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# Freshwater vulnerability under high end climate change. A pan-European assessment

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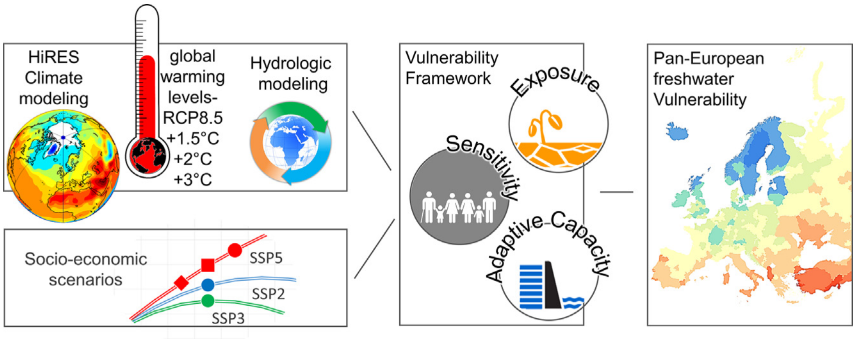
## HIGHLIGHTS

- A Pan-EU conceptual framework for freshwater vulnerability is proposed.
- The approach can support regional level policy making and implementation.
- Most vulnerable countries should invest in human capital.

## GRAPHICAL ABSTRACT



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## ABSTRACT

As freshwater availability is crucial for securing a sustainable, lower carbon future, there is a critical connection between water management and climate policies. Under a rapidly changing climate, it is more important than ever to estimate the degree of future water security. This is a challenging task as it depends on many different variables: the degree of warming and its consequent effects on hydrological resources, the water demand by different sectors, and the possible ameliorations or deteriorations of the effects due to climate change adaptation and mitigation strategies. A simple and transparent conceptual framework has been developed to assess the European vulnerability to freshwater stress under the present hydro-climatic and socioeconomic conditions, in comparison to projections of future vulnerability for different degrees of global warming (1.5 °C, 2 °C and 4 °C), under the high-rate warming scenario (RCP8.5). Different levels of adaptation to climate change are considered in the framework, by employing various relevant pathways of socioeconomic development. A spatially detailed pan-European map of vulnerability to freshwater shortage has been developed at the local administrative level, making this approach extremely useful for supporting regional level policymaking and implementation and strategic planning against future freshwater stress.

## 1. Introduction

Recent climate policies might need to be revised to reach the goals established with the Paris Agreement. State of the art climate projections show that the higher-end climate change scenarios progressively become more probable as the projected warming considerably surpasses

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the 2 °C target. Under such circumstances, the availability of hydrological resources emanates as a vital subject that policy makers will have to manage (Papadimitriou et al., 2016). Future water security is challenging to estimate as it depends on many different variables, such as the degree of global warming and its consequent effects on hydrological resources, the water demand by different sectors, and the possible ameliorations or deteriorations of the effects due to climate change adaptation and mitigation strategies. Climate affects freshwater availability and simultaneously changes the social stress on it, which in turn affects socioeconomic variables that also affect climate. To cope with these complex interactions, socio-economic scenarios are used to derive emissions pathways without (reference) and with climate policies (mitigation scenarios). The derived emissions are then used as input to climate models, to obtain climate change projections. Finally, the climate change projections and socio-economic scenarios are used to evaluate the impact of climate change in combination with adaptation measures. A concept for the assessment of climate change impacts under adaptation strategies is the estimation of vulnerability.

According to the fourth IPCC assessment report (Parry, 2007) vulnerability is a measure of a system's susceptibility to, and inability to cope with, unfavourable climate change impacts, such as climate variability and extremes. Vulnerability is often decomposed into the three major components of exposure, sensitivity and adaptive capacity (Preston and Scientific, 2008) and in the context of climate change depends on the type, magnitude, and rate of change. These constituents of vulnerability -sensitivity, exposure and adaptive capacity- are interrelated and have wide applications in studying environmental changes providing many insights at global, regional or local scale (Smit and Wandel, 2006). The adoption of this concept by the IPCC leads to the “mainstreaming” of adaptation to the concept of many studies dealing with climate change. Although the concept of vulnerability assessment is a widespread methodology of examining the degree of exposure for many environmental systems under change (Turner et al., 2003), the application to drought is not a widespread practice, suggesting the need of increased effort (González Tánago et al., 2016). One of the main reasons is the difficulty in retrieving quantitative information on drought damages and vulnerability (Blauhut et al., 2015). González Tánago et al. (2016) conducted a systematic review of the drought vulnerability assessments in the scientific literature until mid-2015 revealing the broad diversity of the underlying conceptual frameworks and the lack of accordance on the kind and the amount of factors and dimensions that need to be analyzed.

Indicative recent studies on drought vulnerability at the global scale are presented below. Carrão et al. (2016) elaborated on a drought risk map, by combining independent indicators of historical droughts and estimates of drought exposure and vulnerability, finding that potential drought risk is mostly driven by the growth of regional exposure. A more focused approach on world's cereal producing regions was applied to identify vulnerability hotspots following a systematic drought vulnerability assessment framework (Fraser et al., 2013). Naumann et al. (2014) explored different aspects of drought vulnerability using a composite indicator for the identification of drought hotspots over Africa. A good agreement of mapped drought vulnerability and disaster information from the EM-DAT database was established.

Several systematic vulnerability assessment studies have been developed and applied at a continental, regional or national scale over Europe. Alcamo et al. (2008) used inference modeling to capture the susceptibility to drought by quantifying crucial vulnerability indicators. Iglesias et al. (2009) presented components-indices for evaluating social vulnerability to drought and the effect of index weighting through an application to six Mediterranean countries. Salvati et al. (2009) applied a comprehensive framework of mapping vulnerability of land to drought and desertification by combining biophysical and socioeconomic indicators over Italy. Flörke et al. (2011) used a similar to the present study approach to describe the change in European drought vulnerability by the 2050s under the A1B scenario. Perčec Tadić et al. (2014) developed a drought vulnerability map for Croatia based on climatic and geophysical indicators giving a first insight of the drought sensitive areas. The extensive work of the DROUGHT R&SPI FP7 project (Stagge, 2015) provided a systematic categorization of environmental and socioeconomic factors affecting vulnerability and can be used for developing an assessment framework. Blauhut et al. (2016) used several indicators of the previous study for the development of a hybrid framework of probabilistic impact prediction combined with vulnerability assessment for monitoring drought risk at a pan-European level.

Here, a simple and transparent conceptual framework for the assessment of European freshwater vulnerability is developed and applied. Vulnerability to freshwater stress is firstly assessed with respect to current hydro-climatic and socioeconomic conditions and is then compared to future vulnerability, projected for different degrees of global warming (1.5 °C, 2 °C and 4 °C), under the high-rate warming scenario (RCP8.5). Projected vulnerability is estimated for different level of adaptation to climate change, by employing various relevant socioeconomic pathways (SSP2, SSP3 and SSP5).

## 2. Data and methods

### 2.1. Forcing datasets

The forcing datasets used for this study are an ensemble of global high resolution climate model simulations, generated with the use of the EC-Earth3-HR model (Alfieri et al., 2017) in Atmospheric General Circulation Model (AGCM) mode. EC-Earth3-HR was run with prescribed sea surface temperature (SST) and sea–ice concentration, provided by six CMIP5 models. The criterion for model selection was to cover a wide range of uncertainty in the future climate projections. The ensemble includes two models of respectively high and low climate sensitivity (IPSL-CM5A-LR and GFDL-ESM2M), a dry (IPSL-CM5A-MR) and a wet (GISS-E2-H) model and finally two additional global climate models (HadGEM2-ES and EC-EARTH). The selection of the forcing models is based on an analysis of the historical and RCP8.5 results of all CMIP5 models that was done in the HELIX project (www.helixclimate.eu). The climate model output starts from the reference period and spans up to 2100 or 2120 for some models, in order to cover the time-periods that correspond to the examined warming levels (up to +4 °C). One model realization (r2, GFDL-ESM2M) is omitted from the SWL4 impacts' analysis as there were not data available for the SWL4 time-slice. The list of the CMIP5 models used to force the high–resolution climate simulations along with the time of exceedance of three examined Specific Warming Levels (SWLs) for each model are reported in Table 1. The native resolution of the simulation was 0.4°, regridded to 0.5° to fit the PGFv2 (Sheffield et al., 2006) observational dataset that was used as reference for the bias adjustment. The dataset assimilates a range of data sources. These are NCEP–NCAR reanalysis (Kalnay et al., 1996), CRU TS2.0 (Mitchell et al., 2004), GPCP (Huffman et al., 2001), TRMM (Huffman et al., 2007; Huffman and Bolvin, 2013) and NASA Langley SRB (Stackhouse et al., 2000). At a first stage, the reanalysis data variables were bilinearly interpolated to a 2.0° regular grid and the produced gridded dataset was commensurate with the other observation-based datasets. The daily timestep statistics are then adjusted by a series of

**Table 1**
CMIP5 forcing models used to force global high resolution atmosphere only simulations and year when each model exceeds the examined SWLs according to the RCP8.5 scenario.

| Member | Forcing model | Ensemble member | SWL1.5 | SWL2 | SWL4 |
|---|---|---|---|---|---|
| r1 | IPSL-CM5A-LR | r1i1p1 | 2015 | 2030 | 2068 |
| r2 | GFDL-ESM2M | r1i1p1 | 2040 | 2055 | 2113 |
| r3 | HadGEM2-ES | r1i1p1 | 2027 | 2039 | 2074 |
| r4 | EC-EARTH | r12i1p1 | 2019 | 2035 | 2083 |
| r5 | GISS-E2-H | r1i1p1 | 2022 | 2038 | 2102 |
| r6 | IPSL-CM5A-MR | r1i1p1 | 2020 | 2034 | 2069 |