Universität für Bodenkultur

Environmental risk analysis and management

Drought Risk Assessment

Quantifying the Impacts of Droughts

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1. Definition of objective and tasks

Definition of drought

Droughts are hazards which potentially damage the environment, sociology and economy by a temporary imbalance of water availability. It can be activated by different origins and leads to different, but mostly, negative consequences. One of the most important characteristics that vehemently distinguishes drought from other hazards is that drought does not occur abruptly. Drought is distinguished from water scarcity by the permanent lack of water in an area (Tsakiris 2017). However, a clear, universal, and common definition of what qualifies as a drought has not yet been achieved, because this hazard means various consequences in different affected areas and people with their interest (Minucci 2020).

Task of drought risk assessment

Due to global warming, drought risk has become increasingly important and will do so even more in the future. Drought has been an issue in the past, but has been managed based on a passive response, also called crisis management or traditional risk management. However, responding to a disaster usually results in a large waste of resources and is not timely, which is highly ineffective. With the modern risk management plan, which includes a risk assessment, an effective drought prevention and mitigation plan can be created. In Figure X the cycle of disaster management is given. It shows the border between risk and crisis management (Zhang et al. 2016). Drought risk assessment is one part of the risk management plan that results in recommendations for mitigation and adaptation e. g. early warning systems (OECD 2020). Overall, risk analysis and assessment enable early warning of drought risks and provide a scientific basis for targeted defensive measures (Zhang et al. 2016).

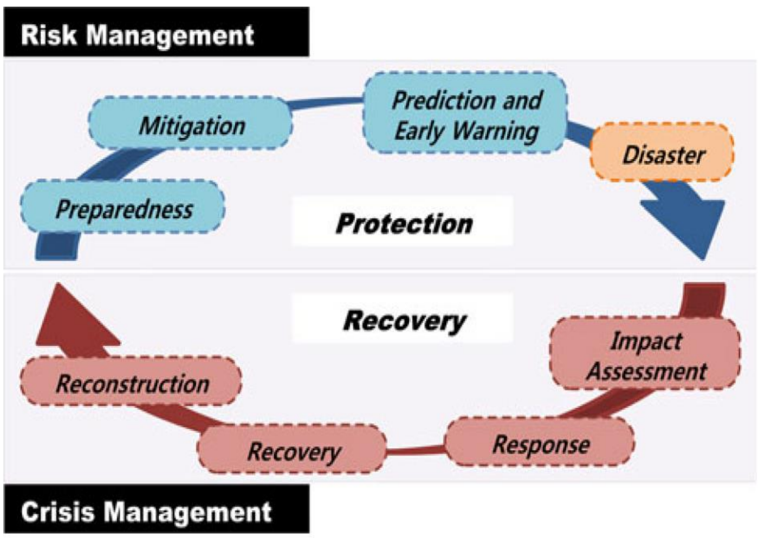

Figure 1: Cycle of disaster management (Nam et al. 2012)

Definition of risk

The definition of risk describes a hazard with its probability of occurrence and its consequences which are damages in risk cases. The damages can be calculated with the exposition, which defines the exposure of population and property and the vulnerability. It describes the susceptibility of the affected community or area.

$$R(X^*) = \int_{X^*}^{\infty} f(X) \cdot D(X) \cdot dX = \sum_{i>X^*} f(X_i) \cdot D(X_i)$$

$$R(X^*) = \sum_{i>X^*} \text{Probability * Vulnerability= Probability*Exposition*Susceptibility}$$

Figure 2: Risk formular (Cutter 1993).

Definition of assessment

The assessment concentrates on estimating and quantifying the risk for a particular area to determine an appropriate and acceptable level of risk and safety (Cutter 1993).

2. Introduction and general description of the problem

Drought risk management

The goal of drought risk management is to create an early warning system and also to provide scientific guidance to support the decisions of stakeholders, society and government to take specific actions. The first goal is prevention; when this is not possible or rarely possible, mitigation measures should be taken. The goal is not only to minimize the overall damage from droughts, but also to maximize socioeconomic benefits. Drought risk management is a systematic process that includes administrative guidance, clear definition of organizational parts, and implementation of drought mitigation measures. The plans made must be considered at all levels: from local to national, and sometimes even international. In addition, it is necessary to develop networks of stakeholders. Stakeholders may be directly or indirectly affected by drought, such as farmers' associations, tourism businesses, and industrial facilities (Zhang et al. 2016).

Drought categories

Drought is usually splitted into drought categories based on their causes and consequences. Depending on the modelling the amount and the separation of categories may differ. The meteorological drought is defined based on precipitation amount and frequency and the evapotranspiration. The hydrological drought using surface water and ground water flows, in detail streamflow or deep percolation data. The agricultural drought, what is also called the vegetation drought, can be assessed analysing soil infiltration data (Tsakiris 2017). The socioecenomic drought can be added, as well as the ecological drought, which impacts the ecological processes necessary for the maintenance of ecosystems and the human life that depends on them. All the different droughts are represented by different popular drought indices which is explained in the following section. Between those different drought categories are connections and dependencies which are shown in Figure 2. Also those types overlap with their defined boundaries. Some drought types are leading to other drought types, which also cannot be represented exactly (Zhang et al. 2016).

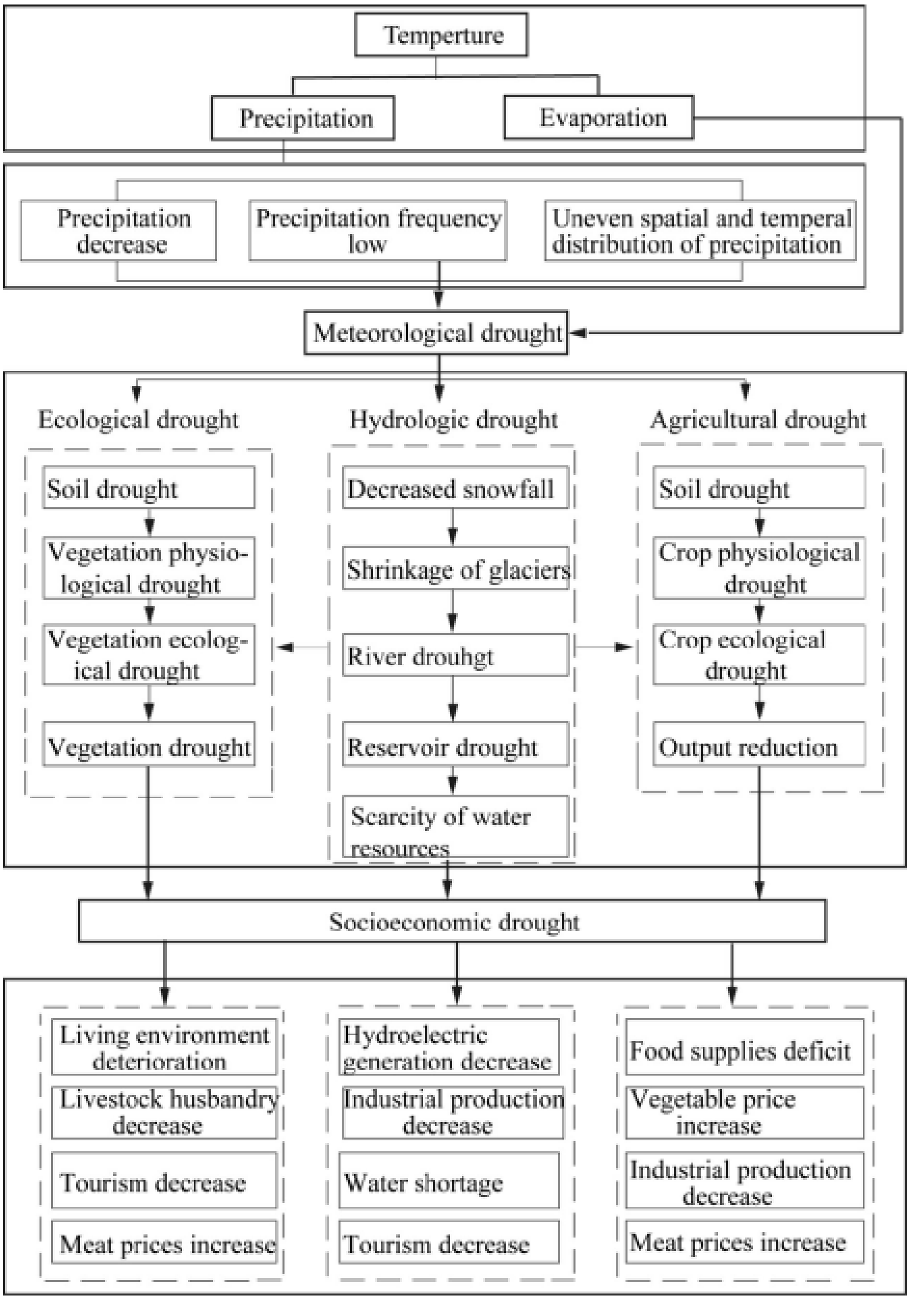

Figure 3: Relationships among the categories of drought (Zhang et al. 2016)

3. Methodology and relevant literature

Risk Analysis

The challenge in describing drought risk lies in the need for indices that take into account the combination of the effects of several factors. The starting point is to define the main factors that cause drought in the area affected or under study. The values at risk, the vulnerability of the environment to drought, and the capacity for prevention and mitigation must be defined. Figure 4 shows a flowchart for drought risk analysis that also considers the context of climate change (Tsakiris 2017).

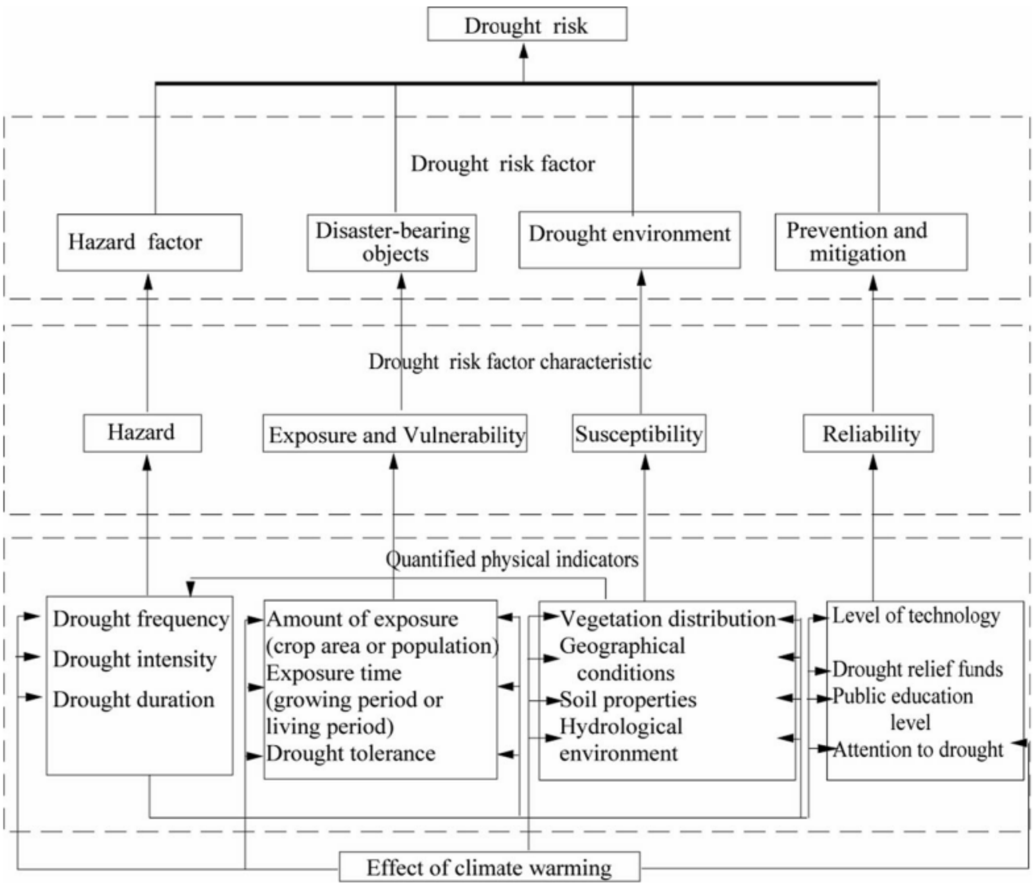

Figure 4: Flowchart for the analysis of drought risk (Zhang et al. 2016)

Drought monitoring

In order to assess the drought risk and to create a suitable drought risk management plan, appropriate data are required. Intensity, cumulative deficit, duration, areal extent and timing of occurrence give information about the drought characterisation. Prior to monitoring, the system under study and the time period to be analyzed must be defined. The drought intensity which combines the effects of precipitation amount and frequency and the category of the drought is needed for the drought monitoring. There are mainly two types of drought monitoring (Zhang et al. 2016).

$$R_{ij} = \sum_{1}^{3} x_{ijk} \cdot V_{ijk} \cdot f_k$$

The first concept is called „water system". It defines an entity with boundaries including watersheds, groundwater, recharge areas, all consumption centres and ecosystems.This concept has to be simplified because it is rather impossible to simultate the reality. Drought is defined as if the entity suffers from persistant natural deficit in water input compared to normal conditions over a significant period of time. For example in the European Union (EU) there are defined categories and ist indices. The standardised precipitation index was defined for the meteorological drought, the fraction of absorbed photosynthetically active solar radiation (fAPAR) for drought impacts on vegetation and the water exploitation index plus (WEI+) for the pressures caused by water abstractions for the hydrological drought.

The other concept is remote sensing through satellite data. It is a tool to record the spatial and temporal distribution of drought at different levels. The indices are usually measured by radiometric measurements of vegetation condition. Monitoring drought in agriculture through remote sensing is of greater interest.

In order to present and visualize the results of drought monitoring, drought variables have to be defined. They are usually calculated separately using univariate frequency analysis. Recently, the dimensions have been studied in relation to each other, which is closer to reality. There is a need to simplify drought monitoring results so that they can be understood by a wide range of people from different backgrounds (e. g. managers and stakeholders) (Tsakiris 2017).

System Vulnerability

Vulnerability is an important influencing factor in risk calculation, so this part will be described in more detail. It depends on exposure, capacity, social conditions, severity of the hazard, and possible connection with other elements or systems. In addition, conditions prior to the onset of the drought have a major influence (Zhang et al. 2016).

Calculation of risk in detail

The annualised risk of each element at risk (R jk) will be presented here in detail. The term shows again the definition of risk which multiply the potential consequences or losses of the element ij in quantitative terms x ijk, the vulnerabilty V ijk is the vulnerability of the i-th element of the j-th sub-system for the k-th level of drought severity and the relative frequency of drought pressure of class k f k. Vulnerability can be expressed as a function between 1 and 0. The maximum value of 1 means a totally unprotected system, and the minimum value of 0 indicates a completely protected system (Zhang et al. 2016).

$$R_{ij} = \sum_{1}^{3} x_{ijk} \cdot V_{ijk} \cdot f_k$$

Figure 5: The average risk of each element at risk (Zang et al. 2016).

The total annualised risk calculates the annual level of losses of the entity due to the drought hazard. The calculated quantity may be the main variable for decision making in the risk managament plan (Zhang et al. 2016).

$$R_{\text{total}} = \sum_{i=1}^{n} \sum_{j=1}^{m} R_{ij}$$

Figure 6: The sum of annualised risks (Zhang et al. 2016)

The calculation of vulnerability is subject to large uncertainties because losses must be estimated for each element at each level of drought. In addition, there are a large number of elements in each subsystem that can end up in numerical losses if calculated in detail with reasonable accuracy. The complexity is very high because the interrelationships of the consequences are multiple and complex. The consequences can be direct or indirect and concrete or not (Zhang et al. 2016).

Relevant literature

Various organizations, institutions, or companies issue guidelines for drought risk assessment and management. It is important to define which category of drought is required, as there are large differences depending on the category. The Organisation for Economic Co-operation and Development OECD, the Food and Agriculture Organization (FAO), the World Meteorological Organization (WMO) and the UN Convention to Combat Drought and Desertification are just a few examples of issuing guidance to various drought-affected stakeholders.

4. Case study

1st case study

Generally, droughts in European regions are increasing. In order to tackle the upcoming challenges and to assure good risk management, research studies for examining vulnerability and risk are founded. Examples for such projects are: Medroplan, Sedemed or Prodim. All of them were located in the Mediterranean basin with slightly different foci on islands or mainlands (Tsakiris 2017).

Overall, those projects aim to find ways to confront drought and water shortage. One major issue pointed out, is the lack of permanent structures and plans to cope with drought. Consequently, changing the approach from "crisis management" attitude to a more proactive one of "risk management" is one of the most important goals set in those projects.

In the framework of Medroplan, the objective was to provide guidelines for drought preparedness plans. That should lead to general improvement in understanding of the causes of droughts and its effects. Furthermore, one expected an exchange of knowhow, technology and expertise among the participants. The project was situated in the Mediterranean. Partner countries were Cyprus, Greece, Italy, Morocco, Tunisia and Spain. A structured plan should allow to reach the mentioned goals in the timeframe of 4 years. Respectively, from 2003 - 2007. According to the determined work packages, a map of related organizations and institutions was created as well as presented in a workshop in Zaragoza with all partners. Following that, terms of reference for drought identification, risk analysis and best practices were carried out and are still part of ongoing work (Gabiña et al. 2004).

Another study assesses the drought risk in Mediterranean agricultural watersheds. Again, promoting the shift from a reactive to a proactive approach is mentioned as a fundamental motivation for this assessment. That is being undermined by the fact, that preparation and mitigation costs are lower than costs arising through potential damage. The area of research in the study are five coastal watersheds in central and southern Tuscany. With an expected rise in frequency and intensity of drought events, the Italian peninsula represents an area strongly affected by climate change.

Complex structures with various demands make it difficult to apply a "one fits all" methodology in drought risk assessment. Nevertheless, general guidelines introduced by the OECD build a reoccurring chore structure for scientific methodology analyzing the impacts of droughts. With minor adaptations, it also was used in the case study of central Italy. Without going into detail, the guidelines were implemented as in the following (Villani et al. 2022).

At first, the conceptual framework needs to be defined. With respect to selected indicators, indices like a Drought Hazard Index (DHI), Drought Exposure Index (DEI) as well as a Drought

Vulnerability Index (DVI) can be established. Those indices then build the Drought Risk Index (DRI).

After clarifying the study area, the identification of the indicators, as the basis for established and implemented indices, is done. During the 4th step: Data acquisition and pre-processing, the selected indicators are transformed from absolute to relative values. By that, comparison between different locations within the study area is possible. As an important step of facilitation, the assessment of multicollinearities then is assuring the relevancy and eligibility of every indicator. In the 6th step, a weighting method is used to guarantee normalized values of the indicators used for the calculation of the indices. Before finalizing the common method used for drought risk assessment with the archetype analysis, the robustness of the created model needs to be tested. In the case study of Villani et al., this was done by considering internal and external validations.

The archetype analysis allows the final simplification and interpretation of the acquired results. In the presented case study the output of that step was a hierarchical cluster analysis showing the recurrent patterns of drought indicators within the selected municipalities. The spatial visualization of the clustering is illustrated in the figure below (Villani et al. 2022).

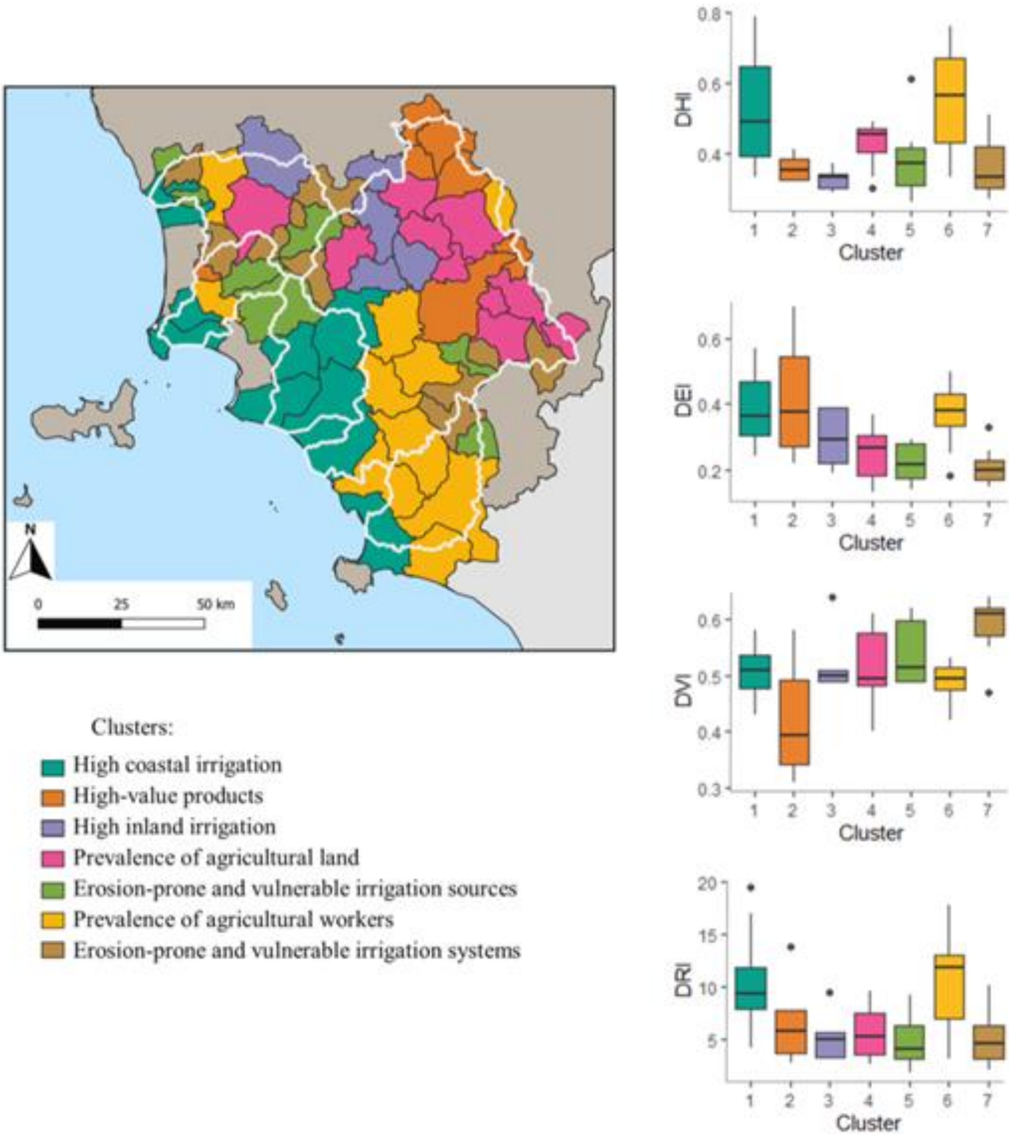

Figure 7: Spatial visualization of the clusters identified in the Tuscany region (Villani et al. 2022)

After successfully applying the described method, the authors stated that the southernmost municipalities of Tuscany are facing the most risk of facing severe droughts. In addition, the high water consumption of the coastal regions, especially in the summer months, needs the attention and major efforts of its local decision-makers (Villani et al. 2022).

2nd Case study

To exemplify diverse approaches concerning drought risk assessment in scientific research, another case study from a different part of the world needs to be presented. In the scope of a County from China, drought risk of farmers considering their planting behaviors and awareness was assessed. This indicates a major difference to the previous example of watersheds in Italy. The focus is entirely set on the possible impact of agricultural droughts on farmers and their business but not generally on nature. However, again different indicators are identified. Not only objective indicators entailing economic or ecological factors but subjective factors are taken into account as well. By that, important aspects such as farmer awareness of disasters and their enthusiasm to resist them are considered (Guo et al. 2022).

In the popular equation of risk being the product of hazard, exposure and vulnerability, the last mentioned factor plays a fundamental role in the method applied in this study. Vulnerability is crucial for determining the degree of loss to farmers triggered by different drought intensities. Subjective indicators like farming behavior or ability of resisting to disasters are influencing farmers vulnerability. With respect to that, the relation of farmer vulnerability to drought vulnerability is described on 3 dimensions: the farmer adaptability, the sensitivity of farmers to different crops and the environmental vulnerability. The following equation visualizes that connection:

Vulnerability = Crop sensitivity + Environmental sensitivity – Adaptability

The general framework of the used drought risk assessment in this study is presented in the figure below (Guo et al. 2022).

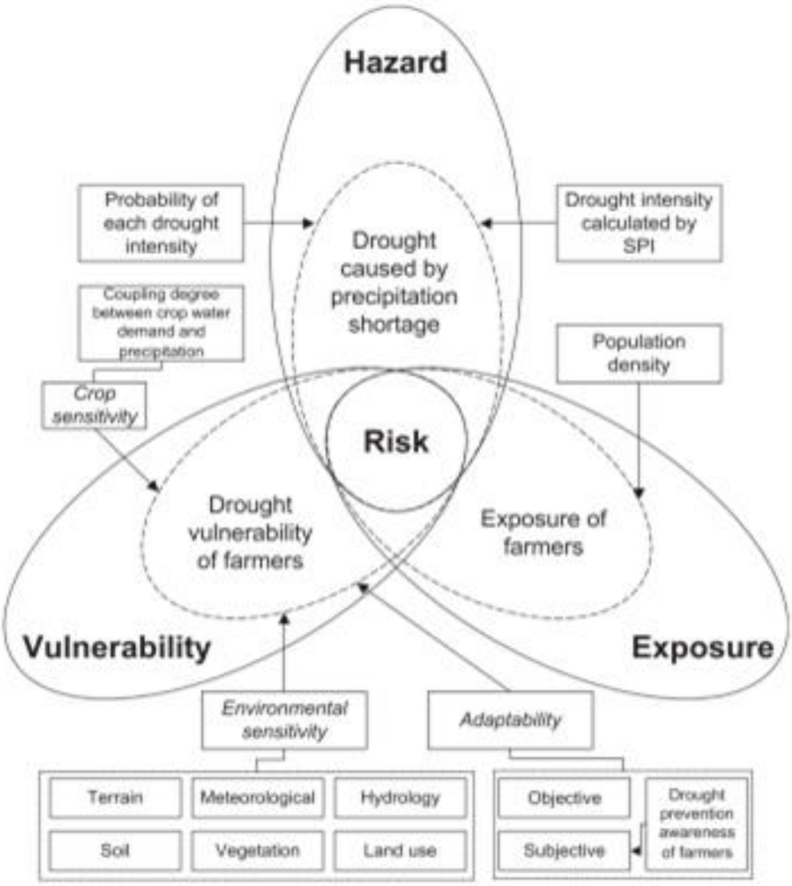

Figure 8: Used framework of drought risk assessment in the study by Guo et al. 2022)

As the basic methodologic approach of this study is of higher importance than the exact study area, there will not be a detailed description of the examined agricultural area. That being said, one has to mention that the research was done in Xinghe County (northern China).

The used data in this assessment was gathered according to three different categories:

Environmental and geographic element data like precipitation, elevation or soil texture; regional statistical data including river network, irrigation or tap water coverage data; household survey data such as farmland area or family composition but disaster awareness as well. Like already said in the methodological part of this paper, one common option for gathering data is through satellites. The environmental and geographic elements are based on this technique.. As well as in the study in central Italy, the Standardized Precipitation Index (SPI) is used to analyse the meteorological drought intensity. Therefore, like seen in the figure above, the SPI is part of the drought risk assessment framework (Guo et al. 2022). It can be calculated like in the following formula:

$$SPI = S \times \frac{t - (c_3 t + c_2)t + c_1}{[(d_3 t + d_2)t + d_1]t + 1}$$

$$t = \sqrt{\ln \frac{1}{F^2(x)}}$$

Figure 9: Calculation of the SPI Index (Guo et al. 2022)

Where: x is the precipitation value in a year. F(x) is the precipitation distribution probability related to the Gamma function (Γ): F(x) > 0,5 resulting in S = 1 and all other F(x) in S = -1. C1 – c3 and d1 - d3 are the approximate parameters of the Γ distribution function converted to cumulative frequency.
To then calculate the risk of drought in the study area, the probability of drought grades occurring was measured in the following equation:

$$H = \omega_1 \times ld + \omega_2 \times md + \omega_3 \times sd + \omega_4 \times ed$$

Figure 10: Risk of drought as sum of the propability of occuring drought grades (Guo et al. 2022)

H stands for the disaster caused by a drought; ld (light) ; md (medium); sd (severe); ed (extreme) indicate the severity of the drought and $\omega_1 - \omega_4$ represent the weights for the grades of drought intensity ranging from 0,1 – 0,4.
Following the hazard assessment starting with the calculation of the SPI and ending with the disaster caused by drought (H), the vulnerability assessment refers to the drought adaptability of farmers. Like already mentioned before, one has to distinguish between the objective and the subjective dimension. The overall drought adaptability of farmers is illustrated as:

$$AD = \mu_1 \cdot oa + \mu_2 \cdot sa = f(Ec, So, Hu, Ma) + f(Pbd, Rdd, Rad)$$

Figure 11: Evaluation of the farmers' drought adaptability (Guo et al. 2022)

Where: μ_1 and μ_2 are the weights for various adaptability dimensions; oa/sa stand for (objective -/subjective adaptability) and Ec (economic), So (social), Hu (human), Ma (material) are components of the objective adaptability evaluation, whereas Pbd, Rdd and Rad represent the response consciousness of farmers before, during and after the disaster meaning the subjective adaptability evaluation.

For determination of the weight of each index, entropy method and Analytic Hierarchy Process (AHP) are used. Without going into detail, one should briefly identify AHP as a subjective and entropy method as objective. The combination of them is crucial to include both indicator types.

As a final methodical step, environmental sensitivity and crop sensitivity were evaluated. It was put forward that farming structure of the crops is affected by the farming behavior of the farmer. Consequently, farmers behavior has an impact on the vulnerability of the crops. Furthermore, six different characteristics were taken into account to measure environmental sensitivity: Meteorology, hydrology, soil, terrain, land use and vegetation. The amount of dimensions is requesting broad data gathering. That emphasizes the complexity of this kind of drought risk assessment approach.

After outlining the methodology, there are a few key results that have to be mentioned in order to summarize the outcome of the research. All the results were categorised and then mapped according to the equation of risk being the product of hazard, vulnerability and exposure (Guo et al. 2022).

The figure below illustrates the drought risk assessment and consistency with farmers' drought loss.

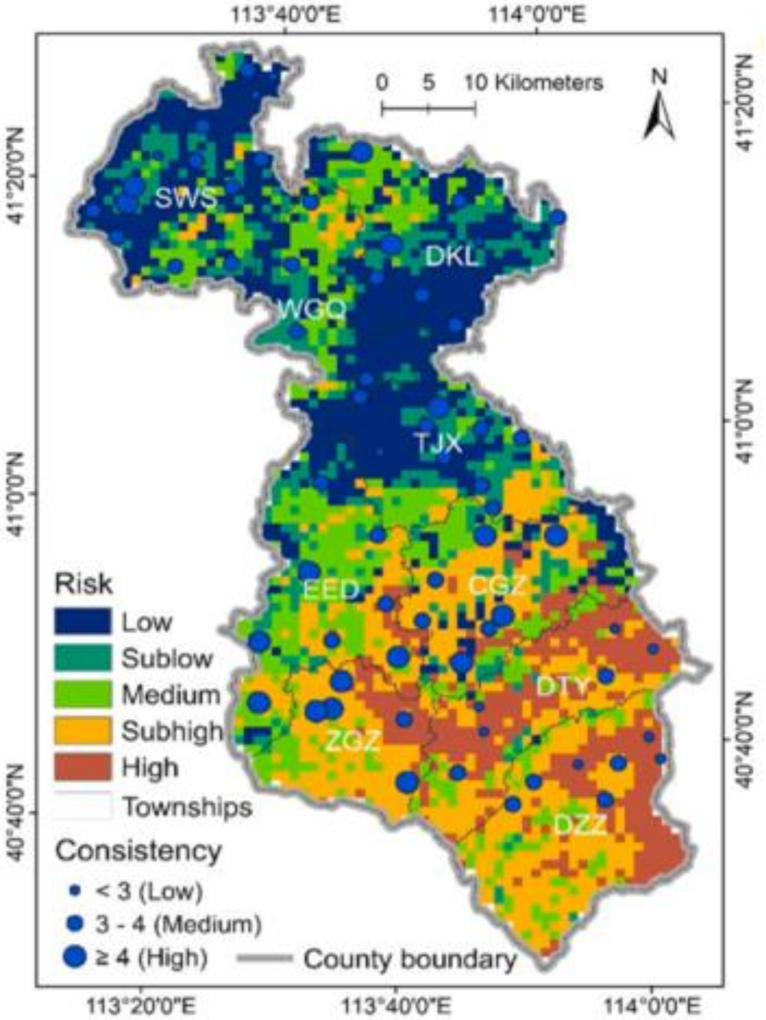

Figure 12: Drought risk assessment and consistency with farmers' drought loss (Guo et al. 2022)

Generally, the drought risk for Xinghe County is high in the southern and low in the northern part. The increasing drought intensity levels have led to a decrease in spatial probability differences among the municipalities. However, the central achievement of the study lies in the inclusion of subjective indicators in the process of the vulnerability assessment. Consequently, it provides reference for government policies to reduce farmers' vulnerability to droughts and local drought risk. Examples were: strengthening the support for breeding farmers or encouraging them to focus on raising livestock (Guo et al. 2022).

5. Discussion and Conclusions

The diversity of drought hazards, their different consequences, the different boundary conditions of the unit under study, the different types of calculations, etc., lead to a wide range of possible outcomes and thus to a wide range of possible drought risk management plans, and may lead, for example, to very different governmental actions. Drought risk management not only exhibits great diversity at all levels, but also uncertainty, which is propagated in the calculations. The uncertainty even gets higher through

The complexity of drought and its impacts requires complex macroeconomic modeling tools to identify indirect and direct economic impacts. The high demand for resources for detailed modeling leads to wide disparities in the quality of drought analysis reports. The conclusion is that it is difficult to reliably link and connect drought data and their outcomes from management plans between different countries (OECD 2020).

The study in central Italy illustrates a general problem in research. Often, drought hazard is not used to predict the impact of these extreme weather conditions but to predict the risk. It is crucial to not fail in this central focus during research activities. However, an essential process in drought risk assessment is the establishment of indicators that are fundamental for creating a suitable model. Choosing the right number of indicators as well as appropriate weighing of them, enables a suitable approximation of reality. Methods like multicollinearity analysis are useful to exclude redundant indicators and prevent over – simplifications that lead to unrealistic estimates (Villani et al. 2022).

In some cases, objective indicators and factors might not be enough to assess drought risk. An example would be evaluating the susceptibility of farmers to drought. Also subjective factors like the farming behavior of the farmer directly affects the growing of the crops. Consequently, there is a link between subjective factors and crop vulnerability. Without considering subjective factors as essential for the assessment of vulnerability, representative and valid results are not easily achieved (Guo et al. 2022).

6. Summary

Droughts are hazards that can potentially damage the environment, sociology and economy through a temporary imbalance of water availability. Droughts have different origins and lead to a high variability of negative consequences depending on the affected area and its condition. Therefore, there can be no clear detailed definition of drought. Drought does not occur suddenly, which in the past led to a passive response, also called crisis management. Greater efficiency in reacting to drought disasters requires risk management. To define preparedness, mitigation and prediction measures, the drought risk of a given area must be assessed. The assessment requires drought categories to focus on the consequences, the importance of which varies depending on the case. Drought is divided into meteorological, hydrological, agricultural, socioeconomic and ecological drought. However, the separation is not entirely clean and the categories have interdependencies, again showing the high complexity of droughts. Nevertheless, drought risk is defined by multiplying the probability of a hazard and the vulnerability of the area under study. Vulnerability depends on the exposure of the population and property and the susceptibility of the affected community or area.

As stated various times within this seminar paper, the complex structures make it generally difficult to apply a "one fits all" methodology in drought risk assessment. The results could be seen in the presented case studies. Different models aim to assess the drought risk in different contexts. In order to show the variety of scientific approaches in drought risk assessment, two case studies from different parts of the world were presented. Especially the study in Italy emphasized that a well balanced number and type of indicators is fundamental to gather the right data to pave the way for a proactive risk management. The second study taken place in China, pointed out that sometimes it is crucial to not only rely on objective but subjective parameters. Only by that one can set the basis for a complete and reliable drought risk assessment. Ideally, the scientific research should then be a reference for policy makers in order to prevent future disasters and guarantee a sustainable drought risk management.

7. References

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