Multi-sectoral and systemic drought risk in forested cold climates: Stakeholder-informed vulnerability factors from Sweden

~~User-Validated Drought Vulnerability Factors in Forested Cold Climates: Multi-Sectoral Perspectives from Sweden~~

Elin Stenfors[1], Malgorzata Blicharska[2], Thomas Grabs[1], Claudia Teutschbein[1]

1 Uppsala University, Department of Earth Sciences, Program for Air, Water and Landscape Sciences, Villavägen 16, 75236 Uppsala, Sweden

2 Uppsala University, Department of Earth Sciences, Program for Natural Resources and Sustainable Development, Villavägen 16, 75236 Uppsala, Sweden

Correspondence to: Elin Stenfors (elin.stenfors@geo.uu.se)

Abstract. There is a global call for proactive drought risk management, stressing the need to further our understanding of the systemic nature of drought risk. Proactive drought risk management requires not only an understanding of the drought hazard itself, but also of the underlying vulnerabilities in socio-hydrological systems. As a result, drought vulnerability assessments are increasingly conducted across the globe. However, drought vulnerability is complex and shaped by the social, ecological and hydroclimatic context. Thus, understanding how vulnerability is manifested depending on regional, sectoral or societal differences is crucial. ~~Yet, a detailed overview of drought vulnerability factors relevant for socio-hydrological systems in specific climate regions and ecozones, is currently lacking~~. Therefore, ~~a first ever attempt was made to~~ we here present an assessment ~~identify user validated~~ of the practical relevance and relative impact of various drought vulnerability factors ~~, relevant~~ for water-dependent sectors and societies in forested cold climates. ~~User validation~~ The analysis was ~~performed through~~based on the results of an online survey conducted in Sweden~~, Northern Europe,~~ targeting stakeholders from seven water dependent sectors, working in authorities, private and public enterprises, NGOs and trade associations. Respondents were asked to rate a comprehensive list of vulnerability factors, connected to sectoral and societal vulnerability as well as governance, based on their perceived impact on drought risk in their sector as well as for society as a whole. ~~The study successfully identified several relevant drought vulnerability factors for the climate region, as well as the relative impact of each vulnerability factor on drought risk in sectors as well as society.~~ Results showed that the relevance and impact of individual vulnerability factors differed ~~for different~~across sectors, ~~where~~ with the forestry sector especially standing~~s~~ out compared to other sectors. Furthermore, the results indicate regional differences in societal vulnerability factors. The substantial list of vulnerability factors found to be relevant by the respondents ,demonstrates the complex nature of drought risk, as well as the importance of adopting cautiousness when selecting generic vulnerability factors for applied vulnerability assessments. Furthermore, the results provide a comprehensive guide to both sectoral and societal drought vulnerability in socio-hydrological systems located in forested cold climates.

1 Introduction

In recent years, Europe has experienced large scale drought events, the most recent in 2022 when the continent faced unprecedented drought conditions (Faranda et al., 2023), and the 2018-2019 drought that affected large parts of Europe including the high-latitude regions of Scandinavia (Bakke et al., 2020; Teutschbein et al., 2022).

Droughts are slow on-set and recurrent phenomenon (Wilhite, 1996) capable of affecting various aspects of socio-hydrological systems. Brought on by climatic variability that creates regional water deficits compared to normal conditions, droughts can manifest in all climatic zones (Wilhite, 1996). They are generally classified into four drought types based on where in the hydrological system they arise; meteorological (precipitation deficit sometimes combined with evapotranspiration), soil moisture (soil moisture deficit), hydrological (negative anomalies in surface or groundwater), and socioeconomic drought (impacts on water as an economic good) (Mishra and Singh, 2010; Van Loon, 2015; Wilhite and Glantz, 1985). ~~As many sectors in society are dependent on water, drought impacts can be wide ranging and cascading (UNDRR, 2021), and analyzing and understanding drought vulnerability of these sectors can potentially improve drought risk management and the resilience of socio-hydrological systems. There is currently no interdisciplinary consensus on how to define and conceptualize drought vulnerability (Ciurean et al., 2013; Fuchs and Thaler, 2018). However, it can broadly be explained as an entity's predisposition to drought-related harm (Füssel, 2007; Turner et al., 2003), influenced by the drought type, its duration (Adger, 2006) and location (Turner et al., 2003). Consequently, indicators used to measure vulnerability will depend on factors like management practices, cultural context and historical hydrological conditions (Taylor et al., 2009), with the importance of each factor differing based on the specific hydroclimatic and social conditions of the area (McEwen et al., 2021).~~

~~In recent years, Europe has experienced large scale drought events, the most recent in 2022 when the continent faced unprecedented drought conditions (Faranda et al., 2023), and the 2018-2019 drought that affected large parts of Europe including the high-latitude regions of Scandinavia (Bakke et al., 2020; Teutschbein et al., 2022). In particular the 2018 drought had several impacts on Sweden. The combination of high temperatures and low precipitation gave rise to hydrological and agricultural droughts in several parts of the country (Sjökvist et al., 2019; Stensen et al., 2019). It impacted sectors including energy, agriculture, water, and forestry, along with the environment, and resulted in various cascading effects (Sjökvist et al., 2019). Crop yields for a variety of crops were halved compared to the five year average (Lantmännen, 2018), resulting in an estimated loss of 10 billion SEK in irretrievable harvests (LRF, 2019). Furthermore, harvest losses and dry conditions created a pasture and fodder shortage for farm animals and emergency slaughter increased drastically with waiting times being up to six months long (Sjökvist et al., 2019). Consequently, availability of grains, dairy product and meat was reduced. The drought impacts on the hydrological system also affected several sectors. Inflow to hydropower reservoirs was exceptionally low, which ultimately created a 50-70% rise in electricity prices during the summer of 2018 (Sjökvist et al., 2019). Several Swedish municipalities saw water shortages, where 85 municipalities introduced restrictions on irrigation and 100 municipalities urged its inhabitants to lower their water consumption (Krisinformation, 2018). The reduced water flows also had an impact on ecosystems. For example, water courses housing important nursery habitats for salmon and sea trout dried up (S. V. T. Nyheter, 2018). The dry conditions of 2018 also resulted in forest fires over large areas in Sweden. Forest resources worth 900 million SEK were lost due to the fires (Sjökvist et al., 2019). Several Swedish counties were affected and in total 25 000 forest hectares were lost, with more than 500 individual forest fires identified during the period (MSB, 2018).~~ ~~As m~~Many sectors in society are dependent on water. ~~.~~ The interconnectedness and interdependencies between sectors as well as

80 society can give rise to wide ranging drought impacts ~~can be~~ with cascading and ripple effects~~wide ranging and~~

81 ~~cascading~~ (Hagenlocher et al., 2023; UNDRR, 2021). Consequently, there is a growing call for understanding the

82 systemic nature of risk (UNDRR, 2019), incorporating multi-sectoral and whole-of-society systems perspectives

83 (Hagenlocher et al., 2023; Stefanski et al., 2025). Such endeavors require an understanding, not only of the drought

84 hazard itself, but of the underlying vulnerabilities of a system, that can exacerbate the impacts of a drought. ~~, and~~

85 ~~a~~Analyzing and understanding drought vulnerability ~~of these sectors~~ can ~~potentially~~ improve drought risk

86 management and the resilience of socio-hydrological systems. T~~T~~here is currently no interdisciplinary consensus

87 on how to define and conceptualize drought vulnerability (Ciurean et al., 2013; Fuchs and Thaler, 2018; Jamshed

88 et al., 2023; Rufat and Metzger, 2024; Turesson et al., 2024). ~~However, i~~It can broadly be explained as an entity's

89 predisposition to drought-related harm (Füssel, 2007; Turner et al., 2003), influenced by the drought type, its

90 duration (Adger, 2006) and location (Turner et al., 2003). Consequently, indicators used to measure vulnerability

91 will depend on factors like management practices, cultural context and historical hydrological conditions (Taylor

92 et al., 2009), with the importance of each factor differing based on the specific hydroclimatic and social conditions

93 of the area (McEwen et al., 2021). Yet, indicator-based assessments often use the same set of vulnerability

94 indicators, independent of the context of the assessment (Hagenlocher et al., 2019). ~~(King Okumu et al., 2020)~~

95 Due to the contextual nature of drought vulnerability, Stenfors et al. (2024) presented a conceptual model for

96 drought vulnerability in forested cold climate regions, based on a substantial list of vulnerability factors that

97 influence drought risk in the climate and eco-region. The model divides vulnerability factors into three distinct

98 categories: (1) direct water consumers, i.e., factors linked to sectors or groups using water directly (e.g., for

99 drinking water, watering crops, etc.), (2) indirect water consumers, i.e., factors related to societal groups that use

100 water indirectly through consumption of goods that need water for production (e.g., food, energy, etc.), and (3)

101 governance processes and plans, such as policies and plans concerning drought, financial ability to adapt or

102 respond to drought, where factors connected to the category can affect both sectors and society as a whole. T

103

104 ~~Due to the increasing drought risk even in generally water abundant regions, like Scandinavia, it is important to~~

105 ~~assess drought vulnerability, as it can help identify effective measures, prepare for potential negative effects of~~

106 ~~droughts and for designing proactive drought management plans. Yet, no comprehensive assessment has been~~

107 ~~conducted to determine what constitutes drought vulnerability, incorporating sectors such as forestry, agriculture,~~

108 ~~water resources & supply as well as society for forested cold climates. Stenfors et al. (2024) took an initial step~~

109 ~~in this direction by presenting a conceptual model for drought vulnerability in forested cold climate regions. By~~

110 ~~studying available literature on drought vulnerability in these regions, several vulnerability factors were identified~~

111 ~~and used to form a conceptual model for drought vulnerability. The model divides vulnerability factors into three~~

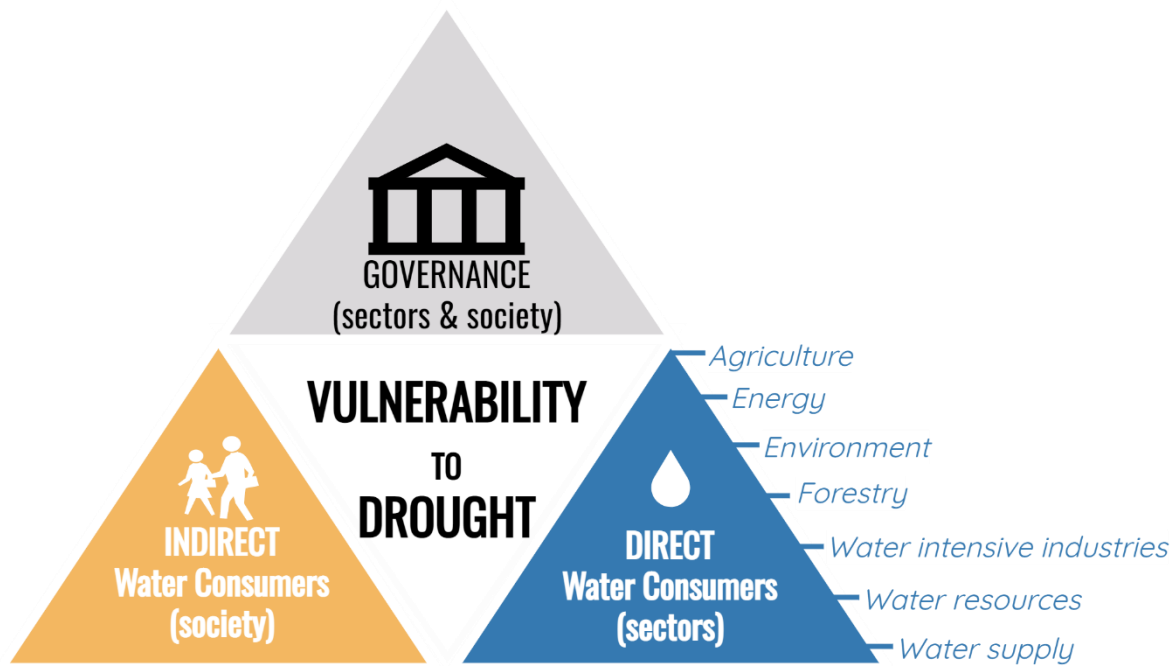
112 ~~distinct categories (Figure 1): (1) direct water consumers, i.e., factors linked to sectors or groups using water~~

113 ~~directly (e.g., for drinking water, watering crops, etc.), (2) indirect water consumers, i.e., factors related to societal~~

114 ~~groups that use water indirectly through consumption of goods that need water for production (e.g., food, energy,~~

115 ~~etc.), and (3) governance processes and plans, such as policies and plans concerning drought, financial ability to~~

116 ~~adapt or respond to drought, where factors connected to the category can affect both sectors and society as a~~

117 ~~whole.~~

heir literature review identified more than 80 factors relating to drought vulnerability in the climate region. However, the practical relevance of the identified factors for practitioners, as well as the relative impact of the vulnerability factors within and across different societal sectors is still unknown. For example, one of the most commonly used vulnerability factors in the reviewed literature is irrigation(Stenfors et al., 2024). Meanwhile, only approximately 3% of Swedish agriculture is irrigated (The Swedish Board of Agriculture, 2024) which raises the question on the relevance of this factor in a local setting. HenceAs numerous vulnerability factors where identified in the literature review by Stenfors et al. (2024), f, further work is required to validate assess these factors and in order to better understand their systemic relevance and relative impact on multi sectoral and societal drought risk in in socio hydrological systems in forested cold climates. Such information is valuable when designing vulnerability assessments in the climate region, as common approaches often involve combining several vulnerability factors into a vulnerability index, used to assess the vulnerability of a study region(Blauhut et al., 2016). Index-based vulnerability assessments often incorporate vulnerability factors either by assigning them equal weights (Fekete, 2012; Tate, 2012), indicating that each factor has the same influence on drought risk (Tate, 2013), or by assigning weights to capture the relative importance of each factor on the vulnerability profile of the study area (Engström et al., 2020; Meza et al., 2020; Ortega-Gaucin et al., 2018). Whilst index-based approaches are a simplification of the complex and dynamic nature of vulnerability, it has been shown that assigning weights to the incorporated vulnerability factors, can improve the precision and robustness of the assessments (Martín et al., 2017; Moshir Panahi et al., 2023) and provides a deeper understanding of societal heterogeneities (Moreira et al., 2023) and local specificities(Martín et al., 2017). A commonly used method for assigning weights is to incorporate expert knowledge through stakeholder engagement. For example, Martín et al. (2017) involved an expert panel consisting of local practitioners for adjusting indicator weights to their community vulnerability index for natural hazards, and Hung and Chen (2013) used an analytic network process involving focus group meetings

144 for assessing vulnerability to climatic hazards in a river basin in Taiwan ~~User validation is a powerful tool for~~
145 ~~gaining insights from end users and leveraging collective knowledge to ensure the selected factors are appropriate~~
146 ~~for their intended use (Rykiel, 1996).~~ . Similarly, ~~This approach was previously utilized by~~ Meza et al. (2019)
147 used a survey study to ~~study~~ assess the relative importance of drought vulnerability ~~factors~~ indicators for
148 agriculture and water supply on a global scale. The importance of vulnerability factors vary depending on study
149 region and incorporating participatory weighting techniques offer valuable insights into the distinct characteristics
150 of an area or region (Moreira et al., 2023). ~~However, there are currently no studies on~~ Hence, expert knowledge
151 and stakeholder perceptions can help identify drought vulnerability factors in forested cold climates specifically
152 adapted to ~~end user~~ stakeholder needs in different socio-economic sectors. Furthermore, index-based approaches
153 incorporating multisectoral or holistic perspectives usually focus on a combination of sectors such as agriculture,
154 water supply ~~(Shiravand and Bayat, 2023)~~, energy, and industry (Engström et al., 2020; Kim et al., 2015; Radeva
155 and Nikolova, 2020; Shiravand and Bayat, 2023; Wang and Sun, 2023), often failing to incorporate the forestry
156 sector which is an important sector in forested climate regions and forestry-dependent economies. Meanwhile,
157 Melo et al. (2020) and Tidwell (2016) argued for the importance of forests for water, energy, and food securities
158 and the need to update nexus perspectives to include a forest dimension when analyzing multi-sectoral
159 vulnerability to natural and socio-economic hazards (Melo et al., 2020).
160 .
161

162 ~~Hence, this paper provides a comprehensive analysis of the most impactful drought vulnerability factors for water~~
163 ~~dependent sectors and societies in forested cold climates, validating their relevance for effective drought risk~~
164 ~~management.~~ This paper aims to fill this gap and identify the most influential drought vulnerability factors for
165 sectoral and cross sectoral vulnerability in forested cold climates, thereby informing applied vulnerability
166 assessments, integrated drought risk management efforts, and whole-of-society adaptation efforts. Using the
167 conceptual framework proposed by Stenfors et al. (2024), the research objectives for this paper are to (1) ~~identify~~
168 ~~relevant~~ assess the sectoral and cross-sectoral relevance of previously identified drought vulnerability factors for
169 water-dependent sectors as well as society in forested cold climates, (2) determine their relative rankings through
170 the use of impact scores, (3) identify the highest-rated vulnerability factors for sectoral and cross sectoral
171 ~~individual water dependent sectors~~ and societ~~y~~al vulnerability, (4) explore variations in ratings among the
172 respondents, hypothesizing that impact ratings would vary based on ~~end use~~stakeholder's (i) sectorial focus or
173 type of organization, (ii) geographical location, (iii) level of drought experience, and lastly to (5) improve the
174 current understanding of drought vulnerability by presenting newly discovered vulnerability factors reported by
175 the respondents.

2   Methods

2.1   Study area

178 This study focuses on Sweden in northern Europe. With a population of 10.5 million people over a land area of
179 approximately 408,000 km^2, Sweden has an average population density of approximately 25,8 inhabitants per
180 square kilometer where the northern inland areas are much less populated compared to the southern and coastal
181 areas of the country.   Forestry and agriculture make up 2,5% and 1,3% of Sweden's GDP respectively. Energy
182 production is made up of nuclear (30%), hydropower (35-45%), and wind power (18-20%).

183 Sweden is divided into three climate zones according to the Köppen-Geiger classification (Beck et al., 2018). The
184 climate ranges from tundra (ET) in the Scandinavian Mountains in north-western Sweden with monthly mean
185 temperatures below 10 °C, subarctic boreal (Dfc) climate with cool summers, very cold winter, and seasonal snow
186 cover and soil frost during winters in central and northern Sweden, and a warm-summer hemi boreal (Dfb) climate
187 zone in southern Sweden. Most areas currently classified as Dfb and Dfc climate zones are projected to shift into
188 Cfb and Dfb climates respectively by 2070–2100 (Beck et al., 2018). A majority of Sweden's land area is covered
189 by forests (69%), followed by wetlands (9%), shrubs and grassland (8%), agriculture (8%), human settlements
190 (3%) and open land (3%) (SLU, 2015). It has historically been seen as a country with abundant water resources,
191 with an average annual precipitation of 784 mm during the period of 1961-2020 combined with low
192 evapotranspiration. The mean annual temperature during the period was 2.6 °C, with an increasing temperature
193 corresponding to 0,037 °C per year or a total warming of 2.2 °C during the observation period (Teutschbein et al.,
194 2023b).

195

196 Sweden has three levels of government: national, regional and local. On a regional level, Sweden is divided into
197 21 counties whose political tasks are divided between regional councils and county administrative boards.
198 Regional councils comprise county-elected decision-makers, while the county administrative boards are
199 government bodies within the counties. At the local level, Sweden has 290 municipalities, each with an elected
200 municipal council that handles municipal decision making. From a water management perspective, Sweden is
201 divided into five water districts, based on the bounds of major sea basins and catchment areas. As a result, the

regional and local authorities can be part of more than one water district. Each water district is appointed one of the county administrative boards to act as the water district authority. The water district authority manages the aquatic environment in the water district by, for example, preparing management and action plans, coordinating water management work on county administrative boards and municipalities, and collaborating with authorities and other interested bodies on national to local level. Local authorities are responsible for providing water supply, either directly or through municipally owned water enterprises. According to Statistics Sweden (2022), a large majority of Swedish households (87%) are connected to public drinking water networks, where approximately 51% comes from surface water. However, there are regional differences in household connectivity to public drinking water, ranging from 69% in Gotland to 94% of Stockholm county (Statistics Sweden, 2022).

The agricultural sector accounts for four percent of the total freshwater water use in Sweden, with large regional variations (Vattenuttag, 2024). Freshwater use in the agricultural sector mainly comprises crop irrigation and drinking water for animals. The majority of irrigation water is used in the southern-most county Skåne in Sweden (56% of total water use for irrigation) that accounts for 41% of the irrigable area (i.e. the maximum area that can be irrigated using available equipment and water) in Sweden (Statistics Sweden, 2022). However, there are large uncertainties regarding the amount of water used for irrigation as well as its water source. Surveys conducted in the 1970s and 1980s, showed that 85% of irrigation water use came from surface waters and the rest was mainly from private groundwater aquifers. During 2020, industrial water use accounted for 2 097 million cubic meter of water use, out of which 47% was used as cooling water in electricity production. There are three water intensive industries that account for approximately 80% of the total industrial water use: paper & pulp industry, chemical production, and steel and metal works (Statistics Sweden, 2022).

The 2018 drought had several impacts on Sweden. The combination of high temperatures and low precipitation gave rise to hydrological and agricultural droughts in several parts of the country (Sjökvist et al., 2019; Stensen et al., 2019). It impacted sectors including energy, agriculture, water, and forestry, along with the environment, and resulted in various societal effects (Sjökvist et al., 2019). Crop yields for a variety of crops were halved compared to the five-year average (Lantmännen, 2018), resulting in an estimated loss of more than 900 million USD[1] in irretrievable harvests (LRF, 2019). Furthermore, harvest losses and dry conditions created a pasture and fodder shortage for farm animals and emergency slaughter increased drastically with waiting times being up to six months long (Sjökvist et al., 2019). Consequently, availability of grains, dairy product and meat was reduced. The drought impacts on the hydrological system also affected several sectors. Inflow to hydropower reservoirs was exceptionally low, which ultimately created a 50-70% rise in electricity prices during the summer of 2018 (Sjökvist et al., 2019). Several Swedish municipalities saw water shortages, where 85 municipalities introduced restrictions on irrigation and 100 municipalities urged its inhabitants to lower their water consumption (Krisinformation, 2018). The reduced water flows also had an impact on ecosystems. For example, water courses housing important nursery habitats for salmon and sea trout dried up (S. V. T. Nyheter, 2018). The dry conditions of 2018 also resulted in forest fires over large areas in Sweden. Forest resources worth 84 million USD[1] were lost due to the fires (Sjökvist et al., 2019). Several Swedish counties were affected and in total 25 000 forest hectares were lost, with more than 500 individual forest fires identified during the period (MSB, 2018).

---

[1] Currency as of February 2025: 1 USD = 10.75 SEK

2.2 The original drought vulnerability framework

Based on the conceptual framework described by Stenfors et al. (2024), vulnerability factors can be divided into three categories connected to the attributes of (1) direct water consumers (here-after: sectoral factors), i.e., groups or sectors that use water directly (e.g., irrigation or drinking water), (2) indirect water consumers (societal factors), which consist of groups or sectors that use water indirectly by consuming goods that require water for their production (e.g., food or energy), (3) governance processes and plans (governance), that is governing processes, policies, tools, and plans that affect a sector or society's ability to cope and adapt to drought (~~Figure 1~~). As such, governance factors can affect the vulnerability of both individual sectors and society as a whole.

The conceptual model adheres to the IPCC AR6's (IPCC, 2022) definition of vulnerability, i.e., *"vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt". S*usceptibility is an elements' predisposition to harm by an external or internal stressor, coping capacity is its ability to react and respond to a stressor and adaptive capacity is its ability to learn from past stressors and anticipate future stressors. The conceptual model was developed on the basis of a literature review, identifying vulnerability factors studied or applied in countries with forested ecoregions and cold or continental climates. After analysis, the 83 identified vulnerability factors were divided into those relating to *sectors* as direct water consumers (51 factors), *society* as indirect water consumers (9 factors), and *governance* affecting all water consumers (23 factors), forming the conceptual framework for the present study. These identified vulnerability factors are related to adaptive capacity, coping capacity or susceptibility and can be broadly subcategorized into ten categories based on their overall attributes (Table 1~~Table 1~~), with the full list of vulnerability factors and their corresponding subcategories available in the supplementary materials (S1, S2).

Table 1. Overview of the number of sectoral, societal, and governance vulnerability factors included in the survey, divided into ten subcategories based ~~too~~on their general attributes. Short names for each subcategory, which are used in the results section, are shown in parenthesis. The subcategories are also marked to indicate whether they involve factors related to adaptive capacity (A), coping capacity (C) and/or susceptibility (S) (Stenfors at al. 2024).

Subcategory (Short name)	Total	Sectors	Society	Governance	A	C	S
Societal properties and demographics (Demographics)	3		3				●
Available funds and financial capacity (Funds)	5	5				●	●
Characteristics of authority (Authority)	6			6		●	
Presence of irrigation (Irrigation)	4	4				●	
Presence of policies and plans (Policies)	9			9	●	●	
Conditions of surrounding setting (Setting)	14	9	5			●	●
Species characteristics (Species)	9	9			●		●
Presence of Anthropogenic stress (Stress)	8	8					●
Water supply (Supply)	11	10	1		●	●	●
Availability of tools and resources (tools)	14	6		8	●	●	
Total	**83**	**51**	**9**	**23**			

2.3 Data Collection & Analysis

2.3.1 Survey design

In order to find vulnerability factors relevant for Swedish water-dependent sectors as well as society, an online survey was designed based on the vulnerability factors identified by Stenfors et al. (2024). The survey targeted six water dependent sectors: energy (i.e., hydropower, nuclear, thermal etc.), agricultural (i.e., crop, animal husbandry etc.), environmental (aquatic and terrestrial ecosystems), water supply (drinking water production and distribution), water resources (water resource management), forestry (conservation and production) and water intensive industry (i.e. paper and pulp, chemical production, or steel and metal works).

The survey was designed using a 5-point rating scale where stakeholders from different sectors (from now on called "respondents") were asked to rate vulnerability factors based on their perceived impact on drought risk in their sector on a scale from 0 (no impact) to 4 (high impact). The respondents could also opt out by selecting "I don't know" to each factor. After rating the chosen factors, the respondents were asked to rank how confident they were in their rating on a 5-point scale ranging from 0 (highly unsure) to 4 (highly confident).

The survey was divided into three sections: (1) collection of background information on respondents, (2) rating of vulnerability factors for particular sectors, and (3) rating of vulnerability factors for society as a whole. In order to analyze the results in relation to experience, sector, organization type and location, respondents were asked in section one to provide information on their primary sectorial focus, the type of organization they belonged to, and the Swedish county they primarily operated in. They were also asked to judge their level of experience and knowledge concerning drought-related issues in their field on a scale of 0 (no experience) to 4 (large experience). Section two focused on sector-specific vulnerability, where respondents were asked to rate 51 sectoral drought vulnerability factors as well as the 23 vulnerability factors related to governance, on the impact on drought risk in their sectors. All respondents were presented the same list of sectoral and governance vulnerability factors, regardless of what sector they primarily worked with. This allowed for comparative analysis of what factors are regarded as relevant and irrelevant for the different sectors. Section three addressed societal vulnerability and included the 23 governance factors as well as 9 societal factors, common to all respondents. In this section, respondents were asked to rate the impact of these factors on drought risk for Swedish society. The respondents were also given the opportunity to suggest their own additional factors in both section two and three. As described above, the same 23 governance factors were included in both section two and section three in order to analyze the impact of these factors on sectoral as well as societal drought vulnerability separately.

The survey was designed in English and Swedish, and respondents could choose their preferred language. All survey questions and corresponding response options are presented in the Supplementary materials (S8).

2.3.2 Survey recipient selection

With the aim of identifying and selecting potential recipients of the survey, a recipient identification matrix was designed. The matrix used five criteria:

- **Knowledge** – can the recipient potentially provide insight into drought vulnerability in their sector?
- **Sector** – is the potential recipient part of one of our surveyed sectors?
- **Location** – where in Sweden is the potential recipient located and do they improve the geographical spread of knowledge attainment?

304   •   **Organisation type –** does the potential recipient belong to one of our surveyed interest groups (i.e.
305   governmental/local authority, academia/research institute, private/state/municipal owned organization,
306   regional/national sector association, or NGO)?
307   •   **Scale -** does the potential recipient primarily operate on national/regional/local scale (applied to the
308   stakeholder groups: governmental/local authority, NGO and regional/national sector association)?

309 Using the identification matrix, survey recipients from governmental/local authorities (354 recipients),

310 private/state/municipal owned enterprises (81), academia/research institutes (46), regional/national trade

311 associations (45), and NGOs (35) were identified. Generic contact lists for municipalities (290), counties (21) and

312 authority owned competence centers (31) were collected from official sites (SKL.se and naturvardsverket.se).

313 Contact information for individual recipients within the different organization types were identified using three

314 approaches, (1) internet searches combining their organization name and keyworks in Swedish such as "drought"

315 and "water shortage" (30 respondents), (2) searching their organization websites for keywords "drought" and

316 "water shortage" (37), (3) using the general contact information provided on the organization website (143).

317 Furthermore, individual recipients were found through snowballing, where authors or contributors in articles or

318 projects related to drought or water shortages were included (4 recipients).

319

2.3.3 Analysis of survey responses

320
321 All survey responses were transferred and analyzed using Microsoft Excel and RStudio. The survey responses
322 were evaluated using a four-step approach:

323 I. Data cleaning: Initially, survey responses were screened for respondents answering "I don't know"
324   consistently on all factors. These respondents were removed from further analysis.

325 II. Data preparation: To analyze geographical differences, responses were categorized as belonging to counties
326   located in northern (above 60 °N) and southern (below 60°N) Sweden.

327 III. Identification of key factors: Following Meza et al. (2019), factors were considered relevant for a sector if
328   50% or more of the respondents within that sector considered them as having medium high or high impact
329   (corresponding to median scores of 3 or 4) on drought risk. For even number responses, the lower integer
330   median was used. Relevant sectoral vulnerability factors were identified using the median rating for each
331   factor, grouped by sector. As the survey only received one response for the sector "Water intensive industry"
332   and one response that did not indicate its sectorial focus, these two respondents were excluded in the analysis
333   of sectorial factors. For societal factors, relevant vulnerability factors were identified using the median rating
334   per vulnerability factor grouped by the respondents' organization type. To handle "I don't know" responses
335   for individual factors, we used a deletion-based available-case method, also known as pair-wise deletion (Xu
336   et al., 2022). This approach excluded respondents who chose the "I don't know" option only from the
337   analyses related to that specific factor. Consequently, we were able to utilize more of the collected data
338   across various analyses, though each factor rating may be derived from a different subset of respondents.

339 IV. Ranking of key factors using impact scores: The ratings for the factors identified as relevant in step III
340   (ranging from 0 to 4), were normalized to bring them into the range between 0 (no impact) and 1 (high
341   impact), using 0.25 step increments. The factor impact score was then calculated as the mean rating, based
342   on the normalized ratings. Factor impact scores were calculated for each sector and organization type
343   respectively. Factors with an impact score close to 1 are highly impactful on drought risk, whereas indicators
344   with an impact score closer to 0 have less overall impact on drought risk albeit still being relevant for the
345   respondents. The identified impact can be either positive or negative, depending on the vulnerability factor.

346 To test our hypotheses related to the variability of impact ratings of vulnerability factors (ordinal data) identified
347 as relevant in step III, we utilized the Kruskall-Wallis test by ranks. If significant differences between
348 groups/categories were identified, the data was further ~~analyzed~~analysed using pairwise Wilcoxon rank sum tests
349 to calculate pairwise comparisons between group levels with corrections for multiple testing. Kruskal-Wallis test
350 by ranks and Wilcoxon rank sum, are non-parametric tests that can be applied for ordinal data, and have previously
351 been used for assessing differences between group ratings in studies involving participatory approaches and
352 ordinal data (i.e., Cuesta et al., 2022; Mızrak and Aslan, 2020; Teutschbein et al., 2023a). Hypothesis testing of
353 ratings depending on geographical location and drought experience was only carried out for respondent groups
354 with three or more responses for each response alternative (Geographical location: North versus South, Drought
355 experience: limited (rating 0-1), moderate (2), significant (3-4)). Consequently, differences in factor ratings per
356 geographical location was only carried out for the environmental and forestry sector, and for respondents working
357 in authorities or enterprises. Impact of drought experience on factor ratings was studied for the environmental,
358 water resources and water supply sector and for respondents working in authorities.

3 Synthesis of Results

3.1 Respondent characteristics and experience

The survey received 108 responses, corresponding to a 19.3% response rate. Six respondents were solely answering "I don't know" and were removed from further analysis. Out of the remaining 102 responses, 61% of respondents were working at an authority (i.e., governmental, municipal, county administrative board) (Table 2Table 2). Approximately 19% of respondent were working with research (i.e., in academia or at a research institute), followed by enterprises (private, municipal-, or state-owned) (12%), trade associations (7%), or NGOs (2%). Most of the respondents had a sectorial focus on the environmental (34%) or water supply sectors (15.7%), followed by the water resource (14.7%), forestry (13.7%), agricultural (12.8%), and energy sector (6.9%). Only one respondent was working in a water intensive industry and one respondent did not provide a sectorial focus. Within the sectors, a majority of agricultural respondents were working with crop production (54%), animal husbandry (15%), a combination of crop production, animal husbandry and vegetable production (8%), and the rest reported focusing on other forms of agricultural activities (23%). Respondents from the energy sector were mainly working with hydropower (86%), and all water supply respondents were working with drinking water production and distribution (100%). Roughly half of the respondents from the environmental sector worked with both aquatic and terrestrial ecosystems (46%), or either aquatic (236%) or terrestrial (29%) ecosystems respectively. Most respondents from the forestry sector reported working with forestry production (43%) or nature conservation (29%). The water resources sector mainly consisted of respondents working with water resources management (73%). The majority of respondents (84%) was located in southern Sweden. Respondents from northern Sweden (16%) worked at either an authority, enterprise or with research. Apart from water intensive industries and water resources, at least one response was given for both northern and southern Sweden for all sectors. However, only the environmental and forestry sector received more than two responses by respondents located in northern Sweden. A detailed overview of the respondents can be found in the supplementary materials (S4, S5).

Table 2. Overview of respondents, their geographical location divided by north (above 60 °N) and south (below 60 °N), and (a) type of organization, (b) primary sectoral focus.

	North	South	Total
a) Type of organization			
Authority	9	53	**62**
Governmental authority		*12*	*12*
County administrative board	*1*	*1*	*2*
Region	*1*	*4*	*5*
Municipality	*7*	*35*	*42*
Unspecified		*1*	*1*
Research	2	17	**19**
NGO		2	**2**
Enterprise	5	7	**12**
Trade association		7	**7**
Grand Total	**16**	**86**	**102**
b) Sectoral focus			
Agricultural	1	12	**13**
Energy	2	5	**7**
Environmental	7	28	**35**
Forestry	4	10	**14**
Unspecified		1	**1**
Water intensive industry		1	**1**
Water resources		15	**15**
Water supply	2	14	**16**
Grand Total	**16**	**86**	**102**

More than half of the respondents had more than 10 years of experience in their field of work (59%), and significant experience (experience rating of three or higher) concerning drought-related issues (56%). Respondents from the forestry, agricultural and energy sector had a large share of respondents with significant experience in droughts (over 70% of respondents in each sector) (Table 3). The environmental sector had the largest spread in drought experience, where ~~approximately 40~~37 % indicated having a significant experience of drought. Looking at drought experience by place of employment - enterprise, trade association, or research respondent groups had the highest percentage of respondents with significant drought experience. Respondents from authorities had the largest spread, where ~~approximately 50~~47% of respondents had significant experience of drought. Most respondents indicated that they were moderately confident in the factor ratings they provided for drought vulnerability in their sector (43%) and for society as a whole (47%). Approximately one third of the respondents reported having high confidence in their vulnerability factor ratings concerning vulnerability in their sector (33%) as well as for society as a whole (28%), with the rest reporting little to no confidence in their ratings.

Table 3. Drought experience as indicated by the respondents by sector as well as place of employment (0-1 signifies little to no experience, 2 moderate experience, 3-4 significant experience of drought-related issues). Respondents from water intensive industries (1) and with unspecified (1) sectoral focus are excluded from the sector count, and only included in the organization counts.

Sector/organization	Drought experience (% of respondents)			Number of respondents
	Limited (rating 0-1)	Moderate (2)	Significant (3-4)	
Agricultural	8~~1~~	15~~2~~	77~~10~~	13
Energy	14~~1~~	14~~1~~	71~~5~~	7
Environmental	23~~8~~	40~~14~~	37~~13~~	35
Forestry		21~~3~~	79~~11~~	14
Water resources	20~~3~~	27~~4~~	53~~8~~	15
Water supply	19~~3~~	19~~3~~	63~~10~~	16
Grand Total	**16**	**27**	**57**	**100**
Authority	23~~14~~	31~~19~~	47~~29~~	62
Enterprise		33~~4~~	67~~8~~	12
NGO	50~~1~~		50~~1~~	2
Research	5~~1~~	26~~5~~	68~~13~~	19
Trade association	14~~1~~		86~~6~~	7
Grand Total	**17~~17~~**	**27~~28~~**	**56~~57~~**	**102**

3.2   Relevance of vulnerability factors for sectors, society, and governance

Respondents representing the agricultural sector indicated the highest number of *sectoral* factors as being relevant (i.e. having a median rating of three or higher) on drought risk in their sector (35, out of which 21 with a median rating of four), followed by environmental (32, 4), water resources (31~~30,11~~, 12), water supply (26,~~ 9~~8), energy (~~10~~11, 2), and forestry (10, 0) (Table 4~~Table 4~~).

Table 4. The number of (a) sectoral, (b) societal, and (c) governance vulnerability factors included in the survey, the total number of factors considered relevant by one or more water dependent sector or societal organization (i.e., with a median score of 3 or higher), and the number of factors considered relevant by each water dependent sector or societal organization separately. The factor count is divided to represent adaptive capacity, coping capacity and susceptibility as well as subcategories describing the overall attributes of the factors. The subcategories are (see also **Table 1**~~Table 1~~): the societal properties and demographics (short: demographics), available funds and financial capacity (funds), characteristics of authority (authority), presence of irrigation (irrigation), presence of policies and plans (policies), the conditions of the surrounding setting (setting), species characteristics (species), presence of anthropogenic stress (stress), available water supply (supply), and availability of tools and resources (tools). As the respondents were asked to rate factors related to governance (c) both from a sectoral as well as societal perspective, factor relevance is included for both sectors and organizations.

a) *Sectoral vulnerability factors*

		Literature review	Relevant Sector (for >=1 sector)	Relevant Society (for >=1 org.)	Agricultural	Energy	Environmental	Water resources	Water supply	Forestry	Authority	Enterprise	Research	Trade association
					Sectors						**Organizations (society)**			
Sectoral	**Adaptive**	**10**	**9**	**-**	**7**	**1**	**8**	**7**	**4**	**2**	**-**	**-**	**-**	**-**
	Species	2	2	-	1		2			1	-	-	-	-
	Supply	2	2	-	2	1	2	2	1		-	-	-	-
	Tools	6	5	-	4		4	5	3	1	-	-	-	-
	Coping	**10**	**9**	**-**	**8**	**2**	**5**	**65**	**7**		**-**	**-**	**-**	**-**
	Funds	3	2	-	2		1	1	1		-	-	-	-
	Irrigation	4	4	-	4		1	32	3		-	-	-	-
	Supply	3	3	-	2	2	3	2	3		-	-	-	-
	Susceptibility	**31**	**28**	**-**	**20**	**87**	**19**	**18**	**15**	**8**	**-**	**-**	**-**	**-**
	Funds	2	2	-	2				2		-	-	-	-
	Setting	9	9	-	7	4	6	7	5	4	-	-	-	-
	Species	7	6	-	4		3	3		4	-	-	-	-
	Stress	8	7	-	4	32	7	5	5		-	-	-	-
	Supply	5	4	-	3	1	3	3	3		-	-	-	-
	Total	51	46	-	35	1110	32	3031	26	10	-	-	-	-

b) *Societal factors*

		Literature review	Relevant Sector	Relevant Society	Agricultural	Energy	Environmental	Water resources	Water supply	Forestry	Authority	Enterprise	Research	Trade association
Societal	**Coping**	**1**	**-**	**1**	**-**	**-**	**-**	**-**	**-**	**-**	**1**			**1**
	Setting	1	-	1	-	-	-	-	-	-	1			1
	Susceptibility	**8**	**-**	**4**	**-**	**-**	**-**	**-**	**-**	**-**	**4**	**3**	**2**	**4**
	Demographics	3	-		-	-	-	-	-	-				
	Setting	4	-	3	-	-	-	-	-	-	3	2	1	3
	Supply	1	-	1							1	1	1	1
	Total	**9**	**-**	**5**	**-**	**-**	**-**	**-**	**-**	**-**	**5**	**3**	**2**	**5**

c) *Governance factors*

		Literature review	Relevant Sector	Relevant Society	Agricultural	Energy	Environmental	Water resources	Water supply	Forestry	Authority	Enterprise	Research	Trade association
Governance	**Adaptive**	**9**	**9**	**9**	**8**	**3**	**6**	**8**	**8**	**1**	**9**	**37**	**78**	**8**
	Policies	2	2	2	1	1	2	1	1		2	1	1	1
	Tools	7	7	7	7	2	4	7	7	1	7	36	67	7
	Coping	**14**	**13**	**14**	**12**	**63**	**11**	**12**	**12**	**1**	**14**	**4**	**9**	**1211**
	Authority	6	5	63	5	1	3	4	4	1	63	1	42	43
	Policies	7	7	73	6	53	7	7	7		73	13	41	72
	Tools	1	1	17	1		1	1	1		17	3	15	6
	Total	**23**	**223**	**23**	**20**	**96**	**17**	**20**	**20**	**2**	**23**	**117**	**1617**	**1920**

When examining the *sectoral* vulnerability factors based on their connection to adaptive capacity, coping capacity or susceptibility, it was observed that all three categories of vulnerability contain factors that are relevant to one or more water dependents sectors. However, factors relating to the susceptibility of the surrounding settings was the only category of factors that was considered relevant by all sectors. Respondents from all sectors found at least

44% of factors relating to this category, as relevant for drought risk. Similarly, factors relating to the adaptive and coping capacity for water supply, were considered relevant by all sectors except forestry. Instead, the forestry sector mainly found factors relating to species characteristics affecting susceptibility and adaptive capacity, and tools for adaptive capacity as relevant for their sector. Additionally, forestry was the only sector to not find any factors categorized as relating to coping capacity to be relevant for the sector.

nine out of ten sectoral vulnerability factors related to adaptive capacity were considered relevant by at least one sector. The agricultural, environmental, and water resources sector found the largest number of adaptive factors relevant, where the agricultural sector rated at least one factor in each subcategory as relevant for the sector. Conversely, the forestry and energy sector, found the least number of adaptive factors as relevant, where the energy sector only found factors related water supply relevant and the forestry sector found factors related to species characteristics and available tools and resources as relevant.

From the perspective of coping capacity, nine out of ten sectoral factors related to coping capacity were considered relevant by at least one sector. The agricultural sector found the largest number of coping factors relevant, where respondents for example rated all factors relating to the presence of irrigation and two out of three factors related to available funds and financial capacity as relevant. Similarly, the environmental and water supply sectors rated all coping factors concerning water supply as relevant.

Lastly, respondents rated 28 sectoral vulnerability factors connected to susceptibility as relevant to drought risk in their respective sectors. Similar to factors for coping and adaptive capacity, the agricultural sector had the largest number of susceptibility factors seen as relevant for their sector. Among the susceptibility factors, the agricultural and water resources sector found seven out of nine factors relevant concerning the conditions of the surrounding settings (setting), and the environmental sector found seven out of eight factors relating to anthropogenic stress (stress) as relevant for their sector.

Respondents from authorities and trade associations found the largest number of *societal* vulnerability factors as relevant, rating 4 out of 8 factors relating to all categories of societal vulnerability, except *demographics*, as relevant for societal drought risk. This was followed by trade associations (3), enterprises (2) and researchers (1). Interestingly, the Among societal factors, the subcategory *"demographics"* was the only category that was not considered relevant for societal drought risk by any of the respondents groups. In contrast, almost all All 23 vulnerability factors connected to *governance* were relevant for both sectoral vulnerability in at least one sector as well as for vulnerability of society as a whole. Among the sectors, the agricultural, water supply and water resources sectors found the largest number of governance factors as relevant for the sector. When looking at governance factors by place of employment, respondents from authorities found all governance factors relevant for drought risk in society.

3.3   Impact scores for vulnerability factors for sectors, society and governance

The evaluation of *sectoral* vulnerability factors revealed that the agricultural sector accounted for several of the highest impact scores, with impact scores for factors concerning irrigation close to 1 (Figure 1Figure 2). Conversely, the lowest impact scores for the sectoral factors were provided by the energy and forestry sector. The forestry sector tended to rate factors relating to water supply low, giving these factors the lowest impact scores among the sectors. The smallest spread among the impact scores were connected to the conditions of the surrounding settings, where most many sectoral factors included in the subcategory received overall medium high

466   to high impact scores by all sectors, even if the factors were not considered relevant for all sectors. Another

467   category of factors that generally see a slightly smaller spread across different sectors is relating to the presence

468   of tools and resources for adaptive capacity. Even though the forestry and energy sector only found a limited

469   number of factors in the category relevant (one factor each), this category was the only category to not receive

470   impact scores lower than 0.33 by any sector for any of the involved factors. Interestingly, the environmental sector,

471   which had the largest number of respondents among the sectors, gives most factors relating to adaptive capacity

472   similar impact scores. Comparatively, the variation in impacts scores by the environmental sector is larger for

473   factors relating to coping capacity and susceptibility.

Figure 12. Impact scores for sectoral vulnerability factors concerning adaptive capacity (adaptive), coping capacity (coping), and susceptibility, rated regarding their impact on drought risk in water dependent sectors. Filled dots indicate that the factor is considered relevant for the sector (i.e., with a median score of 3 or higher), whereas open circles indicate that the factor is not considered relevant. The point size signifies the percentage of respondents within a sector that provided an impact rating for the factor.

480

481 The five relevant factors relating to *society* were all highly rated by respondents from authorities and trade

482 associations, whereas respondents from research, enterprises and NGOs gave slightly lower impact scores (Figure

483 2~~Figure 3~~). Respondents from all types of organization included in the survey found '*the societal financial*

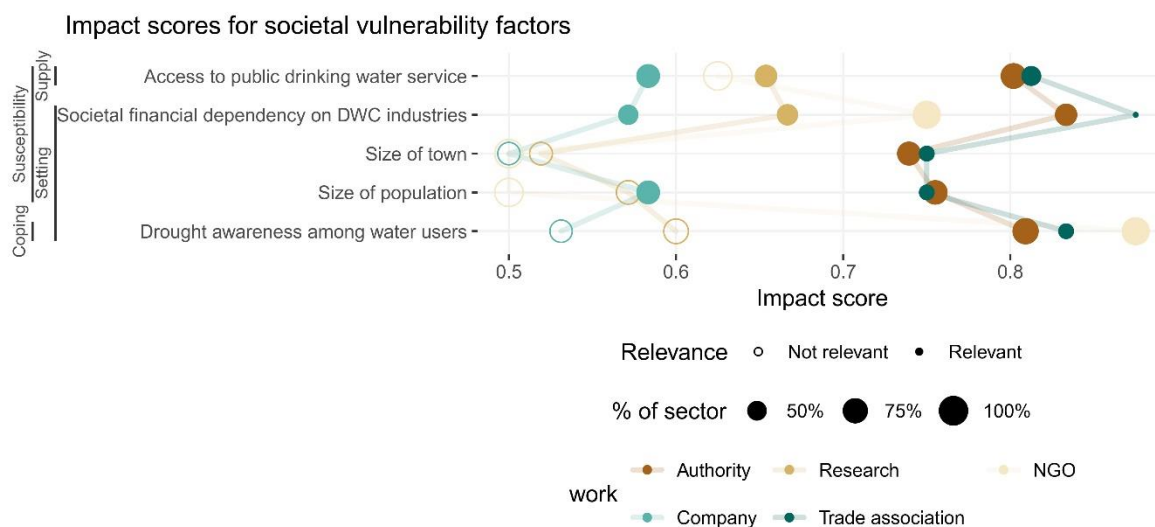
484 *dependency on direct water consuming industries (DWC)*' as relevant for societal drought risk. Apart from this,

485 respondents from research only found '*access to public drinking water*' relevant for societal drought risk, whereas

486 NGOs found the '*drought awareness of water users*' relevant as well as highly impactful. Enterprises found

487 '*access to public drinking water*' and '*the size of population*' to be relevant for societal drought risk, but not rating

488 them   highly.

489

490 **Figure 2~~3~~. Impact scores for societal vulnerability factors concerning coping capacity (coping), and susceptibility, rated**
491 **regarding their impact on societal drought risk. Filled dots indicate that the factor is considered relevant by the**
492 **organization (i.e., with a median score of 3 or higher), whereas open circles indicate that the factor is not considered**
493 **relevant. The point size signifies the percentage of respondents within an organization that provided an impact rating**
494 **for the factor.**

495 Factors relating to *governance* generally receive slightly higher impact scores, both concerning their impact on

496 sectors as well as society, compared to sectoral factors (Figure 3~~Figure 4~~). For example, all factors received impact

497 scores of 0.25 or higher, with the exception for the governance factors '*defined water-use rights*', '*social/physical*

498 *capacity of authorities to offer drought related support*', and '*building standards relating to water efficiency*'.

499 Apart from two factors relating to having a drought management plan, all factors concerning policies and plans

500 that affect coping capacity, were considered relevant for all sectors except forestry, as well as for society as a

501 whole. Overall, four factors receive impact scores of 0.5 or higher by all sectors: '*drought awareness within*

502 *authorities*', '*access to relevant data concerning drought*', '*availability of long-term supply and demand*

503 *assessments*', and '*availability of a drought risk assessment*'. However, no governance factors were considered

504 relevant across all sectors, due partly to the low number of factors considered relevant by the forestry sector. The

505 energy and forestry sector, provided the lowest impact scores for several of the governance factors concerning the

506 impact on drought risk in their sectors. Meanwhile, the highest impact score given by the energy sector, for any

507 sectoral or governance factor, was given to the governance factor '*defined water-use rights*'. This factor was rated

508 highly by respondents across all sectors apart from forestry. Respondents also rated this factor highly when

509 looking at its impact on drought risk for society as a whole. Other governance factors that received high impact

510 scores for sectoral and societal drought risk by at least five sectors were '*having a local water management plan*

511 or '*an authority-level coordinated water strategy*', '*the drought awareness within authorities*', '*having access to*
512 *relevant data concerning drought*', and '*long-term supply and demand ~~assessments~~assessments*'.

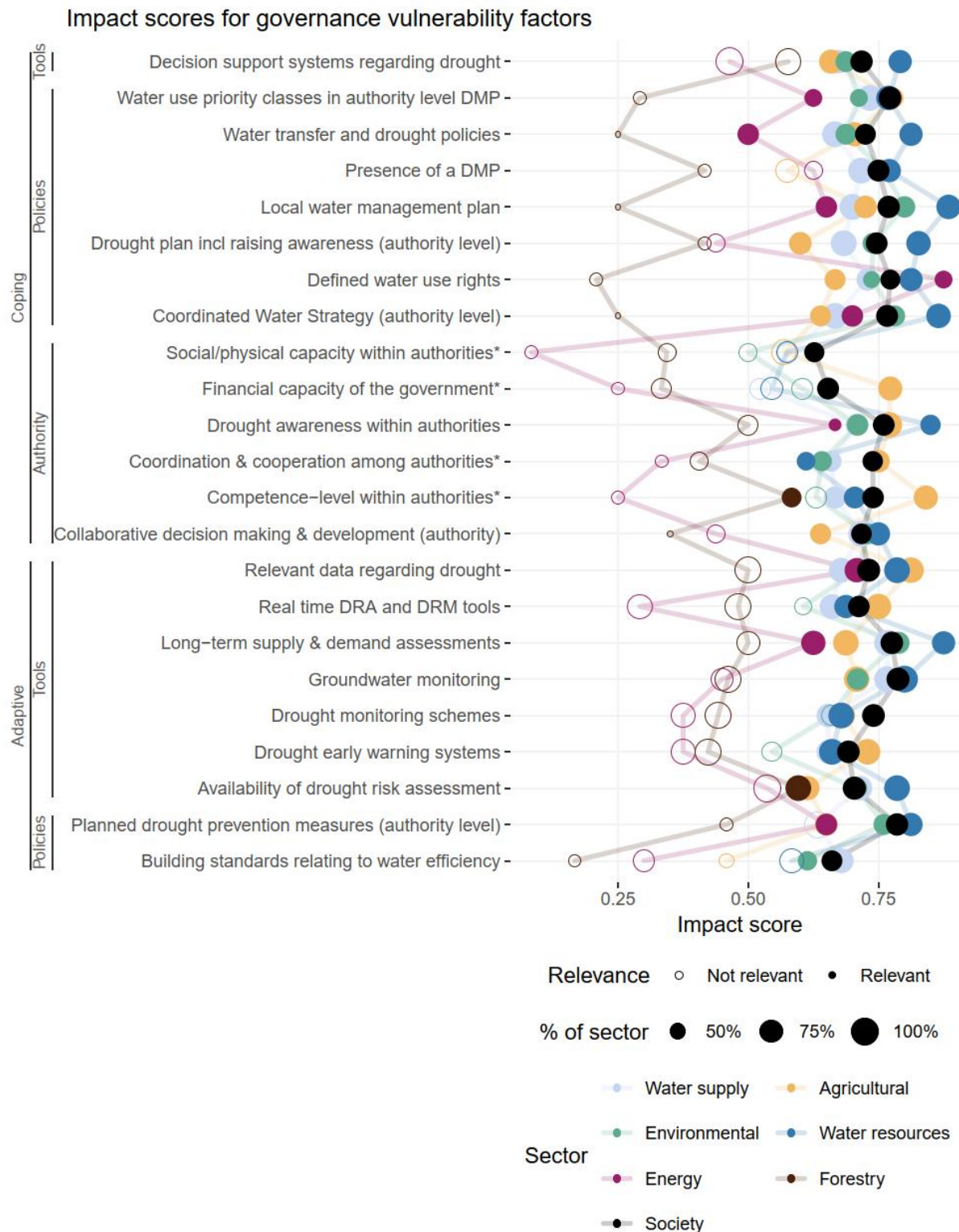



Figure 34. Impact scores for governance related vulnerability factors concerning adaptive capacity (adaptive) and coping capacity (coping) rated both regarding their impact on drought risk in sectors as well as society as a whole.
Filled dots indicate that the factor is considered relevant for the sector or for societal drought risk (i.e., with a median score of 3 or higher), whereas open circles indicate that the factor is not considered relevant. The point size signifies percentage of the respondents within a sector that provided an impact rating for the factor.

3.4 Highest rated vulnerability factors for sectors, society and governance

519

520 Looking at the highest rated *sectoral* vulnerability factors across different sectors, most of the factors were

521 connected to coping capacity or susceptibility ~~or coping capacity~~ (Table 5~~Table 5~~). Only two of the most highly

522 rated sectoral factors concerned adaptive capacity. Certain factors received high impact scores by more than one

523 sector. For example, the soil water holding capacity was among the highest rated factors for the agricultural,

524 environmental and forestry sector. Similarly, the presence of baseline water stress received high impact scores

525 from the agricultural, environmental and water resources sector, and the presence of wetlands lakes and ponds

526 received high impact scores from the energy, environmental and water resources sector. This was reflected in the

527 overall highest rated sectoral factors, for all sectors combined, where the three vulnerability factors received the

528 highest impact scores, followed by ~~presence of water dependent ecosystems and~~ the geographical characteristics

529 and having a reliable water resource for water supply.~~.~~

530 Adaptive- and susceptibility-related factors were the only vulnerability factors to receive high impact~~s~~ scores by

531 the energy and forestry sector, where the energy sector found the presence of wetlands, lakes and ponds, the

532 geographical characteristics, and the possibilities for development of water storage as factors with high impact on

533 drought risk. The forestry sector on the other hand, gave the highest impact score to having growth limiting

534 conditions, followed by the soil water holding capacity and the drought tolerance of current species.

535 **Table 5. The five highest normalized impact scores, where ~~(S)~~ the letters in parentheses indicate vulnerability factors**
536 **concerning ~~susceptibility,~~adaptive capacity (A), coping capacity (C), or ~~adaptive capacity~~susceptibility (A~~S~~). Highly**
537 **rated factors for a sector with the same impact scores are listed arbitrarily. ~~Factors that are highly rated by one or~~**
538 **~~more sector are colored (one color per factor) for easier detectability and navigation in the table.~~**

All sectors

(S) Soil water holding capacity~~(S) Presence of wetlands, lakes and ponds~~	0,8~~2~~0
(S) ~~Soil water holding capacity~~Baseline water stress	0,~~81~~79
(S) ~~Baseline water stress~~Presence of wetlands lakes and ponds	0,~~81~~78
(S) The geographical characteristics~~(S) Water dependent ecosystems~~	0,~~76~~75
(S) ~~The geographical characteristics~~Reliable water resource for water supply	0,~~75~~73

Agricultural		**Energy**	
(C) Water available for irrigation during drought	0.98	(S) Presence of wetlands, lakes and ponds	0,75
(C) Use of effective irrigation systems	0.98	(S) The geographical characteristics	0,75
(C) Use of irrigation	0.94	(A) Possibilities for development of water storage	0,70
(S) Soil water holding capacity	0.92	(S) The elevation	0,70
(S) Reliable water resource for water supply	0.92	(S) Distribution of hydropower plants	0,68
(S) Baseline water stress	0.92		

Environmental		**Forestry**	
(S) Presence of wetlands, lakes and ponds	0,91~~0,93~~	(S) Growth limiting conditions	0.79
(S) Water dependent ecosystems	0,88~~0,90~~	(S) Soil water holding capacity	0.75
(S) Baseline water stress	0,84~~0,85~~	(S) Drought tolerance of current species	0.75
(S) Soil water holding capacity	0,82	(A) Species shift for climate adaptation	0.73
(S) Deteriorating ecosystems	0,79~~0,81~~	(S) Drought resilient seedlings	0.73

Water resources		**Water supply**	
(S) Baseline water stress	0,94	(S) Access to public drinking water service	0,88
(S) Presence of wetlands, lakes and ponds	0,88	(S) The geographical characteristics	0,86
(S) Reliable water resource for water supply	0,87	(S) Reliable water resource for water supply	0,83
(S) Soil water holding capacity	0,82	(C) Alternative water source & water supply	0,83
(S) Water dependent ecosystems	0,81	(C) Sectoral actor's level of available assets	0,83

540 Five *societal* factors were considered relevant by the respondents, where the highest rated factor, the financial

541 dependency of society on direct water consuming (short: DWC) industries, was connected to susceptibility. This

542 was followed by having access to public drinking water services, the drought awareness among water-users, the

543 population size and the size of town. ~~As was seen for~~Similar to the sectoral ratings, access to public drinking water

544 was also highly rated by sectors such as the agricultural, environmental, and water resources sector and being the

545 highest rated factor for the water supply sector.

546 Looking at the highest rated *governance* factors, a majority of the factors were related to coping capacity (Table

547 6~~Table 6~~). Several of the highest rated factors, when respondents rated the impact of governance factors on their

548 sectors, received high impact scores by more than one sector. For example, factors such as having a local water

549 management plan, an authority level coordinated water strategy and the drought awareness within authorities were

550 among the highest rated governance factors for several sectors. The energy and water supply sector both rated

551 having defined water use rights highly, whereas respondents from the agricultural and forestry sectors rated the

552 competence level within authorities to offer drought related support highly. Looking instead at the highest rated

553 governance factors from a societal perspective, presence of groundwater monitoring appears as the highest rated

554 vulnerability factor, closely followed by having planned drought prevention measures at authority level, access to

555 long-term supply and demand assessments, defined water-use rights, and having water-use priority classes in

556 authority level drought management plans (short: DMP).

557 **Table 6. The five highest impact scores for a) governance factors rated on their impact on sectoral drought risk, b)**
558 **societal factors, rated on their impact on societal drought risk, c) governance factors rated on their impact on societal**
559 **drought risk. The letters in parentheses~~(S)~~ indicates vulnerability factors concerning adaptive capacity (A)**
560 **~~susceptibility~~, coping capacity (C), or susceptibility (S) ~~adaptive capacity (A)~~. ~~Factors that are highly rated by more~~**
561 **~~than one sector are colored (one color per factor) for easier detectability and navigation in the table.~~**

a) Impact scores for governance factors for sectors

Agricultural		Energy	
(C) Competence-level within authorities*	0,841	(C) Defined water-use rights	0,875
(A) Relevant data regarding drought	0,813	(A) Relevant data regarding drought	0,708
(C) Water use priority classes in authority level DMP	0,778	(C) Coordinated Water Strategy (authority level)	0,700
(C) Financial capacity of the government*	0,773	(C) Drought awareness within authorities	0,667
(C) Drought awareness within authorities	0,771	(C) Local water management plan	0,650
Environmental		**Forestry**	
(C) Local water management plan	0,800	(A) Availability of drought risk assessment	0,596
(A) Long-term supply & demand assessments	0,788	(C) Competence-level within authorities*	0,583
(C) Coordinated Water Strategy (authority level)	0,781	*(C) Decision support systems regarding drought*	*0,577*
(A) Planned drought prevention measures (authority level)	0,760	*(A) Long-term supply & demand assessments*	*0,500*
(C) Presence of a DMP	0,760	*(A) Relevant data regarding drought*	*0,500*
Water resources		**Water supply**	
(C) Local water management plan	0,885	(A) Long-term supply & demand assessments	0,767
(A) Long-term supply & demand assessments	0,875	(A) Groundwater monitoring	0,767
(C) Coordinated Water Strategy (authority level)	0,865	(C) Water use priority classes in authority level DMP	0,733
(C) Drought awareness within authorities	0,850	(C) Defined water-use rights	0,729
(C) Drought plan incl raising awareness (authority level)	0,827	(C) Presence of a DMP	0,717

b) Impact scores for societal factors for society as a whole

c) Impact scores for governance factors for society as a whole

Societal factors		Governance factors	
(S) Societal financial dependency on DWC industries	0,773	(A) Groundwater monitoring	0,788
		(A) Planned drought prevention measures (authority level)	0,786
(S) Access to public drinking water service	0,750	(A) Long-term supply & demand assessments	0,776
(C) Drought awareness among water users	0,747	(C) Defined water-use rights	0,773
(S) Size of population	0,695	(C) Water use priority classes in authority level DMP	0,772
(S) Size of town	0,668		

562 **3.5 Variations in impact ratings based on sectoral focus, place of employment, geographical location or**

563 **drought experience**

564 Our assessment of *sectoral* factors uncovered significant differences in factors ratings depending on the

565 respondent's sectoral focus for 39 31 sectoral factors (Figure 4a). The forestry sector stood out, having significant

566 differences in impact ratings (p-value <0,05) for several sectoral factors compared to respondents from the

567 agricultural (significant differences seen for 21 factors), environmental (20 factors), water supply (18), and water

568 resources (17) sectors. The main differences were seen for factors connected to water supply, irrigation, and

569 anthropogenic stress. Respondents from the energy sector rated 18 factors significantly different from the

570 agricultural sector, where the differences primarily were seen for factors connected to species characteristics,

571 irrigation and available water supply. Significant differences in factor ratings concerning these three subcategories

572 as well as species characteristics were also seen between the water supply and agricultural sector (11). The impact

573 of place of employment on the sectoral ratings was studied for the environmental, water supply and forestry sector.

574 These sectors had multiple respondents working for at least two different organizations. However, no significant

575 differences were seen in ratings, depending on place of employment for the forestry and environmental sector.

576 For the agricultural sector, significant differences in ratings were only seen for the factor '*Geographical*

577 *characteristics*' (p-value 0.04), between respondents working in research (median rating 2) and trade associations

578 (median rating 4). An overview of the sectoral factors with significant differences in impact ratings can be found

579 in supplementary materials (S6)

580 Significant differences in sectoral factor ratings depending on geographical location were only found for the

581 vulnerability factor '*Geographical characteristics*' (p-value 0.03), by respondents from the environmental sector

582 located in southern Sweden (n = 28) versus the north (7), with an average impact score of 0.73 and 1.00

583 respectively. No significant differences were found between sectoral factor ratings depending on the reported

584 drought experience.

585 No significant difference in *societal* factor ratings were seen per place of employment. When studying factors

586 from a geographical perspective, respondents from northern Sweden found one societal factor relevant for societal

587 drought risk, compared to four factors by respondents from southern Sweden. Respondents from both north and

588 south of Sweden found the societal financial dependency on direct water consuming industries as relevant for

589 societal drought risk. However, no significant differences in societal factor ratings were seen neither between

590 respondents working in enterprises nor authorities in the two locations. Similarly, no significant differences in

591 societal factor ratings depending on the reported drought experience were seen.

592 When looking at differences in factor ratings for the 23 *governance* factors from a sectoral perspective, significant

593 differences were seen for eight factors. Here it was clear that respondents from the forestry sector rated governance

594 factors differently compared to the other sectors, as all significant differences involves the sector. Respondents

595 from the water resources and environmental sector gave significantly different ratings compared to the forestry

596 sector (for seven and five factors respectively), where a majority of the factors were related to water-and drought

597   related policies and plans. ~~This was followed by the agricultural (2), water supply (2) and energy (1) sector~~. When

598   comparing governance factor ratings from a societal perspective per place of employment (Figure 4b), significant

599   differences in factor ratings were found between respondents from authorities and enterprises (2) and research

600   respectively (3). The differences in ratings between the authorities, enterprises and research were seen for the

601   same two governance factors; *'the financial capacity of the government'* and *'the social/physical capacity within*

602   *authorities'* to offer drought related support, where authorities and research also rated the presence of water

603   transfer- and drought policies significantly differently. All governance factors that saw significant differences in

604   impact ratings between sectors or organizations are presented in the supplementary materials (S7).

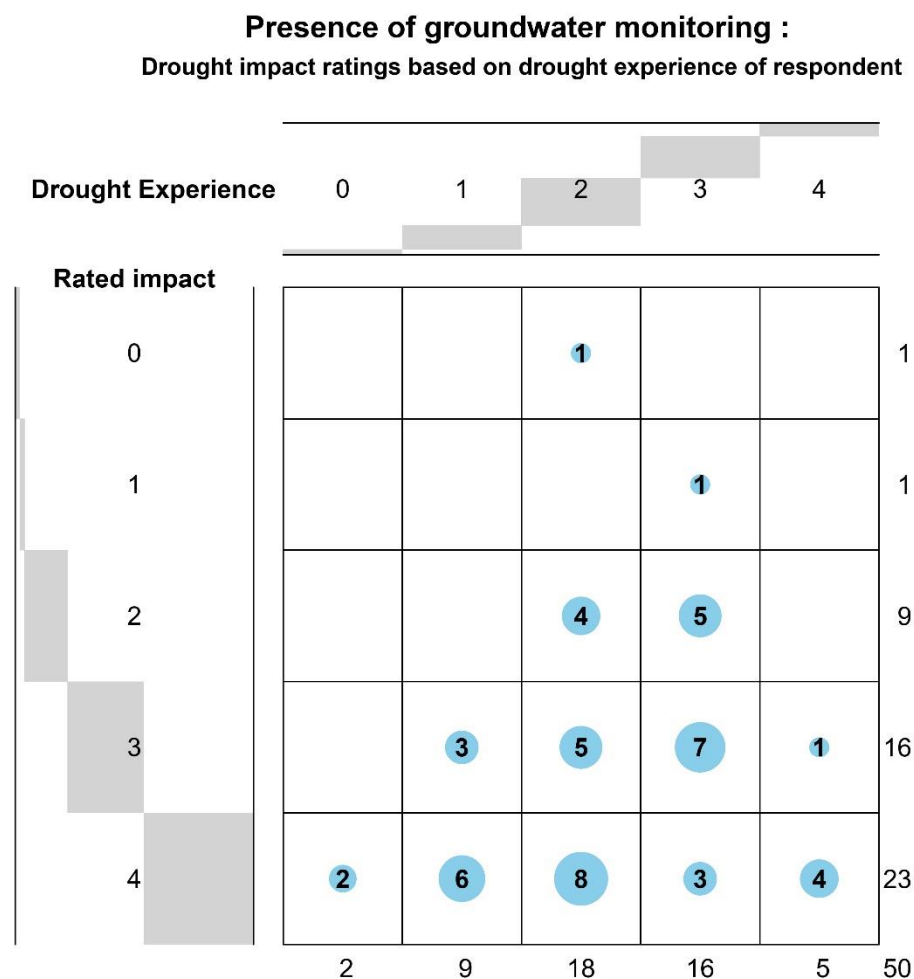
a) Sectoral vulnerability

Sectoral	Water supply (1)	Agricultural (2)	Environmental (3)	Water resources (4)	Energy (5)	Forestry (6)
Funds						
Dependency on sector as only source of income		6				2
Sectoral actor's level of available assets	6	6				1 2
Sectoral actor's level of solvency	3 4 5 6	3 4 5 6	1 2	1 2	1 2	1 2
Irrigation						
Apt size of water permits to sustain irrigation	2 6	1 3 5 6	2 6	6	2	1 2 3 4
Use of effective irrigation systems	2 6	1 3 4 5 6	2 6	2 6	2	1 2 3 4
Use of irrigation	2 6	1 3 4 5 6	2 6	2 5 6	2 4	1 2 3 4
Water available for irrigation during drought	2 6	1 3 4 5 6	2 6	2 6	2	1 2 3 4
Setting						
Presence of wetlands, lakes and ponds		3	2 6	6		3 4
Productivity of land	2 5	1 3 4 5 6	2 5	2	1 2 3 6	2 5
Proportion of fertile soils	2	1 3 4 5 6	2 5	2	2 3	2
Water dependent ecosystems	3		1 6	6		3 4
Species						
Drought resilient seedlings	2	1 5	5		2 3 6	5
Drought resilient stand mixtures		5	5		2 3 6	5
Drought tolerance of current species	2	1 5	5		2 3 6	5
Shallow rooted crops/species	2	1 5			2 6	5
Species shift for climate adaptation (forests)	6				6	1 5
Species suitable for future drought projections		5	5		2 3	
Stress						
Baseline water stress	6	5 6	6	6	2	1 2 3 4
Competing water interests	6	6	6	6		1 2 3 4
Deteriorating ecosystems	3		1 5 6		3	3
Land and soil degradation	5	5	5 6		1 2 3	3
Level of groundwater exploitation	6	6	6	6		1 2 3 4
Water quality deterioration	5 6	6	5 6	6	1 3	1 2 3 4
Supply						
Access to public drinking water service	5 6	5 6	5 6	5 6	1 2 3 4	1 2 3 4
Alternative water source & water supply	6	6	6	6		1 2 3 4
Funding for small scale water projects	2 3 4	1 5 6	1 5 6	1 5 6	2 3 4	2 3 4
Permanent water restrictions	6	3 4 6	2 6	2		1 2 3
Possibilities for development of water storage	6	6	6	6		1 2 3 4
Possibility to expand irrigation practices	2 6	1 3 4 5 6	2 6	2 6	2	1 2 3 4
Regional water distribution networks	6	6	6	6		1 2 3 4
Reliable water resource for water suply	5 6	5 6	6	5 6	1 2 4	1 2 3 4
Governance						
Policies						
Coordinated Water Strategy (authority level)			6	6		3 4
Defined water use rights	6	6	6	6	6	1 2 3 4 5
Drought plan incl raising awareness (authority level)				6		4
Local water management plan			6	6		3 4
Water transfer and drought policies			6	6		3 4
Tools						
Groundwater monitoring	6			6		1 4
Long-term supply & demand assessments			6	6		3 4
Relevant data regarding drought		6				2

b) Societal vulnerability

Governance	Authority (1)	Research (2)	NGO (3)	Enterprise (4)	Trade association (5)
Authority					
Financial capacity of the government*	2 4	1		1	
Social/physical capacity within authorities*	2 4	1		1	
Policies					
Water transfer and drought policies	2	1			

Figure 4. Factors where significant differences (p < 0.05) based on pairwise Wilcoxon rank sum test were observed. Differences in vulnerability factors ratings were observed for a) sectoral actors rating sectoral and governance factors, and b) respondents working in different types of organizations rating governance factors for societal vulnerability. One or more coloured and numbered dots in a column indicate that the sector/organization had significant differences in factor ratings compared to these sectors/organizations. The calculated p-values are found in Supplementary material S6 and S7.

All governance factors were seen as relevant for societal drought risk by respondents from southern Sweden, whereas respondents located in the north found 20 factors relevant. However, no significant differences in governance factor ratings were seen between respondents located in the north, versus south of Sweden, neither for ratings for individual sectors nor society. Significant differences in factor ratings depending on reported drought experience was only seen for the governance factor '*presence of groundwater monitoring*' (p-value 0.042). The factor was generally rated impactful by respondents regardless of the level of drought experience (Figure 5). However, respondents that reported having moderate to moderately significant drought experience (indicating a drought experience rating of two or three), seemed to have a larger spread in their ratings for that factor.

Presence of groundwater monitoring :
Drought impact ratings based on drought experience of respondent

627   3.73.6 **New vulnerability factors identified in the survey**

628   The possibility for the respondents to add their own factors, produced a list of additional sectorial factors (Figure

629   5Figure 6). Out of the additional factors added, the only factor mentioned by more than one respondent was "forest

630   fires" which was mentioned by two respondents.

631   The largest number of additional sectorial factors came from respondents representing the environmental sector,

632   such as factors concerning knowledge of water management among decision makers as well as landowners, and

633   anthropogenic changes to surface waters and water courses (by lowering lake surfaces, dikes, straightening and

634   clearing of water courses). The respondents from this sector also added factors concerning forests, revolving

635   around the area used for production forest and natural forests and presence of forest damages. For the agricultural

636   sector, several of the additional factors suggested revolved around the presence or availability of information on

637   adaptation strategies and knowledge-/evidence-based policies. Financial factors were also mentioned, such as the

638   profitability of investments.

639   Societal factors included a combination of biophysical and socio-economic factors. For example, forest fires,

640   geography and presence of dikes and other anthropogenic changes to water courses were mentioned as impactful

641   vulnerability factors for Swedish society. From a governance perspective, factors such as planning for climate

642   adaptation and coordination between climate adaptation and civil defense were mentioned. One respondent raised

643   the importance of understanding the actual responsibility of different authority levels during drought.

Figure 56. New factors that were mentioned by the respondents divided by sector (as expressed by respondents from the agricultural (yellow), environmental (light green), forestry (dark green), and water supply (blue)) sector and societal factors (pink).

648   **4   Discussion**

649   ~~This study investigated the relative importance of drought vulnerability factors in a Nordic country through user-~~

650   ~~validation. While several studies have assessed drought vulnerability in similar climates and ecozones (Stenfors~~

651   ~~et al., 2024), this is the first attempt to validate a comprehensive list of vulnerability factors for forested cold~~

climate zones and investigate their relative impact on drought risk in the region. Respondents from seven water-dependent sectors were given the opportunity to rate the impact of numerous vulnerability factors, some of which had not been previously used in vulnerability assessments for their sector, providing potential new insights into sectoral drought vulnerability. This study investigated societal, sectoral, and cross-sectoral drought vulnerability factors in a Nordic country based on stakeholder perceptions. Respondents from authorities, private enterprises, research, trade associations and NGO from seven water-dependent sectors were given the opportunity to rate the impact of numerous vulnerability factors, some of which had not been previously used in drought vulnerability assessments for their sector, providing new insights into sectoral and societal drought vulnerability. Results show that each sector has their unique vulnerability profile, however some vulnerability factors are impactful for more than one sector. Among the included sectors, the forestry sector stands out, finding only a low number of listed vulnerability factors to be relevant.

4.1 Capturing the complexity of drought vulnerability

The fact that approximately 90% of the factors used in the literature were deemed relevant by end usersthe stakeholders underscores the broad range of elements that contribute to sector-specific and societal vulnerabilities. The results highlight the complexity of drought vulnerability, showing that a combination of several different factors impacts the overall drought risk of a sector or society as a whole. This finding aligns with studies from other world regions. F, which also identified large numbers of vulnerability factors: For instance, Moshir Panahi et al. (2023) identifiedfound that 44 vulnerability factors played a role in drought vulnerability for Iran when using an impact-based method combined with expert weighting, arguing that the wide range of effective drought vulnerability factors, provides evidence of its complexity. Similar to our results, Moshir Panahi et al. (2023) found that water resources, ecological, and agricultural systems had some of the largest number of factors driving vulnerability. For agricultural and ecological systems, this could reflect the sectors' reliance on both the ecological resilience of species and surrounding settings, as well as on access to reliable water supply. Interestingly, the results show that the respondents working with water resource management, also see factors relating to both ecological resilience as well as water supply as important for the sector. This emphasizes the role of terrestrial ecosystems services for water resource management (Tidwell, 2016), as drought impacts on ecosystem health can affect for example water retention, water quality (Stefanski et al., 2025) as well as stream temperatures (Raheem et al., 2019).

In Meza et al. (2019)'s survey on global drought indicators for agriculture and water supply, 45 vulnerability indicators out of 64 total, were rated as relevant for the agricultural sector. When comparing the top five most relevant indicators identified in their study (i.e. dependency on agriculture for livelihood, cultivation of drought resistant crops, irrigated land, existence of adaptation policies & plans, degree of land degradation & desertification), all factors are among the sectoral and governance factors rated as relevant by agricultural respondents in Sweden. However, when comparing their final impact scores, only the presence of irrigation is included in the five highest rated factors in both studies. Somewhat surprisingly, in contrast to the results from Meza et al. (2019), baseline water stress is not among the five highest rated vulnerability for Swedish water suppliers. However, both baseline water stress and competing water interest do receive high impact scores by the respondents working in the water supply sector. Still, these findings highlight the importance of locally-relevant

692 vulnerability factors, and that the relevance of vulnerability factors can differ depending och climatological and
693 ecological context.

694

695 This information is crucial, as indicator-based assessments often use the same set of vulnerability indicators,
696 regardless of sectoral, contextual and scale-dependent differences (Hagenlocher et al., 2019). The contextual
697 nature of drought vulnerability becomes clearer when comparing our findings with the most commonly used
698 vulnerability indicators globally. For example, factors related to poverty and income are some of the most
699 commonly used vulnerability factors used in people-centered drought risk assessments globally (Hagenlocher et
700 al., 2019). Yet, none of the factors connected to demographics, which have been described and used in several
701 articles as factors connected to drought vulnerability, such as the level of social integration (Alcamo et al., 2008;
702 Erfurt et al., 2019; Hurlbert and Montana, 2015) and socio-economic susceptibility of the population (Acosta &
703 Galli, 2013; Hurlbert & Gupta, 2017; Pappné Vancsó et al., 2016; Raikes et al., 2021) were considered relevant
704 for societal drought vulnerability by the respondents. This contrasts the findings of Englund et al. (2023), who,
705 through participatory approaches, found that several aspects connected to social susceptibility (e.g., Illness &
706 disability, age, income, unemployment, housing) and social integration where important for social vulnerability
707 to floods in the Swedish municipality of Halmstad. Likewise, Turesson et al. (2024) concluded that social
708 vulnerability to climate extreme exists in Nordic countries, finding factors related to for example demographics,
709 income, and social cohesion as contributing to social vulnerability to climate risk in the study region. However,
710 as these studies are not specifically focused on drought hazard but on flood and climatic hazards in general, our
711 results could be an indication that aspects such as social integration and socio-economic susceptibility are less
712 impactful for drought risk in welfare states such as Sweden. Another potential reason for this disconnect could lie
713 in whether societal vulnerability is addressed as an individual condition or a societal one (Orru et al., 2022). In
714 our survey, respondents were asked to rate the societal vulnerability factors regarding their impact on drought risk
715 in society as a whole. Whilst social integration and socio-economic susceptibility may play an important role for
716 drought risk for the individual, the respondents may view such factors as having less impact on overall societal
717 drought risk. Alternatively, the low rated relevance for these factors, can be a reflection of an unwillingness to
718 categorize certain groups or individuals as more vulnerable than others (Orru et al., 2022), and instead putting an
719 emphasis on structural pressures and institutional tools for societal vulnerability. Looking at the factors considered
720 relevant for societal drought risk, these could be seen as relating more to factors exerting pressures on a society,
721 such as the size of population, size of town and the societal dependency on water dependent sectors. Nevertheless,
722 further research is needed to understand the role of social susceptibility for drought vulnerability in the region.

723

724 Local differences in stakeholder perceptions of societal vulnerability were also seen. Only one out of the nine
725 societal vulnerability factors was seen as relevant to societal drought risk by respondents located in the northern
726 part of Sweden, while respondents from southern Sweden rated four factors as relevant. The reasons for the low
727 number of relevant societal vulnerability factors in the north of Sweden could be several. For example, southern
728 Sweden has a much higher population density, as all urban areas with a population over 100 000 inhabitants, are
729 located below the 60th parallel. Future climate projections also generally indicate a general wetting trend in the
730 northern parts of Sweden, and drying trends in southern Sweden (Chen et al., 2021; Sjökvist et al., 2019;
731 Teutschbein et al., 2023b) that could potentially affect drought vulnerability and the perception thereof.

Furthermore, in a study by Teutschbein et al. (2023a) studying drought severity and perceived impacts of the 2017 and 2018 drought years by Swedish municipalities it was shown that the perceived impacts of the drought events decreased in a poleward direction. The study found that the municipalities located north of the 60th latitude perceive none or very weak impacts from the two drought years, as compared to municipalities located south of the 60th latitude who saw differing perceptions of the impacts, ranging from no impacts to very strong impacts. In addition, southern municipalities experienced on average more severe drought conditions than northern municipalities during the 2018 drought event (Teutschbein et al., 2023a). Such differences could potentially affect the overall perception of drought risk and drought vulnerability.

In contrast to social and societal vulnerability, some biophysical factors seem to be less contextual, and could potentially play a more general role to drought vulnerability regardless of climate and, to some extent, sectoral context. For example, factors related to soil characteristics, topography, and water resources have commonly been used globally for drought vulnerability assessments (González Tánago et al., 2016), and were considered relevant for all or most of the sectors included in this study. Likewise, technical factors such as the use of irrigation have commonly been included in vulnerability assessments (González Tánago et al., 2016; Hagenlocher et al., 2019) and were shown to be highly relevant for the agricultural sector by the respondents. Importantly, respondents from the water supply and water resources sectors also stressed the need for effective irrigation system, potentially due to the potential strain on water availability that irrigation can cause.

4.2   New insights to drought vulnerability

Letting all sectors rate the same list of factors (2020)(Moreira et al., 2023)provided new insights into the perceptions of drought vulnerability, for example for the environmental and energy sector. Stenfors et al. (2024) only found a limited number of factors concerning drought vulnerability for the environmental and energy sector in the literature. However, respondents from these sectors found several sectoral and governance factors to be relevant for their sectors. Additionally, the environmental sector also introduced the largest number of new factors suggested by the respondents, such as landowners' and decisions makers' knowledge in water management, presence of straightened water courses or dikes and the age of water permits. This implies that there may have been a significant knowledge gap in how drought vulnerability has been assessed for these sectors historically, versus how it is perceived in the sectors. (Asare-Kyei et al., 2015)Interestingly, the results in this study also showed that the energy sector shared all of its relevant vulnerability factors with several other water-dependent sectors, indicating that there are common interest points between the energy sector, and sectors such as the environmental sector and water resources. The results illustrate the importance of stakeholder engagement and participatory approaches to understand vulnerability. Local expert knowledge not only helps in assessing the relative impact and relevance of standard drought vulnerability factors, but can also introduce new information on how drought vulnerability can be used in future risk assessments(Asare-Kyei et al., 2015).

The design of the survey also enabled analysis of how vulnerability to drought is perceived within sectors, as well as across sectors. Whilst all sectors were shown to have unique vulnerability profiles, similarities across sectors could be found, and all sectors shared factors that were considered relevant and impactful for drought risk with one or more sectors. The results underscore the systemic nature of risk, where underlying societal and sectoral drought vulnerabilities can be relevant for more than one sector. They also highlight the relative importance of

these vulnerability factors in a multi-sectoral and interconnected system, thereby adding valuable insights for, for example, conducting drought risk assessments and designing adaptation policies (Hagenlocher et al., 2023; Stefanski et al., 2025). Much like what was described by Stenfors et al. (2024), respondents showed that vulnerability factors describing drought vulnerability of direct or indirect water consumers, should be combined with factors concerning the governance process, policies, tools and plans that exist to provide drought related support. This provides a roadmap for researchers and policy makers conducting drought vulnerability or risk assessments, indicating that a starting point to any assessment is by identifying the water dependencies present in the studied systems and the vulnerabilities directly connected to such stakeholders. This should then be combined with analysis of the institutional arrangements, policies, and other tools and how they function in providing drought related support in these systems. For example,(2015) the results show that governance factors connected to the presence of water- or drought-related policies were relevant for most sectors, receiving high impact scores from all sectors, except forestry, as well as for society as a whole. This suggests that policy instruments do play a crucial role for lowering drought vulnerability in socio-hydrological systems, both on a sectoral and societal level. This is consistent with several studies on climate risk, disaster and drought management, all arguing that adaptive governance is essential for managing climate-related risks (e.g., Dias et al., 2022; Hurlbert & Gupta, 2016; Nelson et al., 2008). Additionally, the results also show that not only policy instruments are of importance, but also the characteristics of authorities. For example, a majority of sectors showed the importance of drought awareness within authorities and the level of competence, coordination, and cooperation of authorities to offer drought related support. This is in line with Hurlbert and Montana (2015), who stress the importance of competence for responsiveness in water governance. Whilst such factors are difficult to incorporate in applied vulnerability assessments, they highlight the importance of competence-building activities, and cooperation and coordination within and across authorities for managing drought risk. It also shows a limitation of strictly indicator-based vulnerability assessments. Basing vulnerability assessments on strictly measurable, available data provides a starting point for assessing vulnerability, but may overlook important aspects of system vulnerability that cannot be measured or included in such types of assessments. Consequently, the results of indicator-based vulnerability assessments should preferably be put in a wider perspective, stressing such limitations.

From a sectoral perspective, the results highlight that combining governance factors with factors related to the surrounding settings, anthropogenic stress (such as baseline water stress, or competing water interests), and water supply is important when conducting drought vulnerability assessments incorporating vulnerability to drinking water production, energy production, agriculture and the environment. Such factors should then be combined with sector specific vulnerabilities, to further enhance the quality and detail of vulnerability assessments. For such assessments, the calculated impacts scores not only show the impact of the factors within a specific sector, but highlight the patterns of interconnectedness between these sectors. Out of all the sectoral factors, the only two factors that were considered relevant for all sectors were the soil water holding capacity and the geographical characteristics. This indicates that these vulnerability factors are relevant across all water-dependent sectors included in this study, and should preferably be included in drought vulnerability assessments, if possible. (Hagenlocher et al., 2023; Stefanski et al., 2025) It also underscores, the issue of using the same set of vulnerability factors independent of sectoral perspectives (Hagenlocher et al., 2019). Whilst significant differences in factor ratings could be seen between the forestry sector and all other sectors, both regarding sectoral as well as

governance factors, the sector shared most of its identified factors with at least one sector. Incorporating the forestry sector in holistic risk assessments or nexus-approaches has been stressed (Melo et al., 2020; Tidwell, 2016), and the results provide a starting point for inclusion of the sector in factor-based vulnerability assessments. However, whilst both the forestry and agricultural sector share factors relating to for example species characteristics, it is important to note the differences in crop/species rotation time between the two systems. Such temporal differences may have an impact on for example the two sectors' capacity to adapt in the short term. However, as this article mainly focuses on differences in vulnerability perspectives depending on sectoral, societal and regional differences, further research is needed to better understand the influence and incorporation of temporal scales in vulnerability assessments and adaptation efforts.

(Hagenlocher et al., 2019)(2007)(Hagenlocher et al., 2023; Stefanski et al., 2025)In the conceptual framework proposed by Stenfors et al. (2024), the sectoral factors for assessing drought vulnerability in direct water consuming sectors can be divided into vulnerability factors relevant when studying droughts on blue or green water resources respectively, as well as factors that are universally relevant for all direct water consuming sectors, regardless of where in the hydrological system the drought is located. In the conceptual model, blue water entails water available as surface or groundwater, while green water represents water stored as soil moisture in the unsaturated zone (Falkenmark and Rockström, 2006). Consequently, the most relevant vulnerability factors for a sector would be related to whether or not they are mainly dependent on blue or green water resources. This could be seen in some of the sectoral ratings, where respondents from the energy, water supply and water resources sectors tend to give lower impact scores or find certain factors irrelevant for their sectors, whilst the same factors receive high impact scores from respondents from the forestry, environmental and agricultural sector. Conversely, in certain subcategories of sectoral factors, such as available water supply, and availability of water and/or drought related policies and plans the forestry sector does not find any factor relevant for their sector. Further research is needed to better understand how the type of water dependency can influence the relevance of vulnerability factors as well as their impact scores as this would have implications on how factors are chosen when performing vulnerability assessments.

4.3   Implications for whole of society adaptation and policy design

The results provide details on potential areas for adaptation both for specific sectors as well as from a multi-sectoral perspective. For example, several factors relating to water supply and anthropogenic stresses on water supply were considered relevant for many of the sectors. This gives an indication that efforts on for example minimizing water consumption (to reduce baseline water stress), and sourcing reliable or alternative water sources are valuable tools for addressing drought risk for several sectors. Combining such efforts with tools for groundwater and drought monitoring, and policy development focusing on water management and drought prevention is important. Here, respondents stress the importance of having defined water use rights, and water use priority classes. Efforts should also be focused, not only on policy development, but for competence building within and across authorities to be able to provide drought support for a range of water dependent-sectors in the case of droughts, and for coordination and cooperation across authority levels.

849 5   (2019)(2023)(2024)(Orru et al., 2022)(Orru et al., 2022), whereas Ahmadalipour and Morakhani
850 (2018) found 36 relevant vulnerability factors based on expert knowledge for Africa.

851 Out of the 51 sectoral, 8 societal and 23 governance drought vulnerability factors identified in the literature review
852 by Stenfors et al. (2024), 46 sectoral factors were found relevant for sectoral vulnerability and five societal factors
853 were found relevant for societal drought risk by at least one sector or organization type respectively. All 23
854 governance related factors included in the survey were found to be relevant by at least one sector or organization
855 type, for both sectoral drought vulnerability as well as vulnerability for society as a whole. The results highlighted
856 the complexity of drought vulnerability, showing that a combination of different factors impacts the overall
857 drought risk of a sector or society as a whole. The fact that 90% of the factors used in the literature were deemed
858 relevant by end users underscores the broad range of elements that contribute to sector-specific vulnerabilities.
859 This finding aligns with studies from other world regions, which also identified large numbers of vulnerability
860 factors: For instance, Moshir Panahi et al. (2023) identified 44 vulnerability factors for Iran using an impact-based
861 method, whereas Ahmadalipour and Morakhani (2018) found 36 relevant vulnerability factors based on expert
862 knowledge for Africa.

863 The survey included several factors connected to the vulnerability concepts susceptibility, coping capacity and
864 adaptive capacity as described by IPCC AR6 (IPCC, 2022). A vast majority of the factors were considered relevant
865 by at least one actor, however, some factors connected to either adaptive capacity, coping capacity or susceptibility
866 were not considered relevant by the actors included in this survey. This could potentially be a result of regional
867 differences, where some factors are less generalizable than others. In general, factors relating to susceptibility and
868 coping capacity receive the highest impact scores for both sectoral and societal vulnerability factors. Whether this
869 is due to the nature of these factors, potentially being more observable during drought events compared to those
870 associated with adaptive capacity requires further research.(Berman et al., 2012)(Smit and Wandel, 2006) out of
871 all the sectoral factors, the only two factors that were considered relevant for all sectors were the soil water holding
872 capacity and the geographical characteristics, indicating that these vulnerability factors are relevant across all
873 water-dependent sectors included in this study. The two factors are both connected to susceptibility, as they
874 provide insight into an area's predisposition to being affected by a drought.

875 Out of the seven subcategories of sectoral vulnerability factors, three subcategories had all their initial
876 vulnerability factors rated as relevant for drought risk by at least one sector in the survey. These were vulnerability
877 factors connected to the conditions of the surrounding settings, presence of irrigation, available tools and
878 resources. All sectors found more than one sectoral factor relating to the conditions of the surrounding settings as
879 relevant. This suggest that the category involves vulnerability factors that are of high importance to several sectors
880 and could be a potential starting point when analyzing effective measures for drought risk. Additionally, available
881 water supply is a category with vulnerability factors that are seen as relevant for several different sectors, where
882 seven out of eight factors were rated relevant by at least three different sectors. However, out of all the sectoral
883 factors, the only two factors that were considered relevant for all sectors were the soil water holding capacity and
884 the geographical characteristics, indicating that these vulnerability factors are relevant across all water-dependent
885 sectors included in this study. The two factors are both connected to susceptibility, as they provide insight into an
886 area's predisposition to being affected by a drought.

887 Differences emerged between the number of factors rated as relevant depending on the sector or organization type
888 that the respondent belonged to, where for example respondents from the agricultural sector and authorities
889 identified the largest number of vulnerability factors as relevant for their sector or on society, respectively. Out of

the initial 51 sectoral and 23 governance related factors that were included in the survey, the agricultural sector rated 35 and 20 factors respectively as relevant for their sector. In Meza et al. (2019)'s survey on global drought indicators for agriculture and water supply, 45 vulnerability indicators out of 64 total, were rated as relevant for the agricultural sector. When comparing the top five most relevant indicators identified in their study (i.e. dependency on agriculture for livelihood, cultivation of drought-resistant crops, irrigated land, existence of adaptation policies & plans, degree of land degradation & desertification), all factors are among the sectoral and governance factors rated as relevant by agricultural respondents in Sweden. However, when comparing their final impact scores, only the presence of irrigation is included in the five highest rated factors in both studies.

Somewhat surprisingly, in contrast to the results from Meza et al. (2019), baseline water stress is not among the five highest rated vulnerability for Swedish water suppliers. However, the sector instead includes sectoral factors related, for example, to having a reliable as well as alternative water source and the geographical characteristics among its highest rated factors. These factors will also affect the water availability for the sector. Furthermore, when looking at the factors receiving an impact score higher than 0.75, several factors relating to water availability is seen, for example, baseline water stress (0.8) is included, as well competing water interests (0.75). These findings clearly emphasize the importance of locally relevant vulnerability factors, and highlight that factors for forested cold climate can substantially differ from other (e.g. arid) climate regions.

When looking at sectoral differences, responses from the forestry sector stand out compared to the other sectors for several of the vulnerability factors. The sector generally rates factors relating to water supply and irrigation lower than the other sectors, whereas vulnerability factors concerning species characteristics receive higher impact scores. The sector only found two governance factors relevant for drought risk, namely the competence level within authorities to offer drought-related support, and the availability of a drought risk assessment. Significant differences in factor ratings could be seen between the forestry sector and all other sectors, both regarding sectoral as well as governance factors. The differences mainly occurred for factors relating to surface or groundwater availability, or irrigation, which may be an indication that such factors are of differing importance for the sector. As for the energy sector, the survey identified 16 vulnerability factors, comprising sectoral or governance factors, considered relevant for drought risk in the sector. The relevant vulnerability factors were connected to the presence of policies and plans, the conditions of surrounding settings, anthropogenic stress, available water supply, and availability of tools and resources. This can be compared with the limited number of factors that were found in the literature in connection to drought vulnerability for the energy sector, such as the distribution and age of hydropower and lack of strategic reserves used by De Stefano et al. (2015) and water stress by Ahopelto et al.(2019). Most of these factors were considered relevant by the respondents, such as baseline water stress and the distribution of hydropower plants. However, the age of hydropower plants was not considered relevant, nor the availability of alternative or reliable water resources. Nevertheless, the lack of strategic reserves, could potentially be linked to the possibilities for development of water storage, a factor that was rated as relevant by the respondents from the energy sector. Interestingly, the results in this study showed that this sector shared all of its relevant vulnerability factors with several other water-dependent sectors, indicating that there are common interest points between the energy sector, and sectors such as the environmental sector and water resources.

Much like the energy sector, Stenfors et al. (2024) only found seven factors concerning environmental drought vulnerability in the literature. However, the respondents from this sector rated 32 sectoral factors and 17 governance factors included in the survey as being relevant for their sector. This implies that there may have been

a significant knowledge gap in how environmental drought vulnerability has been assessed historically, versus how it manifests in the sector. All factors found in the literature connected to this sector were considered relevant by the respondents, and the two highest rated vulnerability factors, '*presence of wetland, lakes and ponds*', and '*presence of water dependent ecosystems*', were both derived from literature assessing or exploring environmental vulnerability to drought (De Stefano et al., 2015; Kvaerner and Klove, 2006). Yet, several additional factors were highly rated by the environmental sector and respondents found relevant factors in all subcategories of sectoral and governance related vulnerability factors. For example, they found all factors related to policies and plans, and seven out of eight factors pertaining to anthropogenic stress as relevant for environmental drought risk. Additionally, the sector also introduced the largest number of new factors suggested by the respondents, such as landowner and decisions makers knowledge in water management, presence of straightened water courses or dikes and the age of water permits. New factors were also identified for the agricultural, water supply and forestry sectors, as well as for society as a whole. Several factors suggested for the agricultural sector and society relate to adaptive capacity, such as '*information and mainstreaming of adaptation strategies for the agricultural sector*' and the '*presence of planning and implementation of climate adaptations*'.

Five out of the nine societal factors were found to be relevant by the respondents, connected either to available water supply or the characteristics of the surrounding setting. However, none of the factors connected to demographics, which have been described and used in several articles as factors connected to drought vulnerability, such as the level of social integration (Alcamo et al., 2008; Erfurt et al., 2019; Hurlbert and Montana, 2015) and socio-economic susceptibility of the population (Acosta & Galli, 2013; Hurlbert & Gupta, 2017; Pappné Vancsó et al., 2016; Raikes et al., 2021) were considered relevant by the respondents. This indicates that such factors potentially are prone to regional differences and should preferably be user-validated before including them as societal factors when using the conceptual framework.

All vulnerability factors connected to governance were considered relevant by at least one sector or organization type, indicating that governance plays a pivotal role across sectors and society. Governance factors connected to the presence of water- or drought-related policies were particularly relevant for most sectors, receiving high impact scores from all sectors, except forestry, as well as for society as a whole. This suggests that policy instruments play a crucial role for lowering drought vulnerability in socio-hydrological systems, both on a sectoral and societal level. This is consistent with several studies on climate risk, disaster and drought management, all arguing that adaptive governance is essential for managing climate-related risks (e.g., Dias et al., 2022; Hurlbert & Gupta, 2016; Nelson et al., 2008). Here, factors such as '*having a local water management plan*' and '*authority level coordinated water strategies*' are seen as valuable instrument for all sectors except forestry. Furthermore, the respondents stress the importance of having defined water use rights and including water use priority classes in drought management plans.

4.4 ~~Only one out of the nine societal vulnerability factors was seen as relevant to societal drought risk by respondents located in the northern part of Sweden, while respondents from southern Sweden rated four factors as relevant. The reasons for the low number of relevant societal vulnerability factors in the north of Sweden could be several. For example, southern Sweden has a much higher population density, as all urban areas with a population over 100 000 inhabitants, are located below the 60th parallel. Future climate projections also generally indicate a general wetting trend in the northern parts of Sweden, and drying trends in southern Sweden (Chen et al., 2021; Sjökvist et al., 2019) that could potentially affect drought vulnerability and the perception thereof. Furthermore, in a study by Teutschbein, Albrecht, et al. (2023b) studying drought severity and perceived impacts of the 2017 and 2018 drought years by Swedish municipalities it was shown that the perceived impacts of the drought events decreased in a poleward direction. The study found that the municipalities located north of the 60th latitude perceive none or very weak impacts from the two drought years, as compared to municipalities located south of the 60th latitude who saw differing perceptions of the impacts, ranging from no impacts to very strong impacts. Furthermore, southern municipalities experienced on average more severe drought conditions than northern municipalities during the 2018 drought event (Teutschbein et al., 2023b). Such differences could potentially affect the overall perception of drought risk and drought vulnerability.~~ Incorporating stakeholder knowledge

Integrated stakeholder engagement in drought risk reduction is important for building drought resilience (UNDRR, 2019), and bridging the gap between scientific and practical knowledge (Moreira et al., 2023). As vulnerability is contextual, participatory approaches can provide valuable insights into regional or local circumstances (Martín et al., 2017; Moreira et al., 2023) and guide effective adaptation research and planning (Fleming et al., 2023). However, participatory approaches come with uncertainties. For example, it has been argued that the results of participatory approaches can be affected by the priorities of the involved stakeholders, as the perceptions of vulnerability will differ between local community members, industries, NGOs or authorities(Fleming et al., 2023). Our study addressed this by incorporating stakeholder working in authorities, academia, industry, trade associations and NGOs. Whilst significant differences in sectoral factors ratings were seen between sectors, the place of employment only generated significant differences in ratings for a limited number of factors. For sectoral vulnerability, this could be an indication that perception of drought vulnerability among the respondents is more closely connected to sectoral knowledge than differences in place of work. This was described by Siegrist and Árvai (2020), who suggested that people working in the same field tend to have similar risk perceptions due to their shared domain-specific knowledge and expertise. However, for societal vulnerability, no significant differences were seen depending on the place of employment or the reported drought experience of the respondents. This could imply that the ratings of societal vulnerability factors are influenced more by the respondent's subjective opinion, rather than the characteristics of the respondents, such as work or drought experience (Moreira et al., 2023). However, since a majority of stakeholder were working for authorities, the overall distribution of place of employment among the respondents may still have an effect on the overall results. For example, the impact scores of governance factors on societal vulnerability, are similar to those given for governance factors for the environmental, water supply, and water resources sectors. These respondent groups were the three largest, with a large percentage of respondents working for authorities.

1003

1004 ~~(Fleming et al., 2023)(2021)~~

1005 ## ~~5.1~~4.5 Further work

1006 ~~In the conceptual framework proposed by Stenfors et al. (2024), the sectoral factors for assessing drought~~
1007 ~~vulnerability in direct water consuming sectors can be divided into vulnerability factors relevant when studying~~
1008 ~~droughts on blue or green water resources respectively, as well as factors that are universally relevant for all direct~~
1009 ~~water consuming sectors, regardless of where in the hydrological system the drought is located. In the conceptual~~
1010 ~~model, blue water entails water available as surface or groundwater, while green water represents water stored as~~
1011 ~~soil moisture in the unsaturated zone (Falkenmark and Rockström, 2006). Consequently, the most relevant~~
1012 ~~vulnerability factors for a sector would be related to whether or not they are mainly dependent on blue or green~~
1013 ~~water resources. This could potentially be seen in some of the sectoral ratings, where respondents from the energy,~~
1014 ~~water supply and water resources sectors tend to give lower impact scores or find certain factors irrelevant for~~
1015 ~~their sectors, whilst the same factors receive high impact scores from respondents from the forestry, environmental~~
1016 ~~and agricultural sector. Conversely, in certain subcategories of sectoral factors, such as available water supply,~~
1017 ~~and availability of water and/or drought related policies and plans the forestry sector does not find any factor~~
1018 ~~relevant for their sector. Further research is needed to better understand how the type of water dependency can~~
1019 ~~influence the relevance of vulnerability factors as well as their impact scores as this would have implications on~~
1020 ~~how factors are chosen when performing vulnerability assessments.~~

1021 Our drought vulnerability survey ~~validated several~~found several vulnerability factors relevant ~~factors previously~~
1022 ~~used for~~ for drought vulnerability in water-dependent sectors, ~~as well as~~ and identified new factors that can be
1023 used when studying drought vulnerability in forested cold climates. However, relevant factors for water-dependent
1024 industries such as paper and pulp production, chemical production and steel and metal works could not be explored
1025 due to the limited amount of responses attained. ~~Furthermore, t~~The study provides a comprehensive list of context-
1026 specific drought vulnerability factors, as well as their relative impact on drought risk depending on ~~water type~~
1027 ~~dependency and~~ sector~~.,~~ but more work is needed to operationalize the factors through suitable indicators. The
1028 results are a starting point for exploring drought vulnerability in forested cold-climate countries (primarily in
1029 northern America and north-eastern Europe), and future research should aim to incorporate the factors in applied
1030 assessments to deepen the understanding of drought risk in the region.

1031 ## ~~6~~5 Conclusion

1032 To confirm and ~~identify~~ investigate relevant vulnerability factors for forested cold climates, respondents from
1033 seven water-dependent sectors employed in five different types of organizations rated drought vulnerability
1034 factors based on their perceived impact on drought risk in their sector and on society as a whole. As hypothesized,
1035 impact ratings differed depending on sectoral focus of the respondents, as well as place of employment for sectoral
1036 and societal vulnerability factors respectively, where significant differences in vulnerability ratings were seen for
1037 several of the studied factors. Furthermore, geographical differences could be seen in the number of societal
1038 vulnerability factors rated as relevant when comparing responses based on respondents' reported geographical
1039 location. Significant differences between ratings made by respondents with little to no experience of droughts
1040 compared to respondents with larger reported experience was only seen for the vulnerability factor '*presence of*
1041 *groundwater monitoring*'.

The conceptual framework proposed by Stenfors et al. (2024) for drought vulnerability in forested cold climate regions as well as the vulnerability factors it was based on, was further ~~validated~~ investigated based on the survey results. Differences in sectoral and governance related vulnerability factor ratings were seen for the included sectors. Looking at vulnerability for society as a whole, all vulnerability factors related to governance were found relevant, whereas only five societal factors were seen as relevant to drought risk by the respondents.

As previous drought events have shown, countries located in forested cold-climate zones are not exempt of drought events. The large list of vulnerability factors, identified as impactful by the sectoral stakeholders in this study, gives an indication of the complexity of drought vulnerability and the many facets in which it can affect societal sectors in these regions, ranging from available water supply, to the presence of drought-oriented policies and plans. However, factors such as the '*soil water holding capacity*' and the '*geographical characteristics*' were considered relevant by all included sectors and should preferably be included in future sectoral drought vulnerability assessments in these climates. As there is a current lack of drought risk and vulnerability assessments in some ~~Nordic~~ forested cold ~~countries~~countries such as Sweden, efforts should be made to further analyze the results obtained in this study for operationalizing the factors through development of relevant drought indicators and identification of suitable data sources. In this context, our study provides a valuable guide into drought vulnerability for six water-dependent sectors as well as for society as a whole to effectively lower drought vulnerability in water-dependent societies.

~~7~~6 Data availability

The data supporting the findings of this study were collected through an online survey with stakeholders, with assurances provided that the data would be anonymized and used solely for the purposes of the corresponding author's PhD project. Due to these ethical considerations and the privacy of the respondents, the data cannot be made publicly available. However, detailed information about the study design, data collection methods, and analysis procedures are provided within the paper. For any inquiries regarding the data, please contact the corresponding author.

~~8~~7 Author Contribution

Elin Stenfors: Conceptualization (lead); data curation (lead); formal analysis (lead); investigation (lead); methodology (lead); project administration (supporting); validation (lead); visualization (lead); writing – original draft (lead); writing – review and editing (lead). Malgorzata Blicharska: Supervision (supporting); visualization (supporting); writing – review and editing (supporting). Thomas Grabs: Conceptualization (supporting); methodology (supporting); supervision (supporting); visualization (supporting); writing – review and editing (supporting). Claudia Teutschbein: Conceptualization (supporting); funding acquisition (lead); methodology (supporting); project administration (lead); supervision (lead); visualization (supporting); writing – review and editing (supporting).

~~9~~8 Competing interests

The authors declare that they have no conflict of interest.

109 **References**

Adger, W. N.: Vulnerability, Global Environmental Change, 16, 268–281, https://doi.org/10.1016/j.gloenvcha.2006.02.006, 2006.

Alcamo, J., Acosta-Michlik, L., Carius, A., Eierdanz, F., Klein, R., Kromker, D., and Tanzler, D.: A new approach to quantifying and comparing vulnerability to drought, Regional Environmental Change, 8, 137–149, https://doi.org/10.1007/s10113-008-0065-5, 2008.

Asare-Kyei, D. K., Kloos, J., and Renaud, F. G.: Multi-scale participatory indicator development approaches for climate change risk assessment in West Africa, International Journal of Disaster Risk Reduction, 11, 13–34, https://doi.org/10.1016/j.ijdrr.2014.11.001, 2015.

Bakke, S. J., Ionita, M., and Tallaksen, L. M.: The 2018 northern European hydrological drought and its drivers in a historical perspective, Hydrol. Earth Syst. Sci., 24, 5621–5653, https://doi.org/10.5194/hess-24-5621-2020, 2020.

Blauhut, V., Stahl, K., Stagge, J. H., Tallaksen, L. M., De Stefano, L., and Vogt, J.: Estimating drought risk across Europe from reported drought impacts, drought indices, and vulnerability factors, Hydrol. Earth Syst. Sci., 20, 2779–2800, https://doi.org/10.5194/hess-20-2779-2016, 2016.

Chen, D., Zhang, P., Seftigen, K., Ou, T., Giese, M., and Barthel, R.: Hydroclimate changes over Sweden in the twentieth and twenty-first centuries: a millennium perspective, Geografiska Annaler: Series A, Physical Geography, 103, 103–131, https://doi.org/10.1080/04353676.2020.1841410, 2021.

Ciurean, R., Schroter, D., and Glade, T.: Conceptual Frameworks of Vulnerability Assessments for Natural Disasters Reduction, in: Approaches to Disaster Management - Examining the Implications of Hazards, Emergencies and Disasters, edited by: Tiefenbacher, J., InTech, https://doi.org/10.5772/55538, 2013.

Cuesta, A., Alvear, D., Carnevale, A., and Amon, F.: Gender and Public Perception of Disasters: A Multiple Hazards Exploratory Study of EU Citizens, Safety, 8, 59, https://doi.org/10.3390/safety8030059, 2022.

Dias, E. M. S., Pessoa, Z. S., and Teixeira, R. L. P.: Adaptive governance and water security in the context of climate change in the semi-arid, Mercator, 21, 1–11, https://doi.org/10.4215/rm2022.e21025, 2022.

Englund, M., Vieira Passos, M., André, K., Gerger Swartling, Å., Segnestam, L., and Barquet, K.: Constructing a social vulnerability index for flooding: insights from a municipality in Sweden, Front. Clim., 5, 1038883, https://doi.org/10.3389/fclim.2023.1038883, 2023.

Engström, J., Jafarzadegan, K., and Moradkhani, H.: Drought Vulnerability in the United States: An Integrated Assessment, Water, 12, 2033, https://doi.org/10.3390/w12072033, 2020.

Erfurt, M., Glaser, R., and Blauhut, V.: Changing impacts and societal responses to drought in southwestern Germany since 1800, Regional Environmental Change, 19, 2311–2323, https://doi.org/10.1007/s10113-019-01522-7, 2019.

Falkenmark, M. and Rockström, J.: The New Blue and Green Water Paradigm: Breaking New Ground for Water Resources Planning and Management, J. Water Resour. Plann. Manage., 132, 129–132, https://doi.org/10.1061/(ASCE)0733-9496(2006)132:3(129), 2006.

Faranda, D., Pascale, S., and Bulut, B.: Persistent anticyclonic conditions and climate change exacerbated the exceptional 2022 European-Mediterranean drought, Environ. Res. Lett., https://doi.org/10.1088/1748-9326/acbc37, 2023.

Fekete, A.: Spatial disaster vulnerability and risk assessments: challenges in their quality and acceptance, Nat Hazards, 61, 1161–1178, https://doi.org/10.1007/s11069-011-9973-7, 2012.

Fleming, C. S., Regan, S. D., Freitag, A., and Burkart, H.: Indicators and participatory processes: a framework for assessing integrated climate vulnerability and risk as applied in Los Angeles County, California, Nat Hazards, 115, 2069–2095, https://doi.org/10.1007/s11069-022-05628-w, 2023.

Fuchs, S. and Thaler, T. (Eds.): Vulnerability and Resilience to Natural Hazards, in: Vulnerability and Resilience to Natural Hazards, Cambridge University Press, Cambridge, iii–iv, 2018.

Füssel, H.-M.: Vulnerability: A generally applicable conceptual framework for climate change research, Global Environmental Change, 17, 155–167, https://doi.org/10.1016/j.gloenvcha.2006.05.002, 2007.

González Tánago, I., Urquijo, J., Blauhut, V., Villarroya, F., and De Stefano, L.: Learning from experience: a systematic review of assessments of vulnerability to drought, Nat Hazards, 80, 951–973, https://doi.org/10.1007/s11069-015-2006-1, 2016.

Hagenlocher, M., Meza, I., Anderson, C. C., Min, A., Renaud, F. G., Walz, Y., Siebert, S., and Sebesvari, Z.: Drought vulnerability and risk assessments: state of the art, persistent gaps, and research agenda, Environ. Res. Lett., 14, 083002, https://doi.org/10.1088/1748-9326/ab225d, 2019.

Hagenlocher, M., Naumann, G., Meza, I., Blauhut, V., Cotti, D., Döll, P., Ehlert, K., Gaupp, F., Van Loon, A. F., Marengo, J. A., Rossi, L., Sabino Siemons, A. S., Siebert, S., Tsehayu, A. T., Toreti, A., Tsegai, D., Vera, C., Vogt, J., and Wens, M.: Tackling Growing Drought Risks—The Need for a Systemic Perspective, Earth's Future, 11, e2023EF003857, https://doi.org/10.1029/2023EF003857, 2023.

Hung, H.-C. and Chen, L.-Y.: Incorporating stakeholders' knowledge into assessing vulnerability to climatic hazards: application to the river basin management in Taiwan, Climatic Change, 120, 491–507, https://doi.org/10.1007/s10584-013-0819-z, 2013.

Hurlbert, M. and Gupta, J.: Adaptive Governance, Uncertainty, and Risk: Policy Framing and Responses to Climate Change, Drought, and Flood, Risk Analysis, 36, 339–356, https://doi.org/10.1111/risa.12510, 2016.

Hurlbert, M. and Montana, E.: Dimensions of adaptive water governance and drought in Argentina and Canada, Journal of sustainable development, 8, 120–137, https://doi.org/10.5539/jsd.v8n1p120, 2015.

IPCC: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press. In Press., 2022.

Jamshed, A., Rana, I. A., Birkmann, J., McMillan, J. M., and Kienberger, S.: A bibliometric and systematic review of the Methods for the Improvement of Vulnerability Assessment in Europe framework: A guide for the development of further multi-hazard holistic framework, Jàmbá Journal of Disaster Risk Studies, 15, https://doi.org/10.4102/jamba.v15i1.1486, 2023.

Kim, H., Park, J., Yoo, J., and Kim, T.-W.: Assessment of drought hazard, vulnerability, and risk: A case study for administrative districts in South Korea, Journal of Hydro-environment Research, 9, 28–35, https://doi.org/10.1016/j.jher.2013.07.003, 2015.

Torkan 2018: https://www.krisinformation.se/detta-kan-handa/handelser-och-storningar/2018/torkan-2018, last access: 29 March 2021.

Uppdaterad skördeprognos 2018: https://www.lantmannen.se/om-lantmannen/press-och-nyheter/skord-2018/, last access: 29 March 2021.

På fredag delas torkastödet ut - så här blir fördelningen - LRF: https://www.lrf.se/mitt-lrf/nyheter/riks/2019/07/pa-fredag-delas-krisstodet-ut---sa-har-blir-fordelningen/, last access: 29 March 2021.

Martín, Y., Rodrigues Mimbrero, M., and Zúñiga-Antón, M.: Community vulnerability to hazards: introducing local expert knowledge into the equation, Nat Hazards, 89, 367–386, https://doi.org/10.1007/s11069-017-2969-1, 2017.

McEwen, L., Bryan, K., Black, A., Blake, J., and Afzal, M.: Science-Narrative Explorations of "Drought Thresholds" in the Maritime Eden Catchment, Scotland: Implications for Local Drought Risk Management, Front. Environ. Sci., 9, 589980, https://doi.org/10.3389/fenvs.2021.589980, 2021.

Melo, F. P. L., Parry, L., Brancalion, P. H. S., Pinto, S. R. R., Freitas, J., Manhães, A. P., Meli, P., Ganade, G., and Chazdon, R. L.: Adding forests to the water–energy–food nexus, Nat Sustain, 4, 85–92, https://doi.org/10.1038/s41893-020-00608-z, 2020.

Meza, I., Hagenlocher, M., Naumann, G., Vogt, J., and Frischen, J.: Drought vulnerability indicators for global-scale drought risk assessments: global expert survey results report., Publications Office of the European Union, Luxembourg, https://doi.org/10.2760/73844, 2019.

Meza, I., Siebert, S., Döll, P., Kusche, J., Herbert, C., Eyshi Rezaei, E., Nouri, H., Gerdener, H., Popat, E., Frischen, J., Naumann, G., Vogt, J. V., Walz, Y., Sebesvari, Z., and Hagenlocher, M.: Global-scale drought risk assessment for agricultural systems, NATURAL HAZARDS AND EARTH SYSTEM SCIENCES, 20, 695–712, https://doi.org/10.5194/nhess-20-695-2020, 2020.

Mishra, A. K. and Singh, V. P.: A review of drought concepts, Journal of Hydrology, 391, 202–216, https://doi.org/10.1016/j.jhydrol.2010.07.012, 2010.

Mızrak, S. and Aslan, R.: Disaster Risk Perception of University Students, Risk Hazard & Crisis Pub Pol, 11, 411–433, https://doi.org/10.1002/rhc3.12202, 2020.

Moreira, L. L., Vanelli, F. M., Schwamback, D., Kobiyama, M., and De Brito, M. M.: Sensitivity analysis of indicator weights for the construction of flood vulnerability indexes: A participatory approach, Front. Water, 5, 970469, https://doi.org/10.3389/frwa.2023.970469, 2023.

Moshir Panahi, D., Blauhut, V., Raziei, T., and Zahabiyoun, B.: Drought vulnerability range assessment: A dynamic and impact-driven method for multiple vulnerable systems, International Journal of Disaster Risk Reduction, 91, 103701, https://doi.org/10.1016/j.ijdrr.2023.103701, 2023.

MSB: MSB:s arbete med skogsbränderna 2018: tillsammans kunde vi hantera en extrem skogsbrandssäsong, 2018.

Nelson, R., Howden, M., and Smith, M. S.: Using adaptive governance to rethink the way science supports Australian drought policy, Environmental Science & Policy, 11, 588–601, https://doi.org/10.1016/j.envsci.2008.06.005, 2008.

Orru, K., Hansson, S., Gabel, F., Tammpuu, P., Krüger, M., Savadori, L., Meyer, S. F., Torpan, S., Jukarainen, P., Schieffelers, A., Lovasz, G., and Rhinard, M.: Approaches to 'vulnerability' in eight European disaster management systems, Disasters, 46, 742–767, https://doi.org/10.1111/disa.12481, 2022.

Ortega-Gaucin, D., De La Cruz Bartolón, J., and Castellano Bahena, H. V.: Drought Vulnerability Indices in Mexico, Water, 10, 1671, https://doi.org/10.3390/w10111671, 2018.

Radeva, K. and Nikolova, N.: Hydrometeorological Drought Hazard and Vulnerability Assessment for Northern Bulgaria, GEOGRAPHICA PANNONICA, 24, 112–123, https://doi.org/10.5937/gp24-25074, 2020.

Raheem, N., Cravens, A. E., Cross, M. S., Crausbay, S., Ramirez, A., McEvoy, J., Zoanni, D., Bathke, D. J., Hayes, M., Carter, S., Rubenstein, M., Schwend, A., Hall, K., and Suberu, P.: Planning for ecological drought: Integrating ecosystem services and vulnerability assessment, WIREs Water, 6, https://doi.org/10.1002/wat2.1352, 2019.

Rufat, S. and Metzger, P.: Vulnerability, Territory, Population: From Critique to Public Policy, 1st ed., Wiley, https://doi.org/10.1002/9781394299249, 2024.

S. V. T. Nyheter: Torkan slår ut fiskens barnkammare, SVT Nyheter, 3rd August, 2018.

Shiravand, H. and Bayat, A.: Vulnerability and drought risk assessment in Iran based on fuzzy logic and hierarchical analysis, Theor Appl Climatol, 151, 1323–1335, https://doi.org/10.1007/s00704-022-04323-x, 2023.

Siegrist, M. and Árvai, J.: Risk Perception: Reflections on 40 Years of Research, Risk Analysis, 40, 2191–2206, https://doi.org/10.1111/risa.13599, 2020.

1208   Sjökvist, E., Abdoush, D., and Axén, J.: Sommaren 2018 - en glimt av framtiden?, 2019.

1209   Vattenuttag:
1210   https://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__MI__MI0902__MI0902D/VattenUttagJord/table/t
1211   ableViewLayout1/, last access: 31 May 2024.

1212   Statistics Sweden: Water Use in Sweden 2020, 2022.

1213   Stefanski, R., Toreti, A., Aich, V., Hagenlocher, M., Lamizana Diallo, B., McDonnell, R., Pulwarty, R. S.,
1214   Svoboda, M., Tsegai, D., and Wens, M.: Drought resilience demands urgent global actions and cooperation, Nat
1215   Water, https://doi.org/10.1038/s44221-024-00373-9, 2025.

1216   Stenfors, E., Blicharska, M., Grabs, T., and Teutschbein, C.: Droughts in forested ecoregions in cold and
1217   continental climates: A review of vulnerability concepts and factors in socio-hydrological systems, WIREs Water,
1218   11, e1692, https://doi.org/10.1002/wat2.1692, 2024.

1219   Stensen, K., Krunegård, A., Rasmusson, K., Matti, B., and Hjerdt, N.: Sveriges vattentillgång utifrån perspektivet
1220   vattenbrist och torka – Delrapport 1 i regeringsuppdrag om åtgärder för att motverka vattenbrist i ytvattentäkter.,
1221   SMHI, 2019.

1222   Tate, E.: Social vulnerability indices: a comparative assessment using uncertainty and sensitivity analysis, Nat
1223   Hazards, 63, 325–347, https://doi.org/10.1007/s11069-012-0152-2, 2012.

1224   Tate, E.: Uncertainty Analysis for a Social Vulnerability Index, Annals of the Association of American
1225   Geographers, 103, 526–543, https://doi.org/10.1080/00045608.2012.700616, 2013.

1226   Taylor, V., Chappells, H., Medd, W., and Trentmann, F.: Drought is normal: the socio-technical evolution of
1227   drought and water demand in England and Wales, 1893–2006, Journal of Historical Geography, 35, 568–591,
1228   https://doi.org/10.1016/j.jhg.2008.09.004, 2009.

1229   Teutschbein, C., Quesada Montano, B., Todorović, A., and Grabs, T.: Streamflow droughts in Sweden:
1230   Spatiotemporal patterns emerging from six decades of observations, Journal of Hydrology: Regional Studies, 42,
1231   101171, https://doi.org/10.1016/j.ejrh.2022.101171, 2022.

1232   Teutschbein, C., Albrecht, F., Blicharska, M., Tootoonchi, F., Stenfors, E., and Grabs, T.: Drought hazards and
1233   stakeholder perception: Unraveling the interlinkages between drought severity, perceived impacts, preparedness,
1234   and management, Ambio, 52, 1262–1281, https://doi.org/10.1007/s13280-023-01849-w, 2023a.

1235   Teutschbein, C., Jonsson, E., Todorović, A., Tootoonchi, F., Stenfors, E., and Grabs, T.: Future drought
1236   propagation through the water-energy-food-ecosystem nexus – A Nordic perspective, Journal of Hydrology, 617,
1237   128963, https://doi.org/10.1016/j.jhydrol.2022.128963, 2023b.

1238   The Swedish Board of Agriculture: Irrigation and Drainage of Agricultural Land 2023, 2024.

1239   Tidwell, T. L.: Nexus between food, energy, water, and forest ecosystems in the USA, J Environ Stud Sci, 6, 214–
1240   224, https://doi.org/10.1007/s13412-016-0367-8, 2016.

1241   Turesson, K., Pettersson, A., De Goër De Herve, M., Gustavsson, J., Haas, J., Koivisto, J., Karagiorgos, K., and
1242   Nyberg, L.: The human dimension of vulnerability: A scoping review of the Nordic literature on factors for social
1243   vulnerability to climate risks, International Journal of Disaster Risk Reduction, 100, 104190,
1244   https://doi.org/10.1016/j.ijdrr.2023.104190, 2024.

1245   Turner, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., Eckley, N.,
1246   Kasperson, J. X., Luers, A., Martello, M. L., Polsky, C., Pulsipher, A., and Schiller, A.: A framework for
1247   vulnerability analysis in sustainability science, Proc. Natl. Acad. Sci. U.S.A., 100, 8074–8079,
1248   https://doi.org/10.1073/pnas.1231335100, 2003.

1249   UNDRR: Global Assessment Report on Disaster Risk Reduction 2019, United Nations, 2019.

1250 UNDRR: Special report on drought 2021, United Nations Office for Disaster Risk Reduction, Geneva, 173 pp.,
1251 2021.

1252 Van Loon, A. F.: Hydrological drought explained, WIREs Water, 2, 359–392, https://doi.org/10.1002/wat2.1085,
1253 2015.

1254 Wang, T. and Sun, F.: Integrated drought vulnerability and risk assessment for future scenarios: An indicator
1255 based analysis, Science of The Total Environment, 900, 165591, https://doi.org/10.1016/j.scitotenv.2023.165591,
1256 2023.

1257 Wilhite: A methodology for drought preparedness, Nat Hazards, 13, https://doi.org/10.1007/BF00215817, 1996.

1258 Wilhite, D. A. and Glantz, M. H.: Understanding: the Drought Phenomenon: The Role of Definitions, Water
1259 International, 10, 111–120, https://doi.org/10.1080/02508068508686328, 1985.

1260 Xu, T., Chen, K., and Li, G.: The more data, the better? Demystifying deletion-based methods in linear regression
1261 with missing data, Statistics and Its Interface, 15, 515–526, https://doi.org/10.4310/21-SII717, 2022.

1262