Intersectoral vulnerability indices as tools for framing risk mitigation measures and spatial planning

MARION DAMM[1]**, ALEXANDER FEKETE**[2]**, JANOS J. BOGARDI**[3]

1 *Bavarian State Ministry of the Environment and Public Health (StMUG), Rosenkavalierplatz 2, 81925 München, Germany*
marion.damm@stmug.bayern.de

2 *Federal Office for Civil Protection and Disaster Assistance (BBK) Provinzialstraße 93, 53127 Bonn, Germany*
alexander.fekete@bkk.bund.de

3 *GWSP, International Project Office, Walter-Flex-Str. 3, 53113 Bonn, Germany*
jbogardi@uni-bonn.de

Abstract Integrated Risk Management demands for interdisciplinary and cross-cutting solutions. Risk mitigation of flood-related hazards needs an overview on existing hazards but also on vulnerabilities. Precise mitigation and adaptation areas of intervention and actions can only be framed based on an integrative assessment of flood-hazard parameters and vulnerability aspects of society and the environment. The contribution to the development of risk mitigation measures lies in the quantitative assessment of social and ecological vulnerability. Vulnerability indices to river floods have been derived along large rivers in Germany using census and spatial data, statistical analyses and GIS. The vulnerability index maps provide an overview on large regions, useful for intersectoral planning, for example spatial planning or civil protection. The social vulnerability index highlights regions which may potentially experience higher losses of human lives, health impacts as being characterised by lack of resources for risk preparedness and recovery, but also by demands on evacuation shelters. The index of social-ecological vulnerability depicts regions that may potentially be negatively affected by floods in terms of their ecosystem service ability. Vulnerability indices have been derived for the two sectors forest and agriculture that are traditionally not within the risk assessment portfolio and may contribute to a more comprehensive disaster risk management.The deduction of relevant sub-indicators and indices was based on statistical methods but also semi-structured expert interviews were used to select the significant indicators. The assessment of social and socio-ecological vulnerabilities followed two different conceptual vulnerability models. This work proves the feasibility of both to serve as basis for semi-quantitative pre-event assessment of vulnerabilities.
Keywords river flooding, vulnerability, risk management, prediction of potential damage

INTRODUCTION

The purpose of this paper is to introduce two approaches to estimate river flood related vulnerabilities of the social and ecological sectors (forestry and agriculture) before the occurrence of floods.

The social vulnerability index highlights regions which may potentially experience higher losses and need more assistance. The index of social-ecological vulnerability depicts regions that may be affected by floods in terms of their ecosystem service ability. The vulnerability index maps provide an overview on national scale with district (county) level resolution. They are useful for intersectoral planning, for example spatial planning or civil protection.

Two methods are presented here to illustrate the manifold directions the emerging vulnerability research may follow. The present paper is based on two recent PhD dissertations where the details of the concepts are elaborated, the approaches conceived and tested. Critical evaluation of the techniques applied as well as the analysis of available data can also be found there.

The derived disaster information system is a web-GIS, developed in collaboration with the Natural Disasters Network NaDiNe. While addressing, specially risk researchers and risk managers, the information is available for the public (Damm, 2010 and Fekete, 2010).

The research leading to the results presented here has been carried out in the interdisciplinary project DISFLOOD developed a Disaster Information System for Large-Scale Flood Events Using Remote Sensing as a joint project of the United Nations University Institute for Environment and Human Security (UNU-EHS), the German Aerospace Centre (DLR) and the GeoResearchCentre (GFZ) in Potsdam.

THE CONCEPT OF VULNERABILITY

Floods are among the most devastating water-related hazard events. While the phenomenon of a flooding river could be classified as a spectacular natural event, the consequences of floods, once they affect people, their settlements, infrastructure, industries and farmlands could turn into genuine disasters. The hazard of the occurrence of a flood is closely associated with the risk of a flood, the expected (multidimensional) losses people and their assets may suffer as a consequence of inundations.

Statistical and trend analyses of floods are not conclusive to prove a significant and universal increase of flood frequencies and magnitudes due to climate change. (Bogardi, 2009).Yet flood losses, like other disaster losses show a significant and steady increase during the last couple of decades (Munich Re, 2004). Consequently there must be additional factor(s) responsible for this discrepancy shown by the trends.

Intensive use of flood prone areas, accumulating wealth, building infrastructures along rivers, but also the lack of knowledge and experience with extreme floods and changes in the social, economic and environmental fabric contribute to the increase of vulnerability of those potentially affected. Vulnerability in the broadest sense is defined as the predisposition to be hurt (UN/ISDR, 2004). Flood risks are defined as the "product" of hazard and vulnerability whereby vulnerability is the least known component of an equation which may express risk *(R)* as a function of the hazard *(H)* and vulnerability *(V)*:

$$R=f(H,V) \tag{1}$$

Thus forecasting the hazard (flood flows, flood levels and flood durations) may not tell the whole story about flood risk, which actually matters more than the natural phenomenon itself. Hence forecasting risk must imply the prediction (or at least an estimate prior to the occurrence of flood) of vulnerability *(V)*.

On its own turn vulnerability is a multidimensional, multiattribute feature. It is usually characterized by its social, economic, environmental, physical (infrastructure) and institutional dimensions. Beyond these main dimensions vulnerability could be captured with a few more attributes. It implies the inherent question "vulnerable to what?", hence without being exposed to this particular "what" – a hazard – people may not seem to be vulnerable. However there is an internal core of vulnerability which does exist and matter irrespective whether the individual or subject is exposed to a hazard or not. This inherent pre-disposition to be hurt is suggested to be defined as a hazard-independent susceptibility. Obviously this could and should also be measured in different dimensions. For example common sense dictates to consider an old and illiterate person as more susceptible than a young educated one even if none of them is exposed to a hazard. Their susceptibility may turn into hazard specific vulnerability once they were exposed to it (like living in a floodplain). Thus vulnerability *(V)* is the function of susceptibility *(S)* and exposure *(E):*

$$V=g(S,E) \tag{2}$$

Vulnerabilities can fortunately be mitigated through certain capacities *(C)* people might have acquired and might deploy prior, during or after the occurrence of a hazard event. These capacities are different from those mitigating the hazard like reservoirs, dikes, flood relief channels etc. They can directly offset vulnerabilities like knowledge of the hazard, savings, insurance or applying solid building codes for houses. Hence the vulnerability which remains to contribute to risk would be:

$$V=h((S,E)-C) \tag{3}$$

where *(C)* represents the capacities to resist, to respond, to bounce back and to adapt. It includes also coping or even the ability to suffer or to absorb harm in any other way.

Given the multitude of their dimensions and their nature as a potential inclination to be hurt, vulnerabilities can only be approximated prior their manifestation during a disaster with the help of proxy variables. As a tool for planning or flood risk forecasting, vulnerability estimates should refer to administrative entities rather than capturing individual features. For this purpose the district scale has been identified as the most appropriate compromise between spatial precision and policy relevant information.

The susceptibility assessment covers whole Germany (well over 400 districts). Flood related vulnerabilities are estimated and shown along the Rhine and Elbe rivers.

INDICATORS AND INDICES: A WORD OF CAUTION TOWARDS A POLICY RELEVANT ASSESSMENT OF VULNERABILITIES

Analyzing complex systems and their properties involves reducing complexity to a degree that we can understand. Simplification is an accepted part of the scientific research process and is associated with choices about how much to simplify and how to do it without misrepresenting reality. Thus, indicators and indices are useful for encapsulating a complex reality in simple terms and permitting comparisons across space and/or time. However there is a danger that indicators may not accurately represent the intended condition or process.

Aggregating indicators creates even more opportunities for subjectivity and thus must be even more critically appraised. By their very nature, the role of indicators is to capture an intangible process so it is not possible to “ground truth” them. Hence, alternative means of validation must be sought. The index as an aggregate measure of several indicators is contingent upon the choice of indicators. There is a real possibility that uninformed choices could filter through and can lead to an invalid index.

A critical evaluation of the limitations of indices is even more imperative given the fact that they link science and policy. By summarizing and simplifying reality they are inherently useful to policy-makers, but the absolute certainties required are often incompatible with the uncertainties of science.

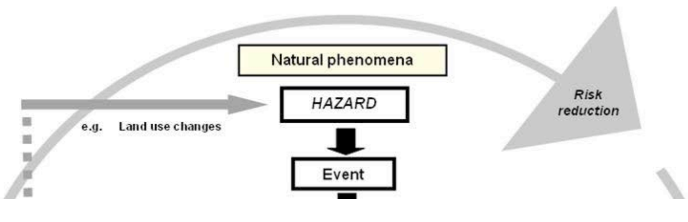
Apart from the named limitations of indicators and indices there is, of course, a variety of advantages that can be mentioned in this context. Indicators enable to simplify the very complex concept of vulnerability; they facilitate the task of mapping and comparing vulnerability across regions; they facilitate communication between profession, public and politics; and they help to assess any progress achieved. More information about pros and cons of composite indicators can be found in Nardo et al. (2005).

Adger et al. (2004) identify two different procedures for indicator selection, the deductive approach and the inductive approach. The deductive approach involves proposing relationships derived from theory or conceptual framework and selecting indicators on the basis of these relationships. When conducting a deductive approach it is important to first create an understanding of the investigated phenomenon and the processes involved, second to identify the main processes to be included in the study, and third to select the best possible indicators for these factors and processes. Inductive approaches involve statistical procedures to relate a large number of variables to vulnerability in order to identify the factors that are statistically significant. Hence, potentially relevant indicators are incorporated in a certain statistical model and indicators are selected on the basis of significant statistical relationships. Expert judgment or/and principal component analysis are common methods to select the final indicators.

Within the DISFLOOD project both techniques were tested. The social-ecological vulnerability (using the so called "Turner Model" (Turner et al, 2003) was assessed by indicators defined by the deductive approach, while the social and infrastructure vulnerability index based on the BBC Model (Birkmann, 2006) was the result of an inductive procedure.

THE BBC MODEL AND ITS USE TO ESTIMATE SOCIAL VULNERABILITY

The BBC framework (Fig. 1) explicitly links vulnerability to the three spheres of sustainability; society, economy and environment. This framework is based on theoretical considerations, how social, economical and environmental dimensions of human security can be integrated with existing hazard and risk concepts. In the BBC framework, vulnerability is put into a chain starting from a natural phenomenon that can evolve to a hazard event and hits an exposed, susceptible population. This group may be equipped with certain capacities to encounter the hazard. Thus its vulnerability is reduced. Vulnerability and hazard together define risk. There are two entry points for risk mitigation: during the pending risk and after the hazard event has started to affect the people. The BBC framework is therefore especially useful to show the interconnections of hazard, vulnerability, and risk within the context of disaster risk management. The BBC framework puts the main analytical components of vulnerability into focus for an assessment. These three components, exposure, susceptibility and capacities, provide the main entry and structuring points for the development of vulnerability indicators. The social, environmental and economic spheres are closely related (see Fig. 1).



The social vulnerability assessment focuses on aspects of potential weaknesses and also capacities of the human population. This means that indicators for social vulnerability have to be selected to be relevant to a hazard context. For example, GDP cannot be taken as a general measure, only with a commented relation to river-flood related vulnerability. On the other hand, the BBC model shows the distinction of hazard analysis as being a different field from vulnerability analysis. The ‘social vulnerability’ component will be assessed by combining a Social Susceptibility Index, including a measure of capacities to reduce this susceptibility, with exposure information.

Fig.2 presents the Social Susceptibility Index for Germany. It is based on indicators capturing (personal) fragility, socioeconomic conditions and regional aspects. All data used here are available from the standard census data of the Federal Statistical Office of Germany. None of these variables seem to be related (directly) to floods, but all capture certain components of socially relevant susceptibilities which matter also in case of a flood. The results clearly indicate that forty years of separation and diverging development paths are still visible and determine to a great degree the different susceptibility and hence vulnerability of the population in the eastern and western part of the country. It is interesting to note that the Ruhr area, irrespective of its economic strength, is among the most susceptible parts of Germany.

Social Susceptibility Index (SSI) per county in Germany
Objective: identifies demographic patterns of susceptibility and capacities towards stresses like river-floods
Aggregation: the simple sum of three indicators: - Fragility - Socio-economic conditions - Regional conditions
Indicator fragility: ratio of elderly residents (>64 years)
Indicator socio-economic conditions: living space per person; (un)employment ratio; education type
Indicator regional conditions: population density; housing type
Data: census data of the Federal Statistical Office in Germany
Standardisation: ratios per county; equal intervals from 1,8 to -1,8

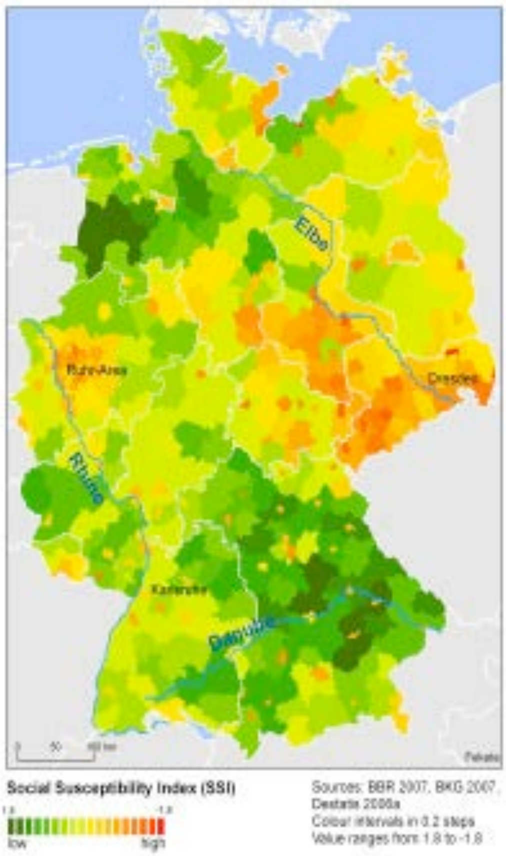


Fig. 2 Social Susceptibility Index (SSI) in Germany

Flood exposure is estimated for the riparian districts along the rivers Rhine and Elbe. The inundation maps prepared are based on the available statistics of floods of at least 200 years of recurrence period. Within a GIS framework the affected districts were classified according to the portion of the inundated area and respective population.

Fig. 3 shows for the Rhine and the non-tidal part of the Elbe rivers the respective degrees of exposures calculated as the percentage of flooded area per settlement area of each district.

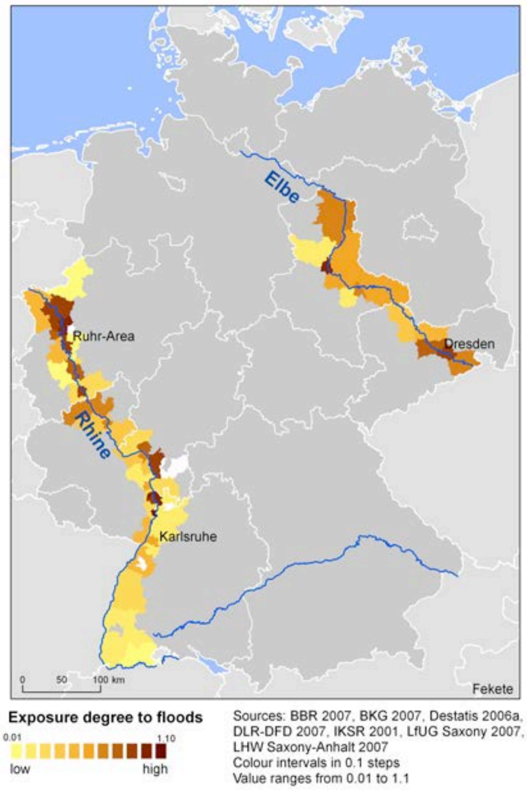


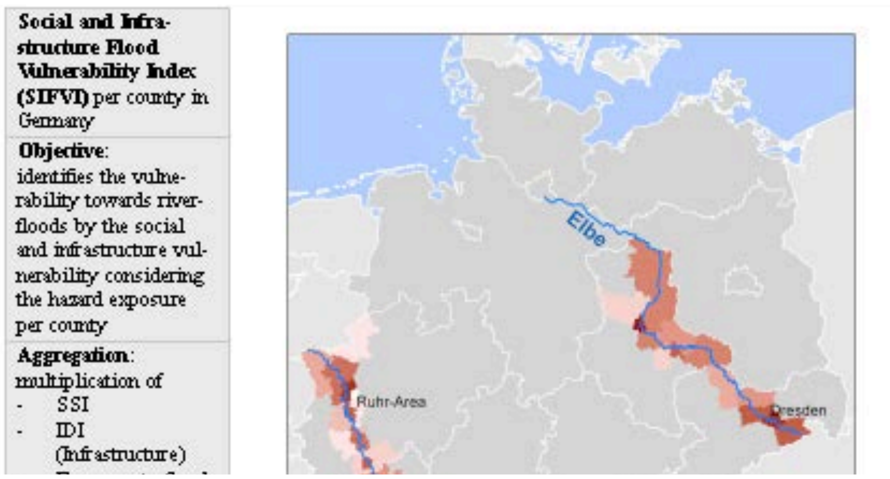
Fig. 3 Flood exposure of riparian districts along the rivers Rhine and Elbe

Social and Infrastructure Flood Vulnerability Index (see Fekete, 2010) is calculated for river floods by the simple formula:

SIFVI= f (social susceptibility index, exposed area of the district, infrastructure density in the district) (4)

Fig. 4 shows the social-infrastructure vulnerability index for the districts located along the two great rivers.

Flood risk and its distribution could be predicted by superposing the SIFVI map with statistical inundation scenarios (hazard forecasting). This risk assessment yields relative, comparable results enabling a ranking of the affected districts without determining the absolute value of risk. It indicates immediately those areas where risk mitigation interventions (from social and infrastructural points of views would be most needed and efficient.



THE "TURNER MODEL" OF VULNERABILITY AND ITS APPLICATION TO ASSESS SOCIAL-ECOLOGICAL VULNERABILITY FOR RIVER FLOODS

This vulnerability framework identifies the social-ecological system (SES) as subject of analysis. SESs are subject to influences that operate and interact spatially, functionally and temporally across a range of nested or overlapping scales and levels. Therefore, it is not sufficient to focus on dynamics and processes at the place of analysis, but to look at influencing factors and drivers beyond the place. The dynamic behavior of vulnerability in SES has to be indicated by integrating feedback loops and interlinkages between the system components.

The vulnerability framework which is used here is adapted from a framework published by Turner et al. (2003). However, some modifications have been made in order to adapt it to the conducted approach.

The conceptual framework (see Fig. 5) presents a systemic approach considering the social-ecological system as subject of analysis. It views vulnerability as related to a certain place constituted by several place-internal processes as well as cross-scale environmental and human influences. Vulnerability is composed of three main elements: exposure, susceptibility and capacities. Elements exposed to a hazard can be human-beings, assets, ecosystems etc. Susceptibility indicates the condition or rate of response of the SES with regard to all perturbations and stresses within the system. Capacities define the ability of a system to resist, cope and adapt to a certain hazard It is important to distinguish conceptually between internal perturbations that determine the current condition in SESs and thus the vulnerability at a particular place and time, and external perturbations that strike a system provoking disturbance and damage.

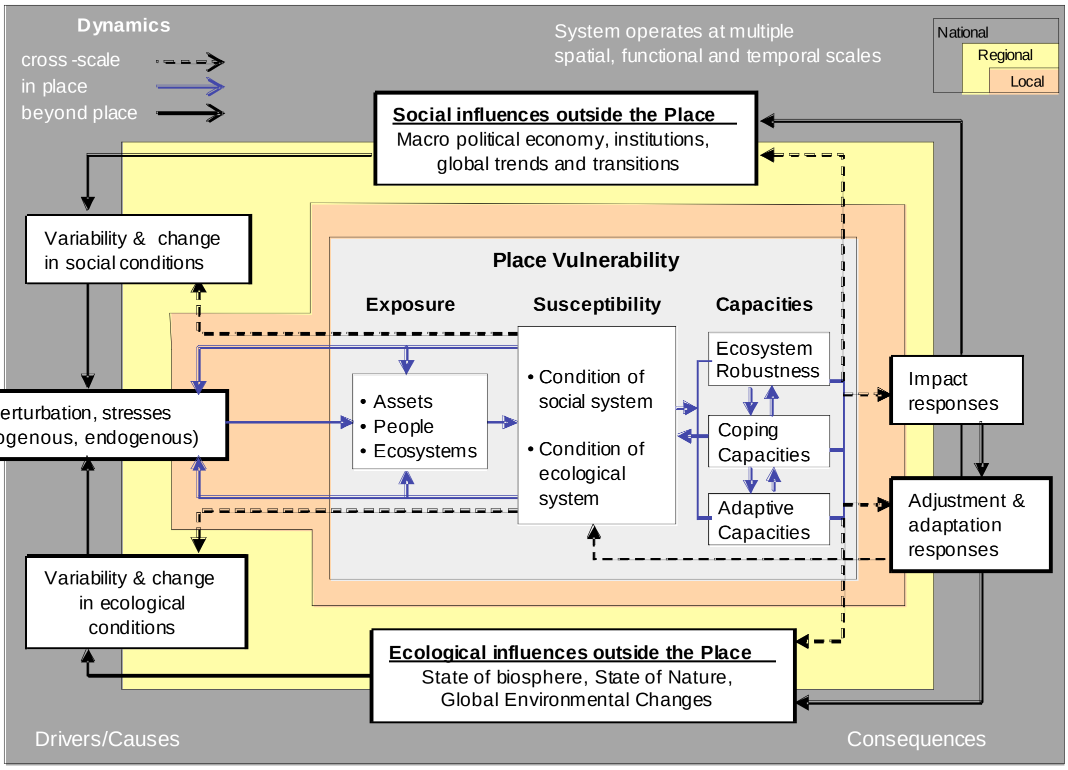


Fig. 5 Vulnerability framework used in this study. Modified from Turner et al. (2003)

Although the framework is only a very simplified reflection of real systems' dynamics, the proposed model is still quite complex for practical use. So far few attempts have been made to implement the framework. A further constraint of the framework is the missing notion of risk. The concepts of risk and vulnerability are very often strongly interlinked in disaster research, see e.g. BBC Model. The Turner Model does not establish any relationship and hence, does not outline how risk is conceptualized.

The social-ecological vulnerability is estimated through the respective assessments of the agricultural and forestry sectors. Exposure, susceptibility and capacities, like in the BBC Model are the key elements of vulnerability. The vulnerability component 'exposure' determines the degree to which a SES is exposed to a specific threat or perturbation. This can be forested or agricultural sites as well as people whose livelihood is dependent on the respective sectors. Exposure is seen as the starting point in a vulnerability analysis. Without having any exposed elements, no hazard specific vulnerability can be detected ($E = 0 \Rightarrow V = 0$).

Susceptibility is the vulnerability component that describes the current state of the SES's elements. In other words susceptibility is a measure to determine the expected rate of deterioration Perturbations in the ecological subsystem can be contamination or pre-damages; in the social subsystem economic stress or political insecurity might impose additional stress on the system. Consequently susceptibility is a dynamic element and is changing continuously over time.

Capacities stand for the combination of all strengths and resources available in the social-ecological system. They reduce the overall level of vulnerability and thus the effects of a striking hazard. The vulnerability component 'capacities' is composed of the three sub-components 'ecosystem robustness', 'coping capacity' and 'adaptive capacity'.

Ecosystem robustness addresses the capacity of the ecological system to absorb and resist disturbance while re-organizing and undergoing change. However, the main functions, structure, identity and feedbacks may essentially be retained (Gunderson, 2000). Coping capacities stand for the means by which people or organizations use available resources and abilities to face adverse consequences that could lead to a disaster (UN/ISDR, 2004). Adaptive capacities refer to a longer time frame and reflect the learning aspects of system behavior in response to disturbances (Gunderson, 2000).

Table 1 summarizes the different indicators selected by the above mentioned deductive approach. The weighted sums technique (Nardo et al. 2005) was applied to create the composite vulnerability index CI_d which aggregates the exposure, susceptibility and capacities of the forestry and agricultural sectors as proxies for the social-ecological system. Indicators were normalized, weighted and subsequently summed up (see Damm 2010).

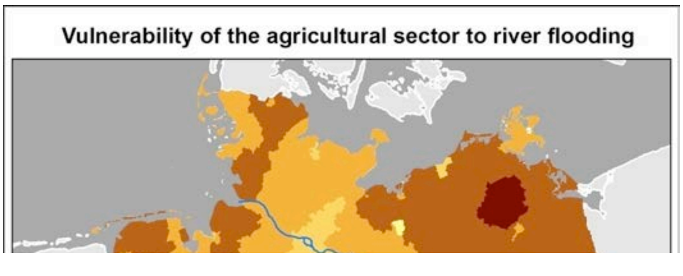
$$CI_d = \sum_{q=1}^{Q} w_q I_{qd} \tag{5}$$

CI = Composite Indicator, *d* = district, *q* = sub-indicator, *Q* = number of indicators, *w* = weight, *I* = normalized indicator

It is important to note that in this assessment, based on the "Turner Model" exposure is not related directly to the spatial extent of the hazard like in the BBC Model. In the social-ecological vulnerability assessment exposure is estimated by the number of people employed in the respective sector and the percentage of the farmland or forest areas within the respective district; hence it is a hazard independent feature. The inundated area (as consequence of an extreme flood) which was used as a measure of exposure in the BBC Model serves here as the proxy measure of the hazard itself. This approximation allows to go a step further and finally assess the flood risk, as a composite measure based on the vulnerability index CI_d and hazard (flood maps) estimates for the agricultural and forestry sectors. Fig. 6 illustrates for the agricultural sector the vulnerability map of Germany. Similar to the SIFVI index (see Fig. 4) the former border between the Federal Republic of Germany and the German Democratic Republic is still detectable.

Forest Sector		
Component	**Sub-component**	**Indicator**
Exposure	Ecological system	% of forested area
	Social system	% of people employed in forest sector
		% of gross value added forest sector
Susceptibility	Human condition	Unemployment rate of the district
	Ecological condition	% of damaged forest
		Water quality index
Capacities	Ecosystem robustness	Forest size
		Forest fragmentation
		Forest type
	Coping capacities	GDP per capita of the federal state
		GDP per capita of district
		Mean income of private households
	Adaptive capacities	Reforestation rate
		% of protected areas
Agricultural Sector		
Component	**Sub-component**	**Indicator**
Exposure	Ecological system	% of farmland
	Social system	% of people employed in agricultural sector
		% of gross value added agricultural sector
Susceptibility	Human condition	Unemployment rate of the district
	Ecological condition	Soil erosion potential
		Water quality index
		Potential contaminating sites
Capacities	Ecosystem robustness	Water retaining capacity
		Filter and buffer capacity
		Dominating land use
	Coping capacities	GDP per capita of the federal state
		GDP per capita of district
		% of farmers with side income
	Adaptive capacities	% of organic farming
		% of protected areas

Table 1 Selected primary indicators for the forestry and agricultural sectors



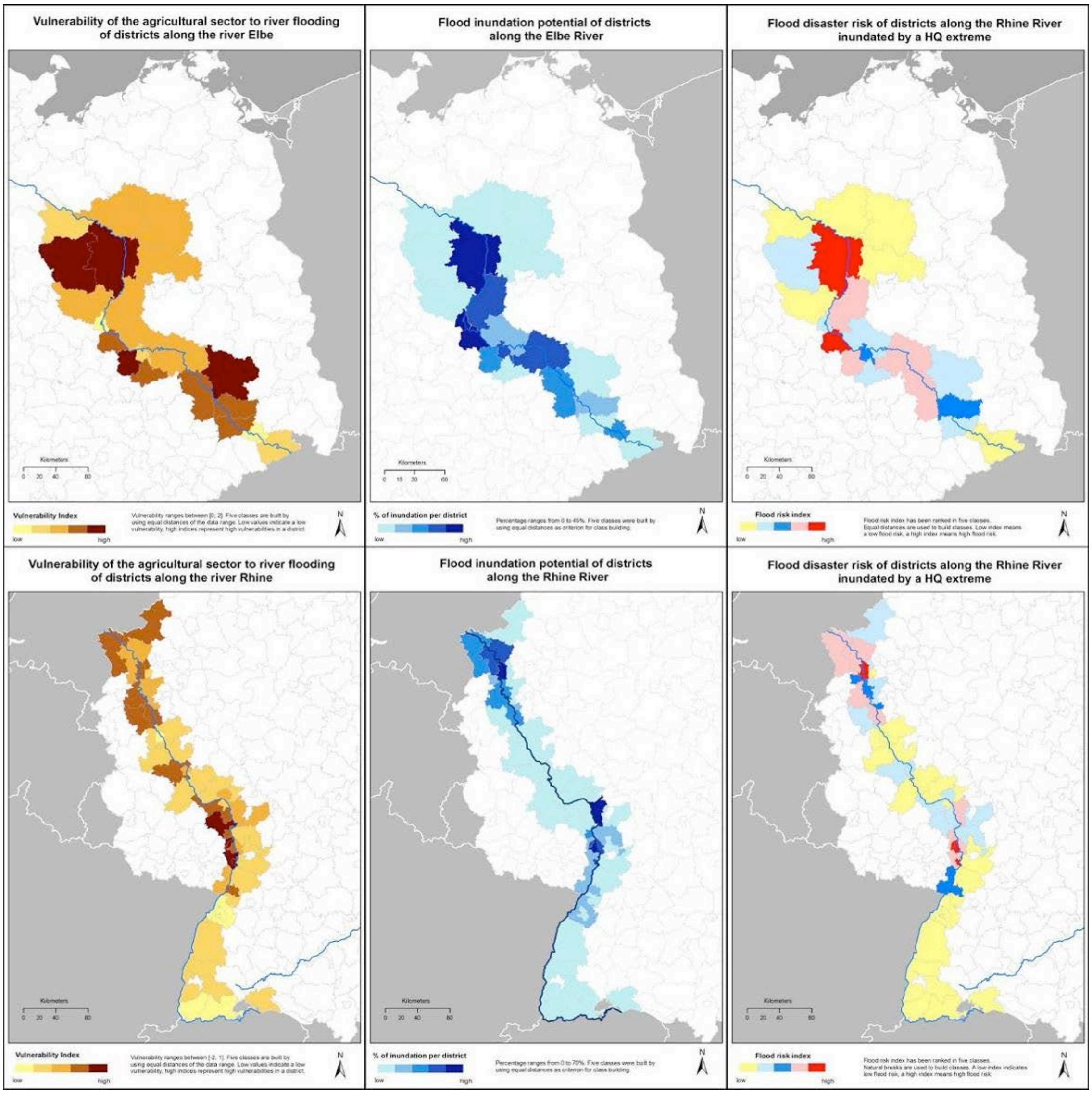


Fig. 7 Presentation of vulnerability, hazard and risk maps for the rivers Elbe and Rhine for the agricultural sector

Figs. 7 and 8 summarize the flood vulnerability, hazard and risk distributions for agriculture and forestry respectively. In the lower part of Fig. 7 vulnerability, hazard and risk are mapped for all districts along the Rhine River that can be affected by a HQ of at least 200 years of recurrence period. Large parts of the Upper Rhine show very low flood disaster risk. The Lower Rhine is characterized by a very heterogeneous risk potential.. The district-independent city ‘Duisburg’ has the highest disaster risk index and is surrounded by other districts with significantly high risk potentials like. Kleve and Wesel. Since almost 70 % of Duisburg’s area might get flooded and vulnerability is at an intermediate level, flood risk is evaluated as very high. Along the Elbe river the districts Stendal and Schönebeck exhibit the highest flood disaster risk indices. Inundations of approximately 40% of the land area and very high vulnerability indices are responsible for high risk values.

For the forest sector vulnerability, inundation potential hazard and flood disaster risk has also been mapped. In Fig. 8 the results are visualized. Again the upper maps show the Elbe River, whereas the lower maps present the Rhine River. Along the Elbe River the districts Wittenberg, Jerichower Land and Stendal exhibit the highest flood risk index. In these districts up to 42 % of the area might get inundated. Combined with high vulnerabilities the disaster risk potential is very high. Duisburg and Frankenthal are again the districts with the highest risk index along the Rhine River. Kleve, Wesel, Speyer and Mannheim are also hot-spots with regard to disaster risk potential of the forest sector. In comparison to the agricultural sector, the Upper Rhine has a higher risk potential due to the higher vulnerabilities in the districts. However, the hot-spot regions remain the Rhine-Neckar region and the Lower Rhine close to the Dutch border.

ISSUES TO BE ADDRESSED: IN LIEU OF A SUMMARY

So far, key elements, structures and underlying theoretical concepts could easily be verified and reconstructed for both vulnerability frameworks, the BBC and the “Turner Model”. However, some analytical constraints still exist which cannot be neglected:

The analytical distinction between the components susceptibility and capacities is not absolutely clear. The vulnerability component ‘capacities’ encompasses the capacities to bounce back, cope with and adapt to hazardous events. These properties depend on the condition of a system which is represented by the susceptibility component. The findings showed that, for instance, healthy and vital ecosystems and societies exhibit high robustness; or economically advantaged regions have stronger capacities to cope with flood events. Thus, both components are strongly interrelated.

Another important aspect which is not clearly solved in the presented models is the exposure component. The vulnerability research community has not agreed on a common interpretation of this component yet. Numerous scholars see exposure closely related to the hazard component while others understand exposure as hazard-independent component of vulnerability like the portion of people and land which can be impacted. Visually, both conceptual models place exposure within the vulnerability frameworks. In this paper exposure was treated both as a hazard-independent component but also as the estimate of the spatial extent of the hazard phenomenon.

The vulnerability assessments cover only one important aspect of disaster risk. Thus, the hazard component has to be incorporated in the calculations to be able to assess disaster flood risk. Therefore, a flood hazard needs to be closely analyzed and defined to capture risk completely. This is no easy task since, for instance, flood intensity is composed of various characteristics such as flood duration, peak flow rate, water depth, flow velocity etc. Moreover, a flood event is not restricted to pure inundation due to high water levels, but is accompanied by further hazards such as a high sedimentation load, debris or even ice sheets during winter floods

Since the major focus of this research was on the development of a sound vulnerability assessment, only one hazard characteristic was selected to demonstrate the assessment of disaster risk along the two rivers Elbe and Rhine. Potential hazard extent was characterized by the HQ having at least 200 years of recurrence period. At district level, the percentage of inundated land area can easily be derived from flood maps. The multiplication of hazard and vulnerability scores produced maps showing flood disaster risk potential of districts along the Elbe and Rhine for the social-ecological sectors (Figs. 7 and 8). Since vulnerability is mapped for all districts in Germany, risk can be assessed for all river systems in the case enough hazard data is available. A valuable basis for a large-scale risk assessment and Germany-wide analysis was thus developed.

The conceptual framework identified in this research can easily be applied on any place and sector worldwide. The framework builds on theories and empirical findings of universal nature and do not refer to a specific region or country. Furthermore, it was shown by this and other studies that different spatial levels can be addressed by the frameworks (Fekete, Damm, Birkmann, 2009).

Transferability across German districts was indeed guaranteed by the selection of methods in the approach. However transfer across national borders has to be done carefully since individual indicators could be proven significant to capture vulnerability under different conditions.

Risk mapping based on detailed vulnerability assessment is still far from becoming a routine exercise. The present paper has shown the potential and feasibility of two promising vulnerability concepts in this regard. In spite of the still ongoing scientific debate over theories and concepts this is a promising result towards improved "forecasting" of risks, their management and ultimately governance.

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