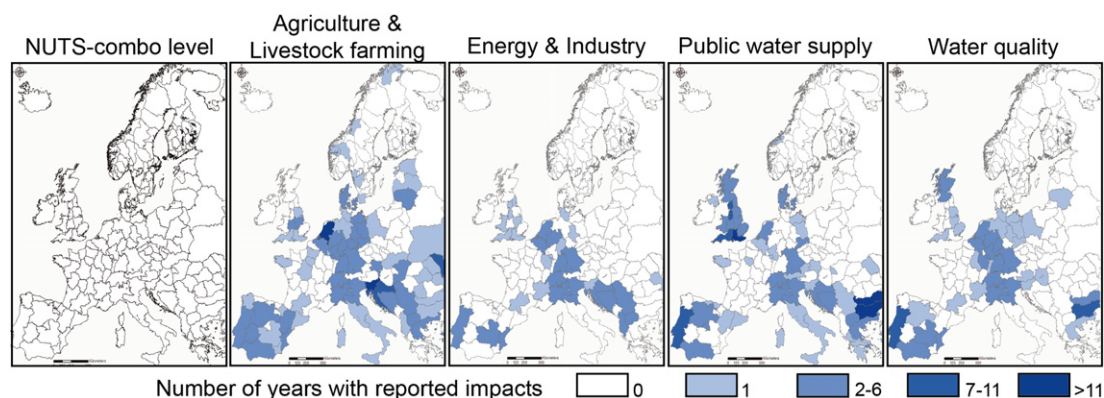


Figure 1. NUTS-combo level map (left) and spatial distribution of the number of years with drought impact reports for the period of 1970–2012 for four selected impact categories.

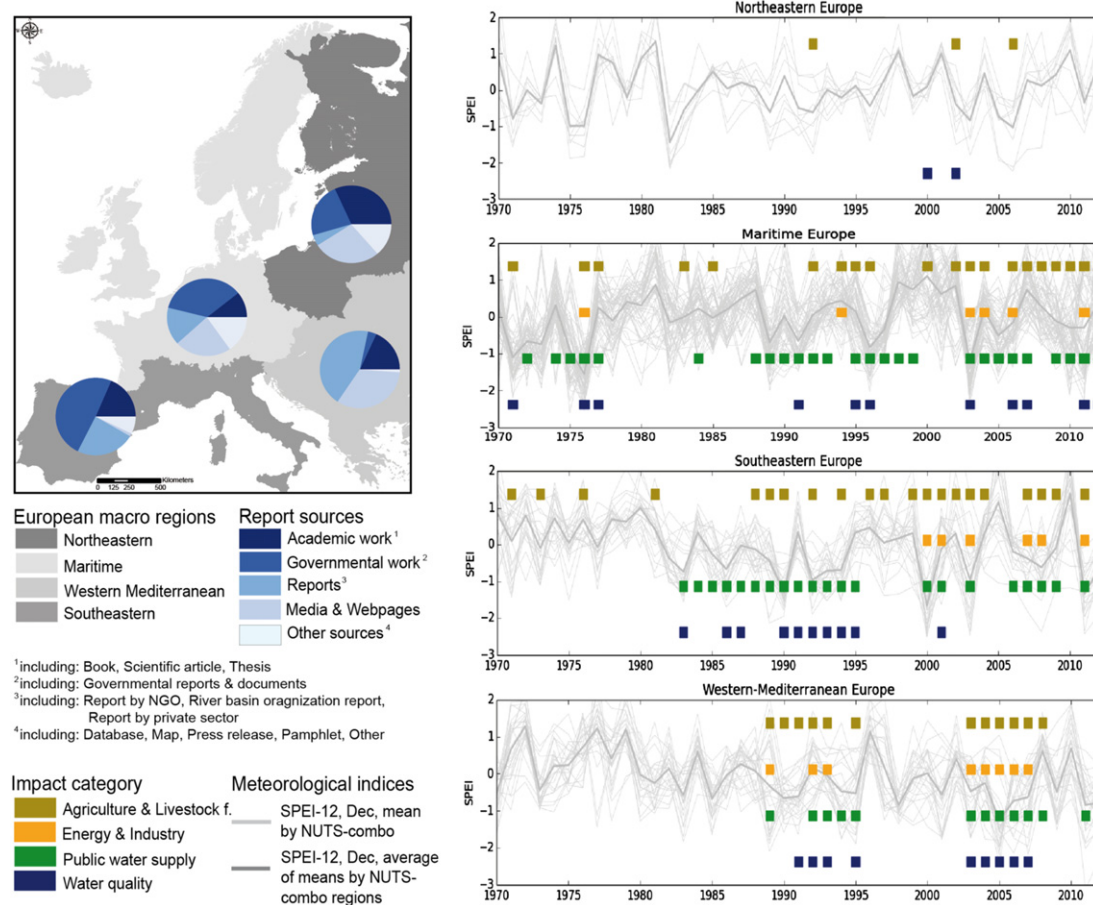


Figure 2. Left: European macro regions with distribution of information sources of drought impact reports, right: time series for each macro regions with years with one or more reported impacts and drought hazard index SPEI by NUTS-combo region (thin line) and macro-region average (bold line).

categories were first re-assigned from their original reporting level to the ‘NUTS-combo level’ (figure 1). While Scandinavia, France and Northeastern Europe have only few entries, Central Europe, Southern and Western Iberia, and the Balkan- regions have many entries in these chosen categories. The category ‘Agriculture & Livestock Farming’ has the highest pan-

European coverage. Impacts on ‘Energy & Industry’ are least represented and mainly available in Central Europe, Southeast Europe and the Iberian Peninsula. Entries on ‘Public Water Supply’ are stronger represented and additionally cover Britain and Southeast Europe with a maximum of reported occurrence in Southern England and Bulgaria. The distribution of

entries for ‘Water Quality’ again are mainly from Central Europe, the Iberian Peninsula and the south-eastern Balkan.

To develop a suitable regional statistical sample for each of the four European macro-regions: North-eastern, Maritime, Western Mediterranean, and Southwestern Europe (figure 2, left), several possibilities were considered: number of reports per year, classified severity of impacts, or occurrence of one or more impact. The former two were biased to reporting differences across Europe (Stahl *et al* 2012). Therefore, 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 time series of impact occurrence for each macro-region and sector. ‘Agriculture & Livestock Farming’ and ‘Public Water Supply’ are also the categories with the most impacted years. Northeast Europe has overall only few entries. The Western-Mediterranean region has entries for two distinct events, the ‘1991–95’ and ‘2004–7’ drought, with all impact categories represented equally. Maritime and Southeast Europe have their entries on drought impacts more distributed over several drought events. ‘Agriculture & Livestock Farming’ and ‘Public Water Supply’ show almost identical pattern of occurrence and spread over the entire period of investigation. For Maritime Europe, ‘Energy & Industry’ and ‘Water Quality’ have less entries, but are distributed equally over time. This differs for Southeast Europe, where impacts for ‘Water Quality’ only are reported from 1983 to 2001, while for ‘Energy & Industry’ entries are reported from 2001 to 2012. Figure 2 also shows that the report sources are generally diverse in all regions, but differ somewhat in the proportions: whereas Maritime Europe, Northeastern Europe and the Western Mediterranean are dominated by academic and governmental work, more drought impact reports in Southeastern Europe stem from non-governmental reports and the media (newspapers, world wide web).

The SPEI

For this study the SPEI (Vicente-Serrano *et al* 2010a) was selected as drought hazard indicator. As an evolution of the well-established standardized precipitation index (SPI) (McKee *et al* 1993) the SPEI was developed to not only account for water input through precipitation, but also for water losses through evaporation. In contrast to SPI, which has a limited interpretability in dry regions (Wu *et al* 2007), SPEI was specifically developed for the semi-arid

environments in Southern Europe (Beguería *et al* 2010, Vicente-Serrano *et al* 2010a, 2010b). SPEI has been shown empirically to be a better suited predictor for a number of environmental variables than SPI, including river flow (Lorenzo-Lacruz *et al* 2010, López-Moreno *et al* 2013). SPEI can be derived from widely available meteorological observations and has been used for drought quantification in the recent literature (Beguería *et al* 2010, Lorenzo-Lacruz *et al* 2010, Wang *et al* 2014). For this study SPEI was 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 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 distribution for standardization (Stagge *et al* in revision a).

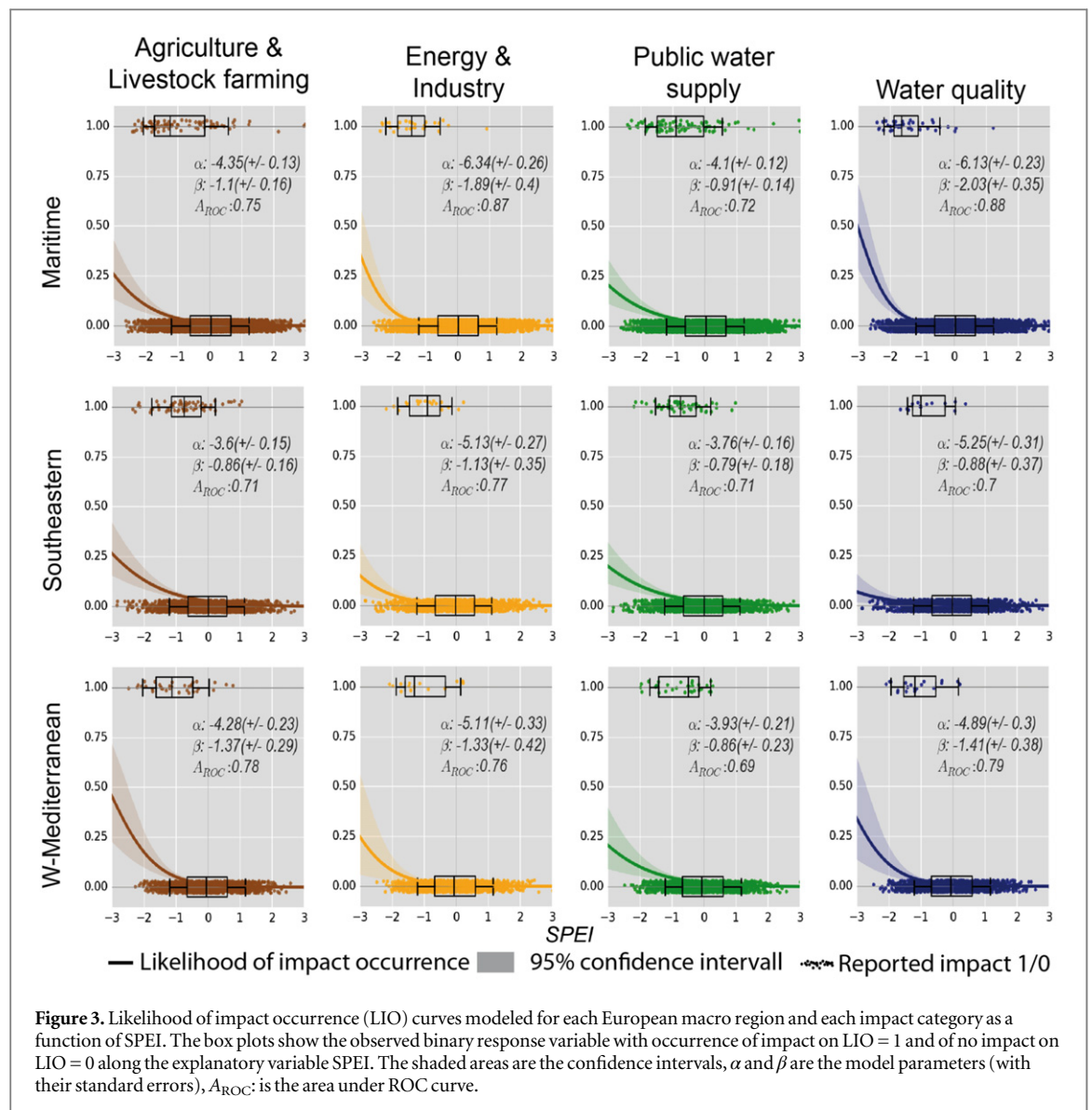
To adapt to the annual resolution of the impact data, the SPEI was calculated for a time scale of twelve months for the month of December for each year from 1970 to 2012 for all grid cells. Then, the mean SPEI-12_{Dec} value of all grid cells within each NUTS-combo region was extracted. The resulting annual drought indicator, the regional mean of SPEI-12_{Dec} will be referred to as ‘SPEI’ throughout this article. Figure 2 shows the time series of this SPEI for all NUTS-combo regions within each of the macro-regions. The variability of the NUTS-combo SPEI values within each macro region can be high (figure 2).

Modeling the likelihood of drought impact occurrence

The aim of this study is to provide quantitative insights into the relation between observed drought impacts and the SPEI. To this end, we follow the approach of previous assessments (Gudmundsson *et al* 2014, Stagge *et al* in revision b), which related drought impact occurrence to drought indicators using binary logistic regression. Logistic regression predicts the likelihood of drought impact occurrence, LIO as

$$\log\left(\frac{\text{LIO}}{1 - \text{LIO}}\right) = \alpha + \beta \cdot \text{SPEI},$$

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 (Harrel 2001, Venables and Ripley 2002, Zuur *et al* 2009). The LIO is hence a measure for the probability of drought impact occurrence, which is dependent on the drought hazard indicator (here SPEI). With this probabilistic model, the occurrence of drought impacts cannot not directly be predicted as ‘impact’ or ‘no impact’, but, the likelihood of drought impact occurrence gives estimates in a range from zero



(0% probability of impact occurrence) to one (100% probability of impact occurrence).

In this study we sampled pairs of the binary response variable (i.e. the drought impact occurrence series) and the SPEI values of all NUTS-combo regions and pooled them into one sample for each macro-region (omitting NUTS-combo regions without any reported impact in the category). Due to the data sampling strategy, as well as the fact that droughts are by definition rare events the number of impact occurrences compared to the number of no-impact occurrences is generally low. However, in most cases, the distributions of impact and no impact occurrence along the predictor variable SPEI are fairly well separated (figure 3, box plots). The logistic regression models were then fitted for each region and each impact category. Only models for which to SPEI was found to be a significant predictor ($p_\beta < 0.01$) were retained for further analysis and application to predict and map the LIO for selected SPEI values.

Following a previous study (Gudmundsson *et al* 2014) model performance was also assessed using the area under the ROCs (receiver operating characteristics) curve, A_{ROC} , which allows to quantify the skill of probabilistic models (Mason and Graham 2002, Wilks 2011). Any $A_{ROC} > 0.5$ indicates that decisions of the resulting model will be on average superior to random guessing and $A_{ROC} = 1.0$ indicates a perfect model (see supplement 2, figure S2 for more detailed information).

Results

For Northeast Europe, the lack of sufficient data prevented robust model identification and therefore had to be excluded from further analysis. For all other macro regions and impact categories the SPEI was found to be a significant predictor and models could be fitted with low standard errors for both coefficients (figure 3). All final model confidence intervals show

similar patterns: the uncertainty increases with increasing LIO.

For impacts on ‘Agriculture & Livestock Farming’ the model for Southeast Europe shows the lowest A_{ROC} (0.71) while the models for Maritime Europe and Western-Mediterranean have higher A_{ROC} (0.75 and 0.78). The LIO curves of Southeastern- and Maritime Europe have rather similar coefficients and hence similar shapes; the LIO curve for Western-Mediterranean has a stronger response to SPEI (higher β coefficient) and shows a pronounced increase of the LIO around $SPEI = -1$. For Maritime and Southeast Europe, LIOs of the models for ‘Energy & Industry’ result in higher A_{ROC} values (0.87 and 0.77) than for ‘Agriculture & Livestock Farming’ while A_{ROC} for the Western-Mediterranean model is slightly lower (0.76). The LIO for Southeastern Europe has the least pronounced response to SPEI (lowest β coefficient) whereas the LIO for Maritime Europe rapidly increases from an SPEI of -1.5 on. Comparable A_{ROC} (0.69–0.73) for each macro region were found for the models of impact category ‘Public Water Supply’. Here, all models have rather similar shapes with a comparably low β and hence small increases of LIO with decreasing SPEI. For ‘Water Quality’ the models are more different. With A_{ROC} of 0.88 and 0.79 the models for Maritime and Western-Mediterranean Europe resulted in the highest model performance. Maritime Europe shows a strong increase in LIO from an SPEI of -1.5 on resulting in the highest LIO (0.49) for all models at $SPEI = -3$. The model for ‘Water Quality’ for Southeast Europe has a smaller A_{ROC} (0.7). Compared to the other regions, its LIO curve has a negative shift with a low increase starting around $SPEI = -1.5$.

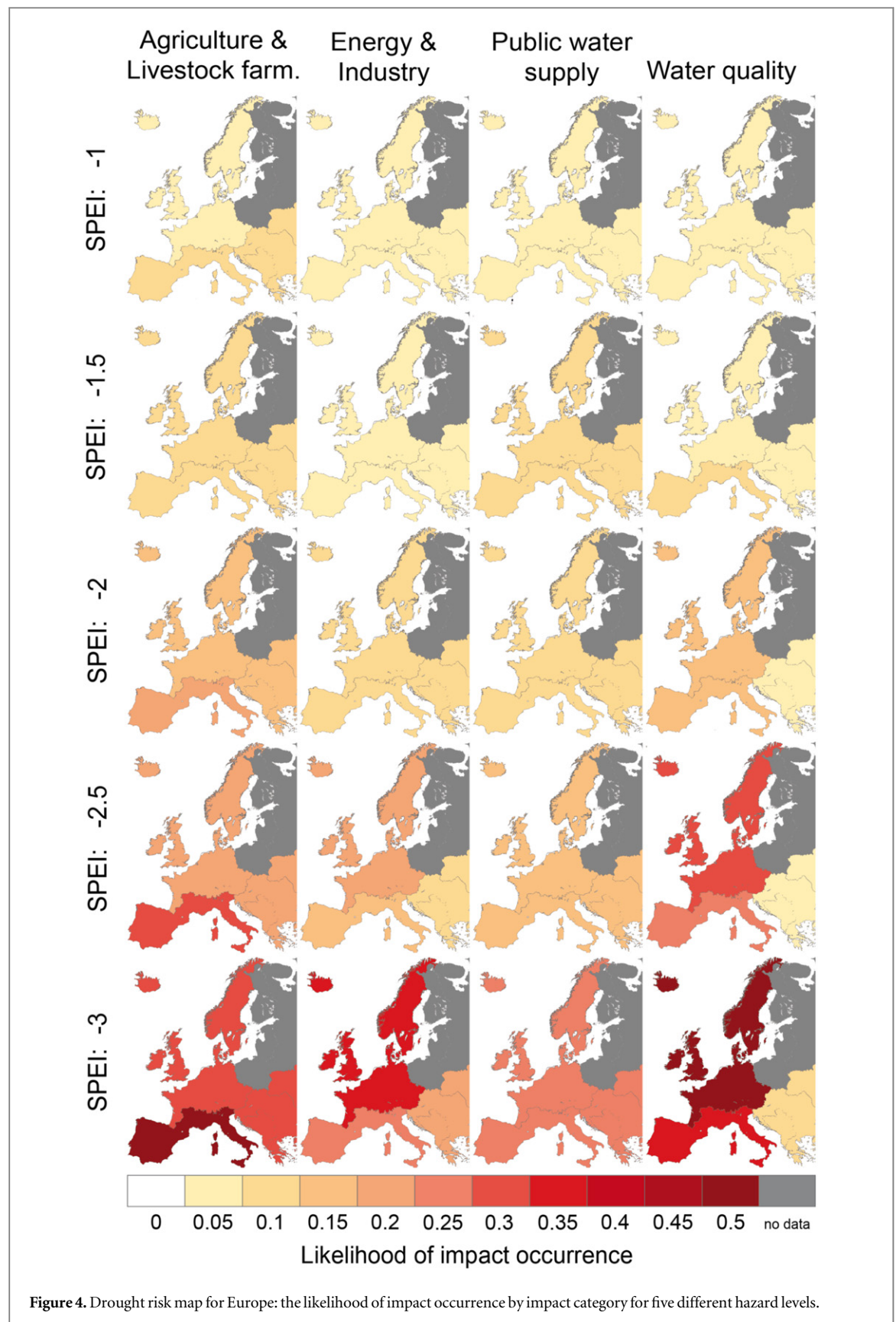
The maps in figure 4 project selected points of the modeled LIO curves in figure 3 onto maps to facilitate regional comparisons. The spatial visualization shows the resulting LIO, which we interpret as a drought risk for each impact category and for five different drought hazard levels ($SPEI = -1, -1.5, -2, -2.5$ and -3). While the LIOs for all impact categories and macro regions are low for $SPEI = -1$, they then increase differently with hazard intensification, although only barely for -1.5 . For all impact categories the risk maps show regional differences mainly for the most severe hazard conditions. The application of the models for ‘Agriculture & Livestock Farming’ and ‘Water Quality’ in general result in the highest risks for a given hazard level, followed by ‘Energy & Industry’, and finally ‘Public Water Supply’. For ‘Agriculture and Livestock Farming’, the risk of drought impacts is highest in Western Mediterranean Europe, reaching a likelihood of 46%, whereas Maritime and Southeast Europe have lower LIOs. In contrast to that, the highest risk for impacts on the sector of ‘Energy & Industry’ is predicted for Maritime Europe (34%); the lowest risk for southeastern Europe (15%). No regional differences in drought risk could be identified for ‘Public Water

Supply’; all models predict comparably low LIO ($\sim 20\%$) under most severe hazard conditions. The impact category of ‘Water Quality’ shows the overall highest and most diverse risk of impact occurrence during drought. For the most severe SPEI condition, for Maritime Europe a LIO of $\sim 50\%$ was modeled, while for the Western Mediterranean a LIO of 34% and for Southeast Europe an even lower risk was modeled.

Discussion

The database on reported drought impacts tapped for this study is a new information source. So far it covers only a fraction of the NUTS-combo regions and years as some countries have not yet been covered well by the overall search for impact reports. In the derived binary variable of impact occurrence, no impact can have two reasons: 1st there was no impact and 2nd no report was found due to sampling focus or local reporting traditions. In addition, the content of the EDII is also somewhat biased in space and time with an overall increasing trend in the number of reports for more recent events. Such biases will reduce as the database will grow. Despite these uncertainties and limitations, the logistic regression models used to predict the likelihood of impact occurrence as a function of SPEI were found to be significant for all four impact categories for three of the four macro regions. The identified models thus allow a quantitative assessment and visualization of regional differences in drought risk across Europe as desired e.g. by Kossida *et al* 2012.

‘Agriculture & Livestock Farming’ are most likely to be impacted by light to moderate drought already, which corresponds to the commonly assumed impact propagation from a meteorological drought to agricultural drought and later to hydrology and economy (Wilhite and Glantz 1985). Our models estimated the risk of impact occurrence in this sector to be highest in the Western Mediterranean region (figure 4). As the Western Mediterranean and Maritime regions are well covered by reported impacts we expect these result to be representative. The presence of drought risk all over Europe shows that drought is not only a Mediterranean problem (Kossida *et al* 2012) but also that the higher risk for the Mediterranean corresponds to previous assessments (EC 2007a, 2008). For the other two regions the results may be more biased to the few sub-regions for which reports were available. The chosen drought indicator, the SPEI-12, may also not be ideal for rainfed and irrigated agriculture alike. Stagge *et al* (in revision b) found shorter lag times to be relevant predictors for example for agricultural impacts in Slovenia. Overall, the result may also be influenced by timelier and more consistent impact reporting for the Agriculture and Water Supply sectors than for other sectors (e.g. Ding *et al* 2010). Impacts on agricultural production experience high public recognition and



tend to be well documented in the media, governmental reports and scientific research. Furthermore, the European Union pays compensation for losses greater than 30%, a serious reason for an early impact-reporting by affected farmers. Information sources of

the impact reports are mainly based on NGO-reports and media, with potentially higher uncertainty in the latter.

'Energy & Industry' are likely to be impacted only for more severe droughts. The highest risk for impacts

on this sector are detected for Maritime Europe which corresponds to the high water abstraction rates for energy production (EEA 2012a) for this macro region. Our models indicate that Southeast Europe has a generally lower likelihood for drought impacts. Rather than indicating a high resilience of this region this result may be influenced by the spatial and temporal distribution of data and droughts are of low relevance for the sector. EDII-data are mainly from the Western Balkan countries, and only start from the year 2000. Hence not all climatic characteristics and past impacts will be captured in the model.

In comparison to the other impact categories, 'Public Water Supply' was modeled to be at lowest risk for similar SPEI values with perhaps the most similar LIO estimates for the three macro regions for which data was available. The chosen twelve month timescale of the standardized drought indicator is likely a good indicator for water supply impacts (Amor *et al* 2009). As EDII data is distributed quite well over space and time the somewhat lower risk for all macro regions might reflect a generally high awareness and level of water resources planning and management.

Impacts on 'Water Quality' show a very different pattern. The category incorporates impacts on several sectors and details of impacts may hence differ regionally. Rather than a high vulnerability, the high risk for impacts on 'Water Quality' for Maritime Europe may instead reflect a more expanded water quality monitoring and controlling network for several sectors. Government reports were ample in these regions (figure 2). However, it may also reflect the commonly less than good ecological status of water bodies in Maritime-Europe (EEA 2012b). The very low risk for Southeastern Europe may also be caused by the reporting tradition and sources or by the same regional bias as for 'Energy & Industry', or alternatively by a lower relevance and awareness of water quality issues. In this region, the results would benefit from an improved impact database.

Some of the decisions for spatial and temporal sampling also affect the results. As the SPEI is a standardized variable, it normally corresponds to a drought with the same occurrence frequency everywhere. Hence the risk maps are a first step towards the kind of mapping as for example done to display the risk of damage for a 100 year flood. The use of the mean SPEI, the annual time scale and the pooling of the samples into regional models, however, limits the sharpness of the distinction between times with or without impacts and the corresponding drought hazard indicator. As data availability increases, the analyses could be repeated at smaller spatial units and higher temporal resolution. Stagge *et al* (in revision b) tested such modeling for a few countries in Europe with promising results and Gudmundsson *et al* 2014 tested a similar method for a drought impact with underlying quantitative data (area burned by wildfire).

Ideally, drought risk mapping should explain differences caused by different vulnerability and exposure to drought. To date most published approaches classify drought risk by a combination of a hazard- and a vulnerability index, where the latter is predominantly obtained as a combination of subjectively weighted vulnerability factors (Iglesias *et al* 2009, Jordaan 2012, Sreedhar *et al* 2013). Several approaches validate their results by past impacts (Aggett 2012, Naumann *et al* 2013, Karavitis *et al* 2014), but without directly statistically linking them to past impacts. Considering the terminology on Disaster Risk Reduction by UNISDR (2009); a hazard is a climatological phenomenon that causes impacts. But the question whether we can already talk about a drought risk if there is no related impact appears to be unresolved, particularly for the use of pre-categorization and fixed risk thresholds. This study defined drought by its impacts: if a system was impacted by a drought it was vulnerable to this drought. The proposed approach thus promotes a paradigm shift to using past drought impacts as a proxy for impact category specific vulnerabilities without the need of subjective weighting procedures.

Conclusion

In contrast to flood risk (e.g. Van Alphen *et al* 2009, Alfieri *et al* 2014), drought risk has not yet been assessed on a pan-European scale, mainly because quantitative information on vulnerability and damages is difficult to obtain. To bridge this gap, the presented study tested the potential of a data-driven approach for modeling the likelihood of drought impact occurrence, derived from the EDII database, as a function of a meteorological drought indicator across Europe. The resulting drought risk maps for impacts in four selected categories illustrate some differences among the European macro regions in the sensitivity to the annual drought hazard levels investigated.

For the most severe droughts in particular, it is shown that drought risk in Europe varies for different impact categories and regions. The highest risk of impact occurrence was detected for 'Water Quality' in Maritime Europe, followed by 'Agriculture & Livestock Farming' in Western Mediterranean Europe and 'Energy & Industry' for Maritime Europe. Merely impacts on 'Public Water Supply' result in overall lower risk estimates. These results suggest that drought risk should be analyzed sector specific.

Future work could improve the specificity of such drought risk maps by separating into climatically more homogeneous regions and by testing other drought hazard indicators, such as the ones used by the European Drought Observatory (<http://edo.jrc.ec.europa.eu/>) or identified in other studies to be relevant for monitoring purposes in different regions. Furthermore, the reported impact data within the EDII database is still biased in a number of ways, including

regionally varying sampling density and preference to some particular impact categories. The work proves, however, that there is potential in the use of impact reports towards the description of the risk of a complex natural hazard such as drought, for which vulnerabilities and damages are difficult to quantify otherwise. Drought risk maps may then become an essential component of drought risk management to foster resilience to this hazard at transboundary scales.

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References

- Aggett G 2012 Overview of the Colorado Drought Vulnerability by sector (Vienna: EGU)
- Alfieri L et al 2014 Advances in pan-European flood hazard mapping *Hydrol. Process.* **28** 4067–77 [Accessed December 2, 2014]
- Beguieria S, Vicente-Serrano S M and Angulo-Martínez M 2010 A multiscalar global drought dataset: the SPEIbase: a new gridded product for the analysis of drought variability and impacts *Bull. Am. Meteorol. Soc.* **91** 1351–6
- Bouma E 2005 Development of comparable agro-climatic zones for the international exchange of data on the efficacy and crop safety of plant protection products *Bull. OEPP/EPPO* **35** 233–8
- Dai A 2012 Increasing drought under global warming in observations and models *Nat. Clim. Change* **3** 52–8
- EC 2008 Drought management plan report—including agricultural, drought indicators and climate change aspects *Water Scarcity and Droughts Expert Network* Luxembourg
- EC 2007a *Mediterranean Water Scarcity and Drought Report, Technical Report—009-2007* Technical report on water scarcity and drought management in the Mediterranean and the Water Framework Directive. Available at: (www.emwis.net/topics/WaterScarcity/PDF/MedWSD_FINAL_Edition)
- EC 2007b *Water Scarcity and Droughts, In-Depth-Assessment, Second Interim Report* (Brussels: EC)
- EEA 2012a EEA- Data and maps. Available at: (www.eea.europa.eu/data-and-maps) [Accessed July 1, 2014]
- EEA 2009 *EEA Signals 2009 Key Environmental Issues Facing Europe* (Copenhagen: European Environment Agency) Available at: (www.eea.europa.eu/publications/signals-2009/at_download/file)
- EEA 2012b *European Waters—Assessment of Status and Pressures* (Copenhagen: European Environment Agency) pp 1–99
- European Commission 2005 *European Regional and Urban Statistics—Reference Guide* (Luxembourg: European Commission)
- Fu X, Svoboda M, Tang Z, Dai Z and Wu J 2013 An overview of US state drought plans: crisis or risk management? *Nat. Hazards* **69** 1607–27
- Gudmundsson L, Rego F C and Seneviratne S I 2014 Predicting above normal wildfire activity in southern Europe as a function of meteorological drought *Environ. Res. Lett.* **9** 084008
- Hargreaves G 1994 Defining and using reference evapotranspiration *J. Irrigation Drainage Eng.* **120** 1132–9
- Harrell J F E 2001 *Springer Series in Statistics*, New York
- Haylock M R et al 2008 A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006 *J. Geophys. Res.* **113** D20119 [Accessed May 25, 2014]
- Iglesias A, Cancelliere A, Wilhite D A, Garrote L and Cubillo F (ed) 2009 *Coping with Drought Risk in Agriculture and Water Supply Systems. Drought Management and Policy Development in the Mediterranean* (Springer Series Advances in Natural and Technological Hazards Research) (Dordrecht: Springer) pp 1–320
- IPCC 2007 *Climate Change 2007: Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Fourth Assessment Report of the IPCC Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press)
- IPCC 2012 Managing the risks of extreme events and disasters to advance climate change adaptation *A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press)
- Jordaan A J 2012 *Drought Risk Reduction in the Northern Cape* (South Africa Bloemfontein: University of the Free State Bloemfontein)
- Karavitis C A et al 2014 Uncorrected proof linking drought characteristics to impacts on a spatial and temporal scale *Water Policy* **16** 1–26
- Knutson C, Hayes M and Philipps T 1998 How to reduce drought risk (Lincoln, NE: National Drought Mitigation Center, University of Nebraska)
- Kossida M et al 2012 Vulnerability to water scarcity and drought in Europe *European Topic Centre on Inland, Coastal and Marine Waters (ETC/ICM)* Prague Available at: (http://icm.eionet.europa.eu/ETC_Reports/VulnerabilityToWaterScarcityAndDroughtInEurope)
- Kumar R 2008 Studies on assessment of vulnerability to drought. Available at: (www.editoria.u-tokyo.ac.jp/projects/awci/5th/file/pdf/091216_awci/4.3-3-2_CR_India2.pdf)
- López-Moreno J I et al 2013 Hydrological response to climate variability at different time scales: a study in the Ebro basin *J. Hydrol.* **477** 175–88 Available at: (<http://linkinghub.elsevier.com/retrieve/pii/S0022169412010074>) [Accessed November 20, 2014]
- Lorenzo-Lacruz J et al 2010 The impact of droughts and water management on various hydrological systems in the headwaters of the Tagus River (Central Spain) *J. Hydrol.* **386** 13–26
- Mason S J and Graham N E 2002 Areas beneath the relative operating characteristics (ROC) and relative operating levels (ROL) curves: statistical significance and interpretation *Q. J. R. Meteorol. Soc.* **128** 2145–66
- McKee T B, Doesken N J and Kleist J 1993 The relationship of drought frequency and duration to time scales *8th Conf. on Applied Climatology* 1
- Naumann G et al 2013 Exploring drought vulnerability in Africa: an indicator based analysis to inform early warning systems *Hydrol. Earth Syst. Sci. Discuss.* **10** 12217–54
- Potop V 2011 Evolution of drought severity and its impact on corn in the Republic of Moldova *Theor. Appl. Climatol.* **105** 469–83
- Sheffield J, Wood E F and Roderick M L 2012 Little change in global drought over the past 60 years *Nature* **491** 435–8 Available at: (www.ncbi.nlm.nih.gov/pubmed/23151587) [Accessed July 14, 2014]
- Spinoni J et al 2013 An overview of drought events in the Carpathian Region in 1961–2010 *Adv. Sci. Res.* **10** 21–32
- Sreedhar G, Nagarjan R and Balaji V 2013 Village-level drought vulnerability assessment using geographic information system (GIS) *Int. J. Adv. Res. Comput. Sci. Softw. Eng.* **3** 1–10
- Stagge J H, Tallaksen L M, Kohn I, Stahl K and Van Loon A 2013 A *European Drought Reference (EDR) Database: Design and Online Implementation. DROUGHT-R&SPI Technical Report No. 12* (www.eu-drought.org/technicalreports)

- Stagge J H *et al* 2014 Standardized precipitation-evapotranspiration index (SPEI): sensitivity to potential evapotranspiration model and parameters *Proc. of FRIEND-Water 2014 (IAHS Publ. 363, 2014) (Montpellier, France)*
- Stagge J H, Tallaksen L M, Gudmundsson L, Van Loon A F and Stahl K in revision a Candidate distribution for climatological drought indices (SPI and SPEI) *Int. J. Climatol.* (pending revisions)
- Stagge J H, Kohn I, Tallaksen L M and Stahl K in revision b Modeling drought impact occurrence based on climatological drought indices for Europe *J. Hydrol.* (in review, acceptance pending revisions)
- Stahl K *et al* 2012 *A European Drought Impact Report Inventory (EDII): Design and Test for Selected Recent Droughts in Europe* (Freiburg: Drought R&SPI.) Available at: (www.eu-drought.org/technicalreports/3)
- Van Alphen J *et al* 2009 Flood risk mapping in Europe, experiences and best practices *J. Flood Risk Manage.* **2** 285–92
- Venables W N and Ripley B 2002 *Modern Applied Statistics with S* (Berlin: Springer)
- Vicente-Serrano S M *et al* 2010a A new global 0.5° gridded dataset (1901–2006) of a multiscalar drought index: comparison with current drought index datasets based on the palmer drought severity index *J. Hydrometeorology* **11** 1033–43
- Vicente-Serrano S M, Beguería S and López-Moreno J I 2010b A multi-scalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index–SPEI *J. Clim.* **23** 1696–718
- Wang Q, Wu J, Lei T, He B, Wu Z, Liu M and Liu D 2014 Temporal-spatial characteristics of severe drought events and their impact on agriculture on a global scale *Quaternary Int.* **349** 10–21
- WHO 2014 Maps and spatial information technologies (Geographical Information Systems) in health and environment decision-making. Available at: (www.who.int/heli/tools/maps/en/)
- Wilhite D A and Glantz M H 1985 Understanding: the drought phenomenon: the role of definitions *Water Int.* **10** 111–20
- Wilhite D A, Svoboda M D and Hayes M J 2007 Understanding the complex impacts of drought: a key to enhancing drought mitigation and preparedness *Water Resour. Manage.* **21** 763–74
- Wilks D S 2011 *Statistical Methods in the Atmospheric Sciences (International Geophysics Series)* 3rd edn vol 100 (New York: Academic)
- Zargar A *et al* 2011 A review of drought indices *Environ. Rev.* **19** 333–49
- Zuur E *et al* 2009 *Mixed Effects Models and Extensions in Ecology With R Statistics for Biology and Health* (New York: Springer)