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

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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 identify user-validated drought vulnerability factors, relevant for water-dependent sectors and societies in forested cold climates. User-validation was performed through 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 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 sectors, where the forestry sector especially stands 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, demonstrate 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.

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

1 Introduction

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).

Due to the increasing drought risk even in generally water abundant regions, like Scandinavia, it is important to assess drought vulnerability, as it can help identify effective measures, prepare for potential negative effects of droughts and for designing proactive drought management plans. Yet, no comprehensive assessment has been conducted to determine what constitutes drought vulnerability, incorporating sectors such as forestry, agriculture,

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

water resources & supply as well as society for forested cold climates. Stenfors et al. (2024) took an initial step in this direction by presenting a conceptual model for drought vulnerability in forested cold climate regions. By studying available literature on drought vulnerability in these regions, several vulnerability factors were identified and used to form a conceptual model for drought vulnerability. The model divides vulnerability factors into three distinct categories (Figure 1): (1) direct water consumers, i.e., factors linked to sectors or groups using water directly (e.g., for drinking water, watering crops, etc.), (2) indirect water consumers, i.e., factors related to societal groups that use water indirectly through consumption of goods that need water for production (e.g., food, energy, etc.), and (3) governance processes and plans, such as policies and plans concerning drought, financial ability to adapt or respond to drought, where factors connected to the category can affect both sectors and society as a whole.

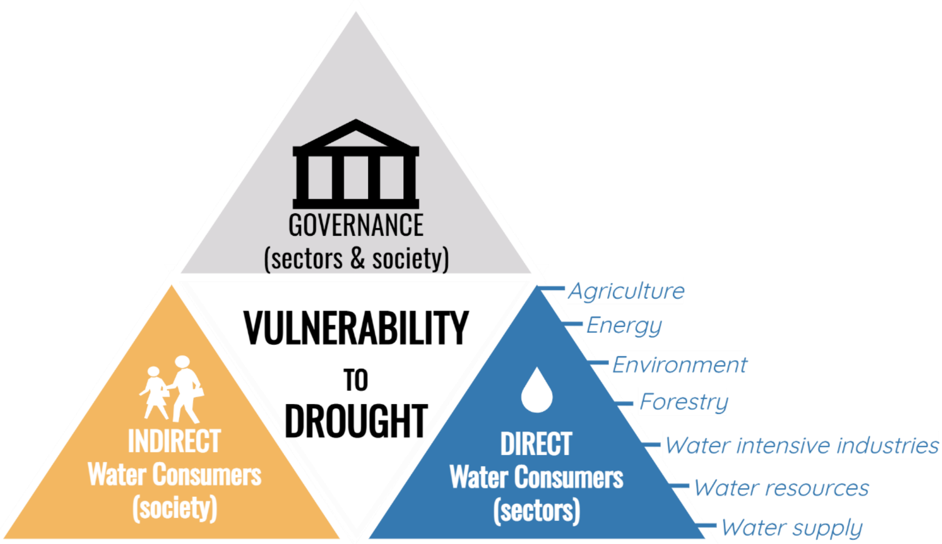

Figure 1. The conceptual framework proposed by Stenfors et al. (2024) that categorizes drought vulnerability as relating to governance processes and plans, Indirect water consumers, or Direct water consumers. Modified from Stenfors et al. (2024).

As numerous vulnerability factors where identified in the literature review by Stenfors et al. (2024), further work is required to validate these factors and to better understand their relative impact on drought risk in socio-hydrological systems in forested cold climates. User-validation is a powerful tool for gaining insights from end users and leveraging collective knowledge to ensure the selected factors are appropriate for their intended use (Rykiel, 1996). This approach was previously utilized by Meza et al. (2019) to study the relative importance of drought vulnerability factors for agriculture and water supply on a global scale. However, there are currently no studies on vulnerability factors in forested cold climates specifically adapted to end-user needs in different socio-economic sectors.

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

Hence, this paper provides a comprehensive analysis of the most impactful drought vulnerability factors for water-dependent sectors and societies in forested cold climates, validating their relevance for effective drought risk management. Using the conceptual framework proposed by Stenfors et al. (2024), the research objectives for this paper are to (1) identify relevant vulnerability factors for water-dependent sectors as well as society in forested cold climates, (2) determine their relative rankings through the use of impact scores, (3) identify the highest-rated vulnerability factors for individual water-dependent sectors and society, (4) explore variations in ratings among the respondents, hypothesizing that impact ratings would vary based on end-user's (i) sectorial focus or type of organization, (ii) geographical location, (iii) level of drought experience, and lastly to (5) improve the current understanding of drought vulnerability by presenting newly discovered vulnerability factors reported by the respondents.

2 Methods

2.1 Study area

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

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

Sweden has three levels of government: national, regional and local. On a regional level, Sweden is divided into 21 counties whose political tasks are dived between regional councils and county administrative boards. Regional councils comprise county-elected decision-makers, while the county administrative boards are government bodies within the counties. At the local level, Sweden has 290 municipalities, each with an elected municipal council that handles municipal decision making. From a water management perspective, Sweden is 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,

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

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, 1000-tal kubikmeter efter region, typ av vatten och vart 5:e år. PxWeb, 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).

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), with the full list of vulnerability factors and their corresponding subcategories available in the supplementary materials (S1, S2).

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

Table 1. Overview of the number of sectoral, societal, and governance vulnerability factors included in the survey, divided into ten subcategories based to 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,

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

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.

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

Using the identification matrix, survey recipients from governmental/local authorities (354 recipients), private/state/municipal owned enterprises (81), academia/research institutes (46), regional/national trade associations (45), and NGOs (35) were identified. Generic contact lists for municipalities (290), counties (21) and authority owned competence centers (31) were collected from official sites (SKL.se and naturvardsverket.se). Contact information for individual recipients within the different organization types were identified using three approaches, (1) internet searches combining their organization name and keyworks in Swedish such as "drought" and "water shortage" (30 respondents), (2) searching their organization websites for keywords "drought" and "water shortage" (37), (3) using the general contact information provided on the organization website (143). Furthermore, individual recipients were found through snowballing, where authors or contributors in articles or projects related to drought or water shortages were included (4 recipients).

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

2.3.3 Analysis of survey responses

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

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

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

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

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

To test our hypotheses related to the variability of impact ratings of vulnerability factors (ordinal data) identified as relevant in step III, we utilized the Kruskall-Wallis test by ranks. If significant differences between groups/categories were identified, the data was further analyzed using pairwise Wilcoxon rank sum tests to calculate pairwise comparisons between group levels with corrections for multiple testing. Hypothesis testing of ratings depending on geographical location and drought experience was only carried out for respondent groups with three or more responses for each response alternative (Geographical location: North versus South, Drought experience: limited (rating 0-1), moderate (2), significant (3-4)). Consequently, differences in factor ratings per geographical location was only carried out for the environmental and forestry sector, and for respondents working in authorities or enterprises. Impact of drought experience on factor ratings was studied for the environmental, water resources and water supply sector and for respondents working in authorities.

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

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 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 (36%) 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**

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

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% 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% 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.

	Drought experience			Number of
Sector/organization	**Limited (rating 0-1)**	**Moderate (2)**	**Significant (3-4)**	**respondents**
Agricultural	1	2	10	13
Energy	1	1	5	7
Environmental	8	14	13	35
Forestry		3	11	14
Water resources	3	4	8	15
Water supply	3	3	10	16
Grand Total	**16**	**27**	**57**	**100**
Authority	14	19	29	62
Enterprise		**4**	8	12
NGO	1		1	2
Research	1	5	13	19
Trade association	1		6	7
Grand Total	**17**	**28**	**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 (30,11), water supply (26, 8), energy (10, 2), and forestry (10, 0) (Table 4).

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

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): 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*

					Sectors						Organizations (society)			
		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
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**	**5**	**7**		-	-	-	-
	Funds	3	2	-	2		1	1	1		-	-	-	-
	Irrigation	4	4	-	4		1	2	3		-	-	-	-
	Supply	3	3	-	2	2	3	2	3		-	-	-	-
	Susceptibility	**31**	**28**	-	**20**	**7**	**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	2	7	5	5		-	-	-	-
	Supply	5	4	-	3	1	3	3	3		-	-	-	-
	Total	**51**	**46**	-	**35**	**10**	**32**	**30**	**26**	**10**	-	-	-	-

b) *Societal factors*

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
	Total	**9**	-	**5**	-	-	-	-	-	-	**5**	**3**	**2**	**5**

c) *Governance factors*

Governance	**Adaptive**	**9**	**9**	**9**	**8**	**3**	**6**	**8**	**8**	**1**	**9**	**7**	**8**	**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	6	7	7
	Coping	**14**	**13**	**14**	**12**	**3**	**11**	**12**	**12**	**1**	**14**	**4**	**9**	**12**
	Authority	6	5	3	5		3	4	4	1	3		2	3
	Policies	7	7	3	6	3	7	7	7		3	1	1	2
	Tools	1	1	7	1		1	1	1		7	3	5	6
	Total	**23**	**23**	**23**	**20**	**6**	**17**	**20**	**20**	**2**	**23**	**11**	**17**	**20**

When examining the vulnerability factors based on their connection to adaptive capacity, coping capacity or susceptibility, it was observed that 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

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

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 found the largest number of *societal* vulnerability factors as relevant, rating 4 out of 8 factors as relevant for societal drought risk. This was followed by trade associations (3), enterprises (2) and researchers (1). Among societal factors, the subcategory *"demographics"* was the only category that was not considered relevant for societal drought risk by any of the respondents.

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 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 sectoral factors included in the subcategory received overall medium high to impact scores by all sectors, even if the factors were not considered relevant for all sectors. Another category of factors that generally see a slightly smaller spread across different sectors is relating to the presence of tools and resources for adaptive capacity. Even though the forestry and energy sector only found a limited number of factors in the category relevant (one factor each), this category was the only category to not receive impact scores lower than 0.33 by any sector for any of the involved factors.

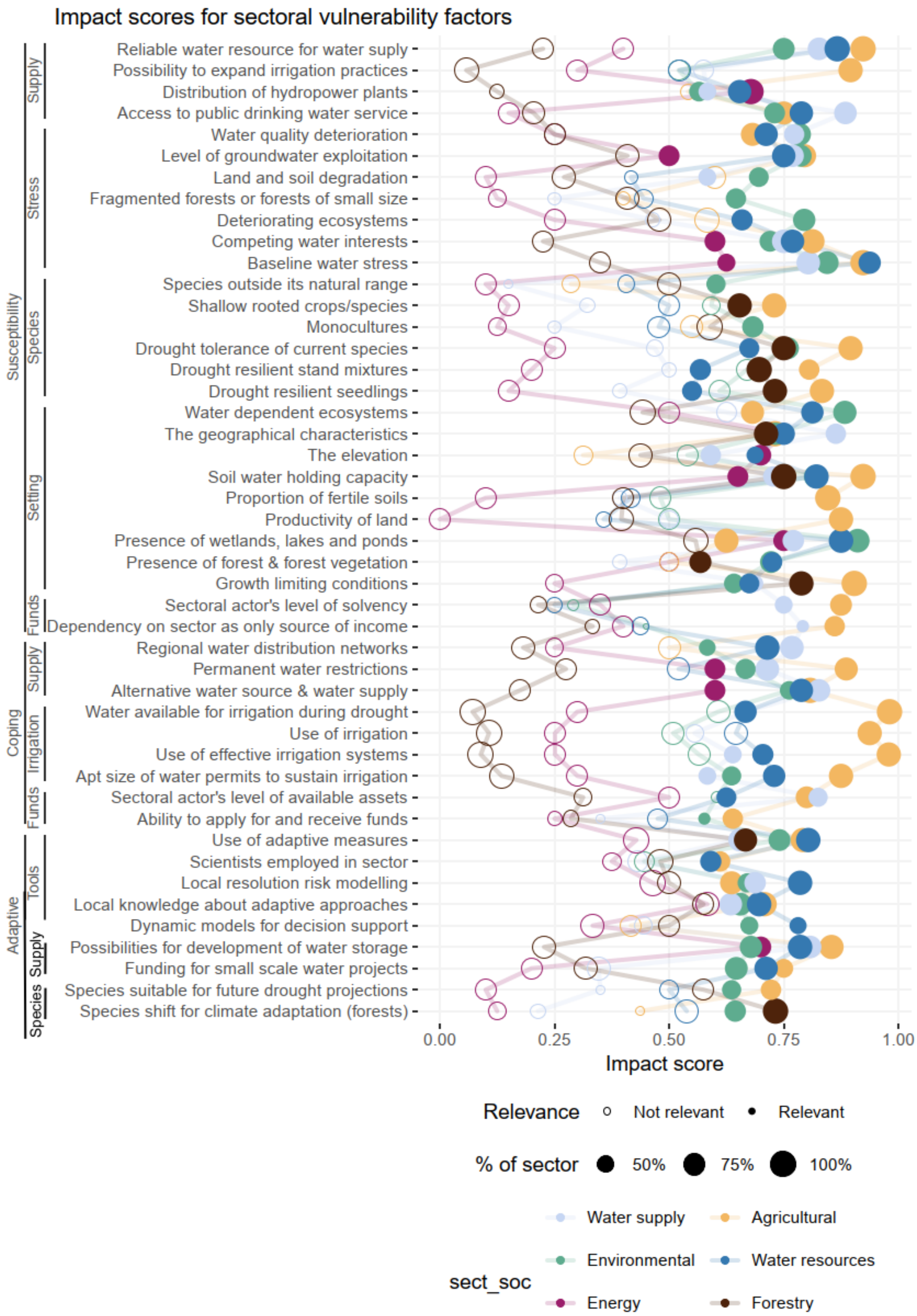

Figure 2. Impact scores for sectoral vulnerability factors concerning adaptive capacity (adaptive), coping capacity (coping), and susceptibility, rated regarding their impact on drought risk in water dependent sectors. Filled dots indicate that the factor is considered relevant for the sector (i.e., 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.

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

The five factors relating to *society* were all highly rated by respondents from authorities and trade associations, whereas respondents from research, enterprises and NGOs gave slightly lower impact scores (Figure 3). Respondents from all types of organization included in the survey found '*the societal financial dependency on direct water consuming industries (DWC)*' as relevant for societal drought risk. Apart from this, respondents from research only found '*access to public drinking water*' relevant for societal drought risk, whereas NGOs found the '*drought awareness of water users*' relevant as well as highly impactful. Enterprises found '*access to public drinking water*' and '*the size of population*' to be relevant for societal drought risk, but not rating them highly.

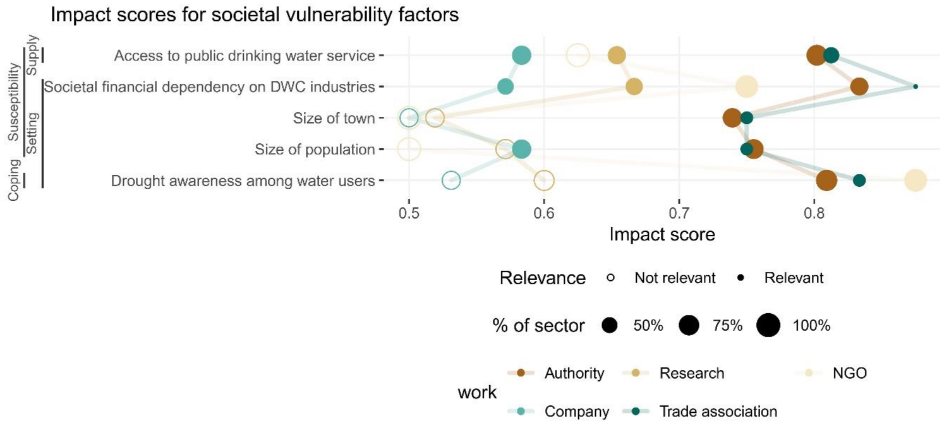

Figure 3. Impact scores for societal vulnerability factors concerning coping capacity (coping), and susceptibility, rated regarding their impact on societal drought risk. Filled dots indicate that the factor is considered relevant by the organization (i.e., with a median score of 3 or higher), whereas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

Factors relating to *governance* generally receive slightly higher impact scores, both concerning their impact on sectors as well as society, compared to sectoral factors (Figure 4). For example, all factors received impact scores of 0.25 or higher, with the exception for the governance factors '*defined water-use rights*', '*social/physical capacity of authorities to offer drought related support*', and '*building standards relating to water efficiency*'. Apart from two factors relating to having a drought management plan, all factors concerning policies and plans that affect coping capacity, were considered relevant for all sectors except forestry, as well as for society as a whole. Overall, four factors receive impact scores of 0.5 or higher by all sectors: '*drought awareness within authorities*', '*access to relevant data concerning drought*', '*availability of long-term supply and demand assessments*', and '*availability of a drought risk assessment*'. However, no governance factors were considered relevant across all sectors, due partly to the low number of factors considered relevant by the forestry sector. The energy and forestry sector, provided the lowest impact scores for several of the governance factors concerning the impact on drought risk in their sectors. Meanwhile, the highest impact score given by the energy sector, for any sectoral or governance factor, was given to the governance factor '*defined water-use rights*'. This factor was rated highly by respondents across all sectors apart from forestry. Respondents also rated this factor highly when looking at its impact on drought risk for society as a whole. Other governance factors that received high impact scores for sectoral and societal drought risk by at least five sectors were '*having a local water management plan*

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

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

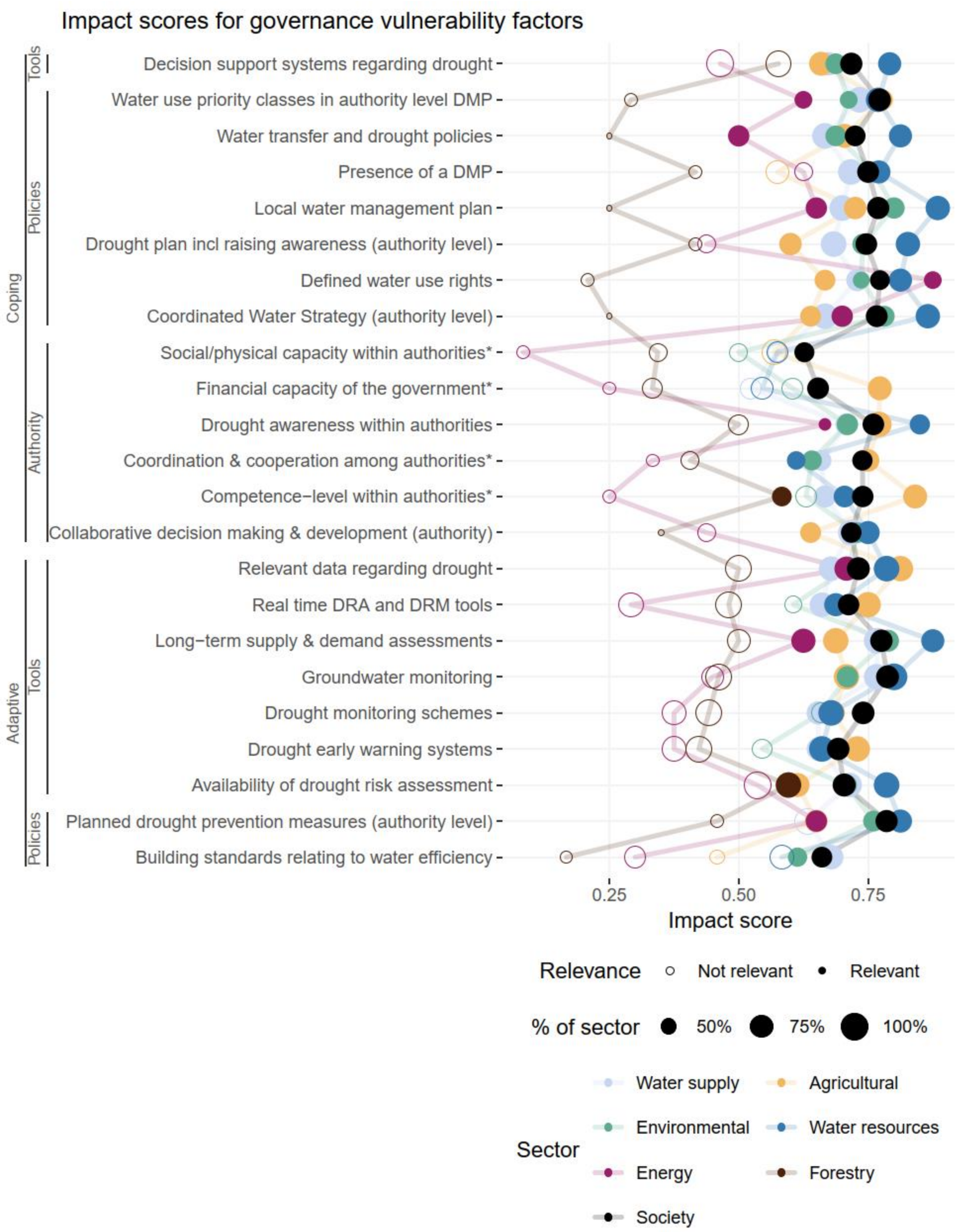

Figure 4. Impact scores for governance related vulnerability factors concerning adaptive capacity (adaptive) and coping capacity (coping) rated both regarding their impact on drought risk in sectors as well as society as a whole. Filled dots indicate that the factor is considered relevant for the sector 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.

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

3.4 Highest rated vulnerability factors for sectors, society and governance

Looking at the highest rated *sectoral* vulnerability factors across different sectors, most of the factors were connected to susceptibility or coping capacity (Table 5). Only two of the most highly rated sectoral factors concerned adaptive capacity. Certain factors received high impact scores by more than one sector. For example, the soil water holding capacity was among the highest rated factors for the agricultural, environmental and forestry sector. Similarly, the presence of baseline water stress received high impact scores from the agricultural, environmental and water resources sector, and the presence of wetlands lakes and ponds received high impact scores from the energy, environmental and water resources sector. This was reflected in the overall highest rated sectoral factors, for all sectors combined, where the three vulnerability factors received the highest impact scores, followed by presence of water dependent ecosystems and the geographical characteristics.

Adaptive- and susceptibility-related factors were the only vulnerability factors to receive high impacts scores by the energy and forestry sector, where the energy sector found the presence of wetlands, lakes and ponds, the geographical characteristics, and the possibilities for development of water storage as factors with high impact on drought risk. The forestry sector on the other hand, gave the highest impact score to having growth limiting conditions, followed by the soil water holding capacity and the drought tolerance of current species.

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

All sectors	
(S) Presence of wetlands, lakes and ponds	0,82
(S) Soil water holding capacity	0,81
(S) Baseline water stress	0,81
(S) Water dependent ecosystems	0,76
(S) The geographical characteristics	0,75

Agricultural	
(C) Water available for irrigation during drought	0.98
(C) Use of effective irrigation systems	0.98
(C) Use of irrigation	0.94
(S) Soil water holding capacity	0.92
(S) Reliable water resource for water supply	0.92
(S) Baseline water stress	0.92

Energy	
(S) Presence of wetlands, lakes and ponds	0,75
(S) The geographical characteristics	0,75
(A) Possibilities for development of water storage	0,70
(S) The elevation	0,70
(S) Distribution of hydropower plants	0,68

Environmental	
(S) Presence of wetlands, lakes and ponds	0,93
(S) Water dependent ecosystems	0,90
(S) Baseline water stress	0,85
(S) Soil water holding capacity	0,82
(S) Deteriorating ecosystems	0,81

Forestry	
(S) Growth limiting conditions	0.79
(S) Soil water holding capacity	0.75
(S) Drought tolerance of current species	0.75
(A) Species shift for climate adaptation	0.73
(S) Drought resilient seedlings	0.73

Water resources	
(S) Baseline water stress	0,94
(S) Presence of wetlands, lakes and ponds	0,88
(S) Reliable water resource for water supply	0,87
(S) Soil water holding capacity	0,82
(S) Water dependent ecosystems	0,81

Water supply	
(S) Access to public drinking water service	0,88
(S) The geographical characteristics	0,86
(S) Reliable water resource for water supply	0,83
(C) Alternative water source & water supply	0,83
(C) Sectoral actor's level of available assets	0,83

Five *societal* factors were considered relevant by the respondents, where the highest rated factor, the financial dependency of society on direct water consuming (short: DWC) industries, was connected to susceptibility. This was followed by having access to public drinking water services, the drought awareness among water-users, the population size and the size of town. As was seen for the sectoral ratings, access to public drinking water was also

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

highly rated by sector such as the agricultural, environmental, and water resources sector and being the highest rated factor for the water supply sector.

Looking at the highest rated *governance* factors, a majority of the factors were related to coping capacity (Table 6). Several of the highest rated factors, when respondents rated the impact of governance factors on their sectors, received high impact scores by more than one sector. For example, factors such as having a local water management plan, an authority level coordinated water strategy and the drought awareness within authorities were among the highest rated governance factors for several sectors. The energy and water supply sector both rated having defined water use rights highly, whereas respondents from the agricultural and forestry sectors rated the competence level within authorities to offer drought related support highly. Looking instead at the highest rated governance factors from a societal perspective, presence of groundwater monitoring appears as the highest rated vulnerability factor, closely followed by having planned drought prevention measures at authority level, access to long-term supply and demand assessments, defined water-use rights, and having water-use priority classes in authority level drought management plans (short: DMP).

Table 6. The five highest impact scores for a) governance factors rated on their impact on sectoral drought risk, b) societal factors, rated on their impact on societal drought risk, c) governance factors rated on their impact on societal drought risk. (S) indicates vulnerability factors concerning susceptibility, coping capacity (C), or adaptive capacity (A). Factors that are highly rated by more 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

Societal factors	
(S) Societal financial dependency on DWC industries	0,773
(S) Access to public drinking water service	0,750
(C) Drought awareness among water users	0,747
(S) Size of population	0,695
(S) Size of town	0,668

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

Governance factors	
(A) Groundwater monitoring	0,788
(A) Planned drought prevention measures (authority level)	0,786
(A) Long-term supply & demand assessments	0,776
(C) Defined water use rights	0,773
(C) Water use priority classes in authority level DMP	0,772

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

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

Our assessment of *sectoral* factors uncovered significant differences in factors ratings depending on the respondent's sectoral focus for 39 sectoral factors. The forestry sector stood out, having significant differences in impact ratings (p-value <0,05) for several sectoral factors compared to respondents from the agricultural (significant differences seen for 21 factors), environmental (20 factors), water supply (18), and water resources (17) sectors. The main differences were seen for factors connected to water supply, irrigation, and anthropogenic stress. Respondents from the energy sector rated 18 factors significantly different from the agricultural sector, where the differences primarily were seen for factors connected to species characteristics, irrigation and available water supply. Significant differences in factor ratings concerning these three subcategories as well as species characteristics were also seen between the water supply and agricultural sector (11). An overview of the sectoral factors with significant differences in impact ratings can be found in supplementary materials (S6)

Significant differences in sectoral factor ratings depending on geographical location were only found for the vulnerability factor '*Geographical characteristics*' (p-value 0.03), by respondents from the environmental sector located in southern Sweden (n = 28) versus the north (7), with an average impact score of 0.73 and 1.00 respectively. No significant differences were found between sectoral factor ratings depending on the reported drought experience.

No significant difference in *societal* factor ratings were seen per place of employment. When studying factors from a geographical perspective, respondents from northern Sweden found one societal factor relevant for societal drought risk, compared to four factors by respondents from southern Sweden. Respondents from both north and south of Sweden found the societal financial dependency on direct water consuming industries as relevant for societal drought risk. However, no significant differences in societal factor ratings were seen neither between respondents working in enterprises nor authorities in the two locations. Similarly, no significant differences in societal factor ratings depending on the reported drought experience were seen.

When looking at differences in factor ratings for the 23 *governance* factors from a sectoral perspective, significant differences were seen for eight factors. Here it was clear that respondents from the forestry sector rated governance factors differently compared to the other sectors, as all significant differences involves the sector. Respondents from the water resources and environmental sector gave significantly different ratings compared to the forestry sector (for seven and factors respectively), where a majority of the factors were related to water-and drought related policies and plans. This was followed by the agricultural (2), water supply (2) and energy (1) sector. When comparing governance factor ratings from a societal perspective per place of employment, significant differences in factor ratings were found between respondents from authorities and enterprises (2) and research respectively (3). The differences in ratings between the authorities, enterprises and research were seen for the same two governance factors; *'the financial capacity of the government'* and *'the social/physical capacity within authorities'* to offer drought related support, where authorities and research also rated the presence of water transfer- and drought policies significantly differently. All governance factors that saw significant differences in impact ratings between sectors or organizations are presented in the supplementary materials (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

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

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.

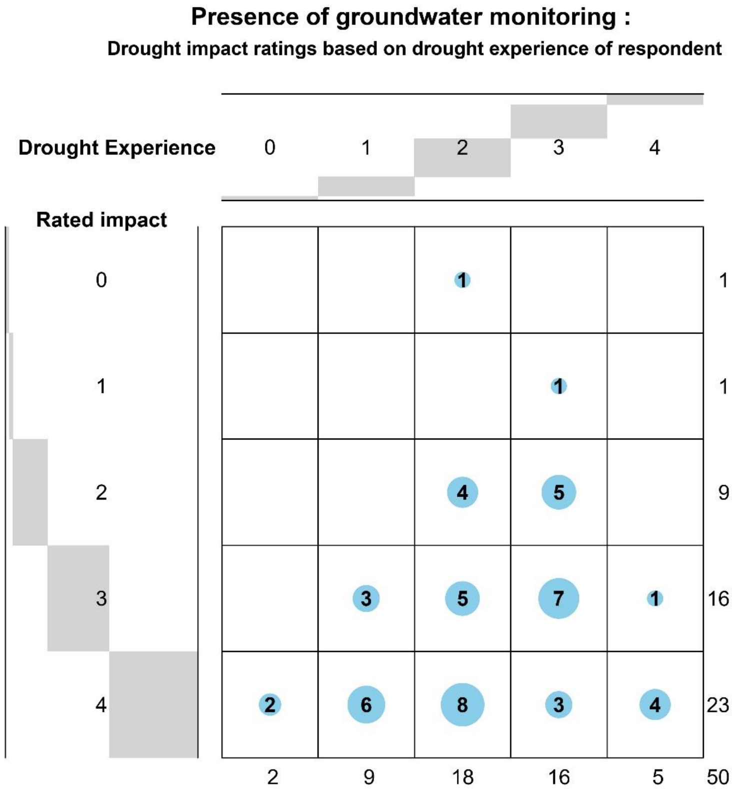

Figure 5. Frequency distribution for impact ratings by respondents working in authorities concerning the presence of groundwater monitoring, divided by impact rating (0-No impact, to 4 -high impact)) and the reported drought experience of the respondent (0 - No experience to 4-large experience). Larger blue dots indicate more frequently observed responses.

3.6 New vulnerability factors identified in the survey

The possibility for the respondents to add their own factors, produced a list of additional sectorial factors (Figure 6). Out of the additional factors added, the only factor mentioned by more than one respondent was "forest fires" which was mentioned by two respondents.

The largest number of additional sectorial factors came from respondents representing the environmental sector, such as factors concerning knowledge of water management among decision makers as well as landowners, and anthropogenic changes to surface waters and water courses (by lowering lake surfaces, dikes, straightening and clearing of water courses). The respondents from this sector also added factors concerning forests, revolving

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

around the area used for production forest and natural forests and presence of forest damages. For the agricultural sector, several of the additional factors suggested revolved around the presence or availability of information on adaptation strategies and knowledge-/evidence-based policies. Financial factors were also mentioned, such as the profitability of investments.

Societal factors included a combination of biophysical and socio-economic factors. For example, forest fires, geography and presence of dikes and other anthropogenic changes to water courses were mentioned as impactful vulnerability factors for Swedish society. From a governance perspective, factors such as planning for climate adaptation and coordination between climate adaptation and civil defense were mentioned. One respondent raised the importance of understanding the actual responsibility of different authority levels during drought.

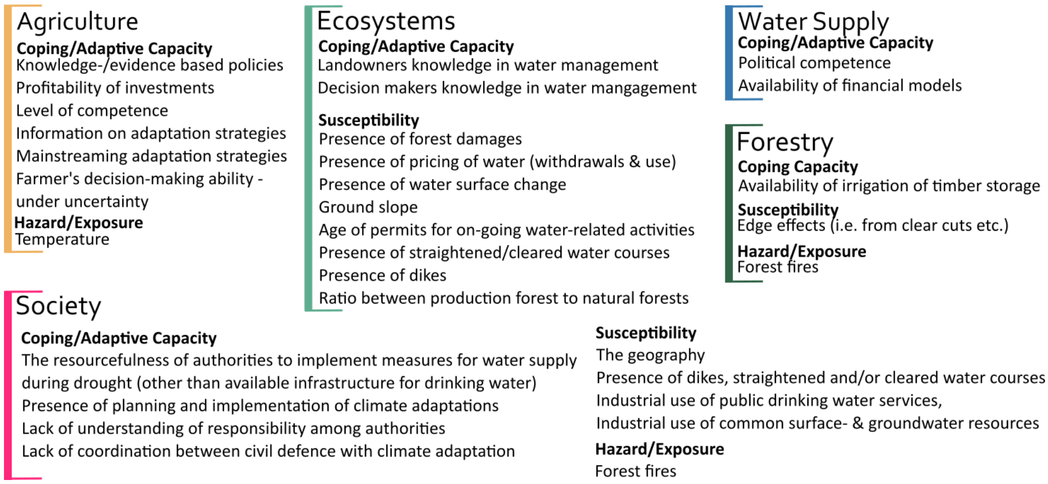

Figure 6. New factors that were mentioned by the respondents divided by sector (as expressed by respondents from the agricultural (yellow), environmental (light green), forestry (dark green), and water supply (blue)) sector and societal factors (pink).

4 Discussion

This study investigated the relative importance of drought vulnerability factors in a Nordic country through user-validation. While several studies have assessed drought vulnerability in similar climates and ecozones (Stenfors 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.

Out of the 51 sectoral, 8 societal and 23 governance drought vulnerability factors identified in the literature review by Stenfors et al. (2024), 46 sectoral factors were found relevant for sectoral vulnerability and five societal factors were found relevant for societal drought risk by at least one sector or organization type respectively. All 23 governance related factors included in the survey were found to be relevant by at least one sector or organization type, for both sectoral drought vulnerability as well as vulnerability for society as a whole. The results highlighted the complexity of drought vulnerability, showing that a combination of different factors impacts the overall drought risk of a sector or society as a whole. The fact that 90% of the factors used in the literature were deemed relevant by end-users underscores the broad range of elements that contribute to sector-specific vulnerabilities.

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

This finding aligns with studies from other world regions, which also identified large numbers of vulnerability factors: For instance, Moshir Panahi et al. (2023) identified 44 vulnerability factors for Iran using an impact-based method, whereas Ahmadalipour and Morakhani (2018) found 36 relevant vulnerability factors based on expert knowledge for Africa.

The survey included several factors connected to the vulnerability concepts susceptibility, coping capacity and adaptive capacity as described by IPCC AR6 (IPCC, 2022). A vast majority of the factors were considered relevant by at least one actor, however, some factors connected to either adaptive capacity, coping capacity or susceptibility were not considered relevant by the actors included in this survey. This could potentially be a result of regional differences, where some factors are less generalizable than others. In general, factors relating to susceptibility and coping capacity receive the highest impact scores for both sectoral and societal vulnerability factors. Whether this is due to the nature of these factors, potentially being more observable during drought events compared to those associated with adaptive capacity requires further research.

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

Differences emerged between the number of factors rated as relevant depending on the sector or organization type that the respondent belonged to, where for example respondents from the agricultural sector and authorities 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

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

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 & 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

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

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 & 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.

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. (2023) 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, Albrecht, et al., 2023). Such differences could potentially affect the overall perception of drought risk and drought vulnerability.

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

https://doi.org/10.5194/egusphere-2024-1988
Preprint. Discussion started: 14 August 2024

model, blue water entails water available as surface or groundwater, while green water represents water stored as soil moisture in the unsaturated zone (Falkenmark & 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 potentially 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.

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

5 Conclusion

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

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.

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).

8 Competing interests

The authors declare that they have no conflict of interest.

https://doi.org/10.5194/egusphere-2024-1988
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