Hydrol. Earth Syst. Sci., 29, 3809–3832, 2025
https://doi.org/10.5194/hess-29-3809-2025

Hydrology and Earth System Sciences
Open Access

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

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Received: 2 July 2024 – Discussion started: 14 August 2024
Revised: 20 March 2025 – Accepted: 12 May 2025 – Published: 15 August 2025

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 an understanding of not only the drought hazard itself, but also the underlying vulnerabilities in sociohydrological systems. As a result, drought vulnerability assessments are increasingly being 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. Therefore, here we present an assessment of the practical relevance and relative impact of various drought vulnerability factors for water-dependent sectors and societies in forested cold climates. The analysis was based on the results of an online survey conducted in Sweden, 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. Results showed that the relevance and impact of individual vulnerability factors differed across sectors, with the forestry sector especially standing 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 using caution when selecting generic vulnerability factors for applied vulnerability assessments. Furthermore, the results provide a comprehensive guide to both sectoral and societal drought vulnerability in sociohydrological 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-onset and recurrent phenomenon (Wilhite, 1996) capable of affecting various aspects of sociohydrological 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). Many sectors in society are dependent on water. The interconnectedness and interdependencies between sectors as well as society can give rise to wide-ranging drought impacts with cascading and ripple effects (Hagenlocher et al., 2023;

UNDRR, 2021). Consequently, there is a growing call for understanding the systemic nature of risk (UNDRR, 2019), incorporating multi-sectoral and whole-of-society systems perspectives (Hagenlocher et al., 2023; Stefanski et al., 2025). Such endeavors require an understanding, not only of the drought hazard itself, but also of the underlying vulnerabilities of a system that can exacerbate the impacts of a drought. Analyzing and understanding drought vulnerability can improve drought risk management and the resilience of socio-hydrological systems. There is currently no interdisciplinary consensus on how to define and conceptualize vulnerability (Ciurean et al., 2013; Fuchs and Thaler, 2018; Jamshed et al., 2023; O'Brien et al., 2007; Rufat and Metzger, 2024; Turesson et al., 2024). 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, duration (Adger, 2006), and location (O'Brien et al., 2004; 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). Yet, indicator-based assessments often use the same set of vulnerability indicators, independent of the context of the assessment (Hagenlocher et al., 2019).

Due to the contextual nature of drought vulnerability, Stenfors et al. (2024) presented a conceptual model for drought vulnerability in forested cold climate regions based on a substantial list of vulnerability factors that influence drought risk in the climate and eco-region. The model divides vulnerability factors into three distinct categories: (1) direct water consumers, i.e., factors linked to sectors or groups using water directly (e.g., for drinking water, watering crops), (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), and (3) governance processes and plans, such as policies and plans concerning drought and financial ability to adapt or respond to drought, where factors connected to the category can affect both sectors and society as a whole. Their 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. Meanwhile, only approximately 3 % of Swedish agriculture is irrigated (The Swedish Board of Agriculture, 2024), which raises the question of the relevance of this factor in a local setting. Hence, further work is required to assess these factors in order to better understand their systemic relevance and relative impact on multi-sectoral and societal drought risk 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 for 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 for assessing vulnerability to climatic hazards in a river basin in Taiwan. Similarly, Meza et al. (2019) used a survey study to assess the relative importance of drought vulnerability indicators for agriculture and water supply on a global scale. The importance of vulnerability factors varies depending on study region, and incorporating participatory weighting techniques offers valuable insights into the distinct characteristics of an area or region (Moreira et al., 2023). Hence, expert knowledge and stakeholder perceptions can help identify drought vulnerability factors in forested cold climates specifically adapted to stakeholder needs in different socioeconomic sectors. Furthermore, index-based approaches incorporating multi-sectoral or holistic perspectives usually focus on a combination of sectors such as agriculture, water supply, energy, and industry (Engström et al., 2020; Kim et al., 2015; Radeva and Nikolova, 2020; Shiravand and Bayat, 2023; Wang and Sun, 2023), often failing to incorporate the forestry sector, which is an important sector in forested climate regions and forestry-dependent economies. Meanwhile, Melo et al. (2020) and Tidwell (2016) argued for the importance of forests for water, energy, and food securities and the need to update nexus perspectives to include a forest dimension when analyzing multi-sectoral vulnerability to natural and socioeconomic hazards (Melo et al., 2020).

This paper aims to fill this gap and identify the most influential drought vulnerability factors for sectoral and cross-sectoral vulnerability in forested cold climates, thereby informing applied vulnerability assessments, integrated drought risk management efforts, and whole-of-society adaptation efforts. Using the conceptual framework proposed by Stenfors et al. (2024), the research objectives for this paper are to (1) assess the sectoral and cross-sectoral relevance of previously identified drought 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 sectoral, cross-sectoral, and societal vulnerability, (4) explore variations in ratings among the respondents, hypothesizing that impact ratings would vary based on stakeholders' (i) sectorial focus or type of organization, (ii) geographical location, and (iii) level of drought experience, and lastly (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 northwestern Sweden with monthly mean temperatures below 10 °C, to subarctic boreal (Dfc) climate with cool summers, very cold winters, and seasonal snow cover and soil frost during winters in central and northern Sweden, to a warm-summer hemiboreal (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 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 $°C\,yr^{-1}$ 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 divided 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 boundaries 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 the 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 % in Stockholm county (Statistics Sweden, 2022).

The agricultural sector accounts for 4 % of the total freshwater 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 southernmost county Skåne (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 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 2097 million cubic meters of water use, 47 % of which 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: the paper and 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 30–60 % lower than the 5-year average (Jordbruksverket, 2019a), resulting in estimated damage of approximately USD 560–930 million[1] (Jordbruksver-

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

ket, 2019b). 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 6 months long (Sjökvist et al., 2019). Consequently, the availability of grains, dairy products, 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 (MSB, 2025). 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 (SVT 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).

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 (hereafter: 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), and (3) governance processes and plans (governance) – that is, governing processes, policies, tools, and plans that affect a sector or society's ability to cope with and adapt to drought. 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 (IPCC, 2023) 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.* Susceptibility is an element's 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 10 categories based on their overall attributes (Table 1), with the full list of vulnerability factors and their corresponding subcategories available in Tables S1 and S2 in the Supplement.

2.3 Data collection and 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" for 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.

Table 1. Overview of the number of sectoral, societal, and governance vulnerability factors included in the survey, divided into 10 subcategories based on their general attributes. Short names for each subcategory, which are used in the "Synthesis of 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			

The respondents were also given the opportunity to suggest their own additional factors in both sections two and three. As described above, the same 23 governance factors were included in both sections 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 Sect. S2 in the Supplement.

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

Using the identification matrix, survey recipients from governmental/local authorities (354 recipients), private/state/-municipally 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 was identified using three approaches: (1) internet searches combining their organization name and keywords in Swedish such as "drought" and "water shortage" (30 respondents), (2) searching their organization websites for the keywords "drought" and "water shortage" (37), and (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).

2.3.3 Analysis of survey responses

All survey responses were transferred and analyzed using Microsoft Excel and RStudio (Kassambara, 2023; R Core Team, 2024; Van Den Brand, 2024; Wickham, 2016; Wickham et al., 2023). 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 a medium to high or high impact (corresponding to median scores of 3 or 4) on drought risk. For even numbered 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 pairwise 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 0–4) 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. 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 Kruskal–Wallis test by ranks. If significant differences between groups/categories were identified, the data were further analyzed using pairwise Wilcoxon rank sum tests to calculate pairwise comparisons between group levels with corrections for multiple testing. The Kruskal–Wallis test by ranks and Wilcoxon rank sum are nonparametric tests that can be applied for ordinal data and have previously been used for assessing differences between group ratings in studies involving participatory approaches and ordinal data (i.e., Cuesta et al., 2022; Mızrak and Aslan, 2020; Teutschbein et al., 2023a). 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 were 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.

3 Synthesis of results

3.1 Respondent characteristics and experience

The survey received 108 responses, corresponding to a 19.3 % response rate. Six respondents solely answered "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 respondents 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 %), and 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 %), or 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 (26 %) or terrestrial (29 %) ecosystems. 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 %) were located in southern Sweden. Respondents from northern Sweden (16 %) worked at an authority, at an 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 Tables S4 and S5 in the Supplement.

Table 2. Overview of respondents, their geographical location divided by north (above 60° N) and south (below 60° N), **(a)** type of organization, and **(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 significant experience with droughts (over 70 % of respondents in each sector) (Table 3). The environmental sector had the largest spread in drought experience, where 37 % indicated having significant experience with droughts. Looking at drought experience by place of employment (enterprise, trade association, or research respondent groups) showed the highest percentage of respondents with significant drought experience. Respondents from authorities had the largest spread, where 47 % of respondents had significant experience with droughts. 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.

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 3 or higher) for drought risk in their sector (35, 21 of which had a median rating of 4), followed by environmental (32, 4), water resources (31, 12), water supply (26, 9), energy (11, 2), and forestry (10, 0) (Table 4).

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-dependent 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.

Respondents from authorities and trade associations found the largest number of *societal* vulnerability factors relevant, rating factors relating to all categories of societal vulnerability, except *demographics*, as relevant for societal drought risk. Interestingly, the subcategory *demographics* was not considered relevant for societal drought risk by any of the respondent groups. In contrast, almost all vulnerability factors connected to *governance* were relevant for 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 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 (Fig. 1). 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 was connected to the conditions of the surrounding settings, where many sectoral factors in-

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

cluded in the subcategory received overall medium–high to high 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 relates 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, this category was the only category to not receive impact scores lower than 0.33 by any sector for any of the involved factors. Interestingly, the environmental sector, which had the largest number of respondents among the sectors, gives most factors relating to adaptive capacity similar impact scores. Comparatively, the variation in impact scores by the environmental sector is larger for factors relating to coping capacity and susceptibility.

The five relevant 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 (Fig. 2). Respondents from all types of organization included in the survey found *the societal financial dependency on direct water-consuming industries (DWC)* to be relevant for societal drought risk. Apart from this, respondents from research only found *access to public drinking water* to be relevant for societal drought risk, whereas NGOs found the *drought awareness of water users* to be relevant as well as highly impactful. Enterprises found *access to public drinking water* and *the size of the population* to be relevant for societal drought risk but did not rate them highly.

Factors relating to *governance* generally receive slightly higher impact scores, concerning their impact on both sectors and society, compared to sectoral factors (Fig. 3). 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 received 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, partly due 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 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* 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*.

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 sectors or societal organizations (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) from both a sectoral and societal perspective, factor relevance is included for both sectors and organizations.

					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
(a) Sectoral vulnerability factors														
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	6	7		–	–	–	–
	Funds	3	2	–	2		1	1	1		–	–	–	–
	Irrigation	4	4	–	4		1	3	3		–	–	–	–
	Supply	3	3	–	2	2	3	2	3		–	–	–	–
	Susceptibility	31	28	–	20	8	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	3	7	5	5		–	–	–	–
	Supply	5	4	–	3	1	3	3	3		–	–	–	–
	Total	51	46	–	35	11	32	31	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
	Supply	1	–	1							1	1	1	1
	Total	9	–	5	–	–	–	–	–	–	5	3	2	5
(c) Governance factors														
Governance	Adaptive	9	9	9	8	3	6	8	8	1	9	3	7	8
	Policies	2	2	2	1	1	2	1	1		2		1	1
	Tools	7	7	7	7	2	4	7	7	1	7	3	6	7
	Coping	14	13	14	12	6	11	12	12	1	14	4	9	11
	Authority	6	5	6	5	1	3	4	4	1	6	1	4	4
	Policies	7	7	7	6	5	7	7	7		7	3	4	7
	Tools	1	1	1	1		1	1	1		1		1	
	Total	23	22	23	20	9	17	20	20	2	23	7	16	19

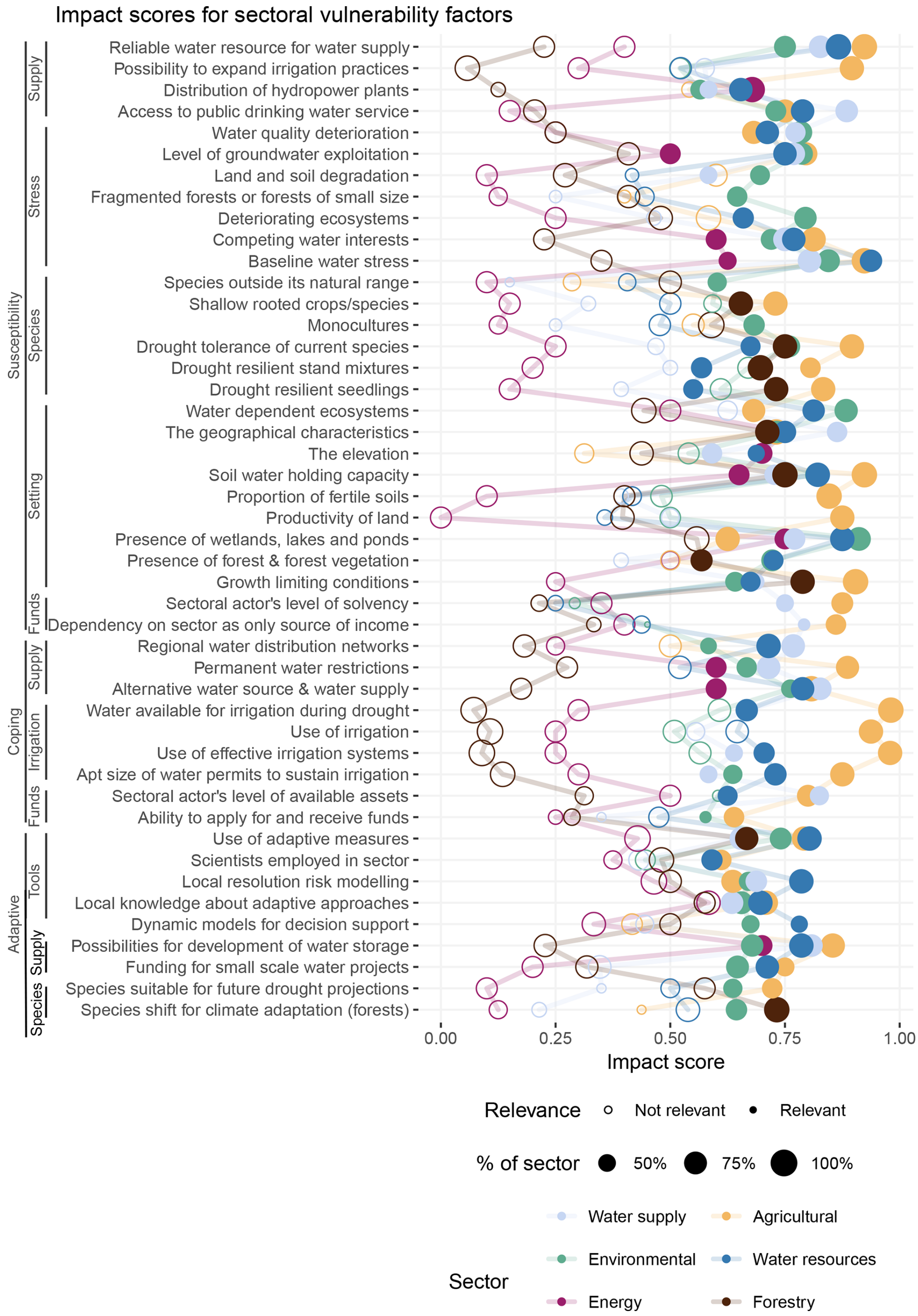

Figure 1. Impact scores for sectoral vulnerability factors concerning adaptive capacity (adaptive), coping capacity (coping), and susceptibility, rated regarding their impact on drought risk in water-dependent sectors. Filled dots indicate that the factor is considered relevant for the sector (i.e., 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.

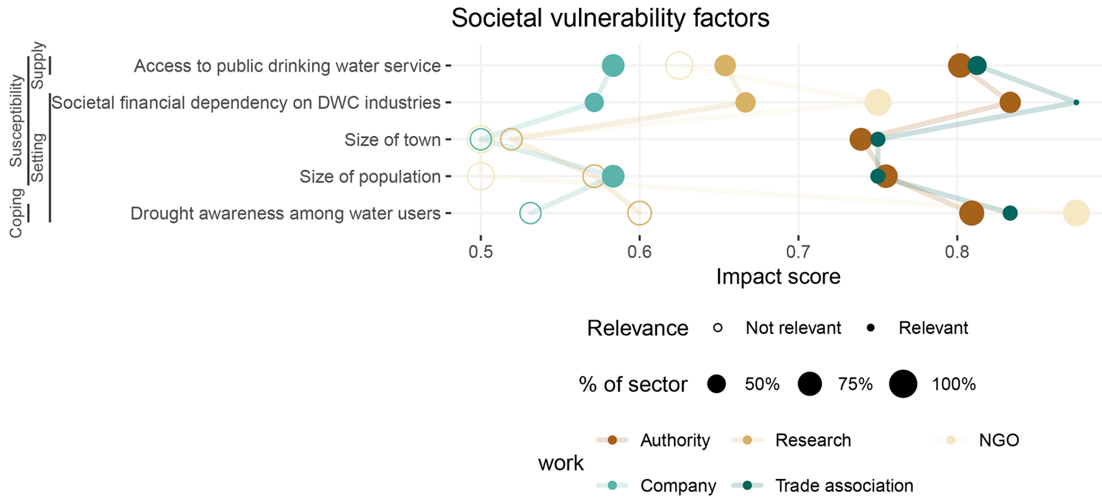

Figure 2. Impact scores for societal vulnerability factors concerning coping capacity (coping) and susceptibility, rated regarding their impact on societal drought risk. Filled dots indicate that the factor is considered relevant by the organization (i.e., with a median score of 3 or higher), whereas 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.

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 coping capacity or susceptibility (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 the geographical characteristics and having a reliable water resource for water supply.

Adaptive- and susceptibility-related factors were the only vulnerability factors to receive high impact 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 to be factors with a 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.

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 the town. Similar to the sectoral ratings, access to public drinking water was also highly rated by sectors such as the agricultural, environmental, and water resources sector and was 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 sectors 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, the presence of groundwater monitoring appears to be the highest rated vulnerability factor, closely followed by having planned drought prevention measures at the 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).

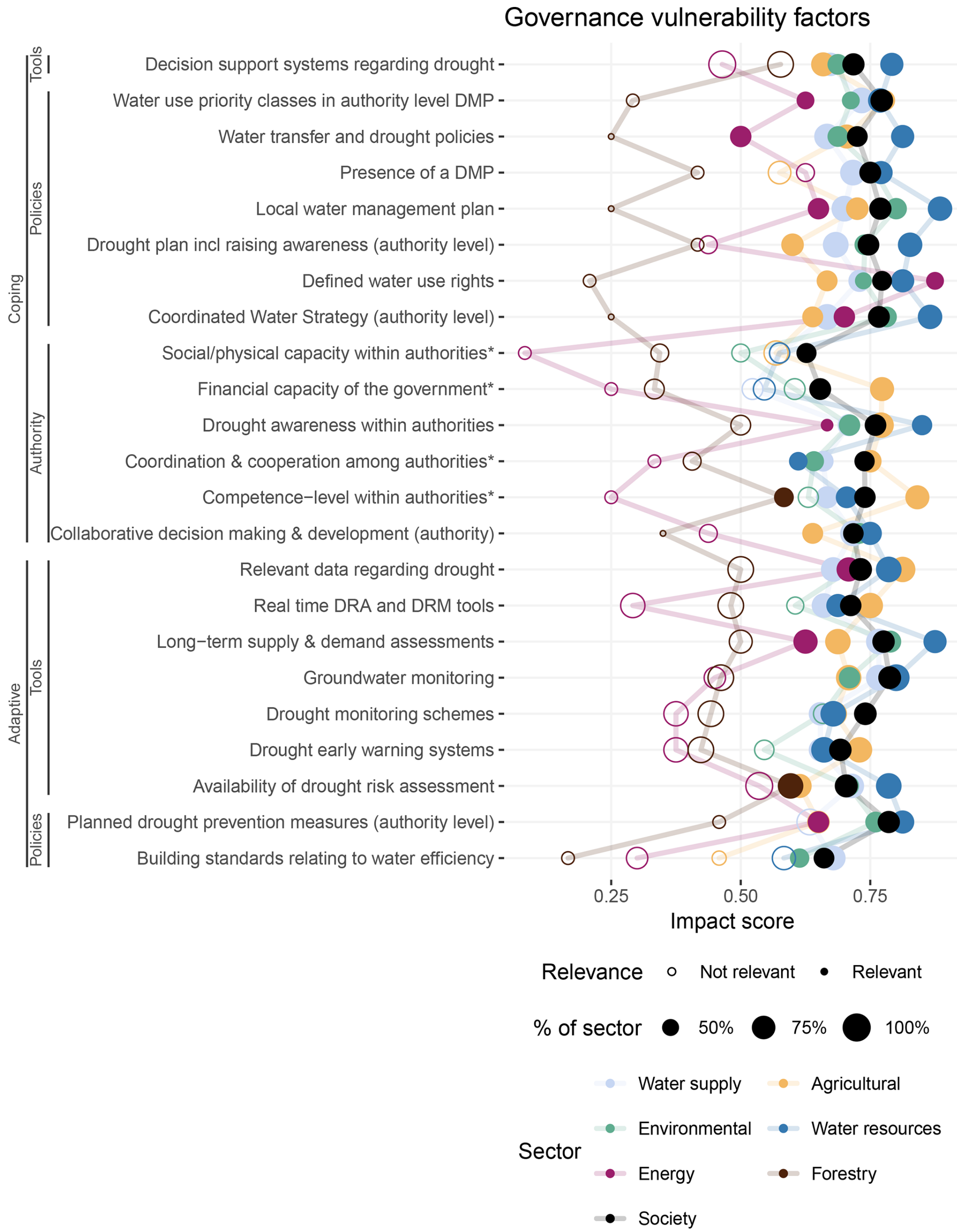

Figure 3. Impact scores for governance-related vulnerability factors concerning adaptive capacity (adaptive) and coping capacity (coping) rated regarding their impact on drought risk in both sectors and society as a whole. Filled dots indicate that the factor is considered relevant for the sector or 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 the percentage of the respondents within a sector that provided an impact rating for the factor. The asterisk (*) indicates "to offer drought-related support".

Table 5. The five highest normalized impact scores, where the letters in parentheses indicate vulnerability factors concerning adaptive capacity (A), coping capacity (C), or susceptibility (S). Highly rated factors for a sector with the same impact scores are listed arbitrarily.

All sectors			
(S) Soil water-holding capacity	0.80		
(S) Baseline water stress	0.79		
(S) Presence of wetlands, lakes, and ponds	0.78		
(S) The geographical characteristics	0.75		
(S) Reliable water resource for water supply	0.73		
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	(S) Growth-limiting conditions	0.79
(S) Water-dependent ecosystems	0.88	(S) Soil water-holding capacity	0.75
(S) Baseline water stress	0.84	(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	(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 and water supply	0.83
(S) Water-dependent ecosystems	0.81	(C) Sectoral actor's level of available assets	0.83

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 31 sectoral factors (Fig. 4a). 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 were primarily 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). The impact of place of employment on the sectoral ratings was studied for the environmental, water supply, and forestry sector. These sectors had multiple respondents working for at least two different organizations. However, no significant differences were seen in ratings, depending on place of employment for the forestry and environmental sector. For the agricultural sector, significant differences in ratings were only seen for the factor *geographical characteristics* (p value 0.04) between respondents working in research (median rating 2) and trade associations (median rating 4). An overview of the sectoral factors with significant differences in impact ratings can be found in Table S6 in the Supplement.

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 differences 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

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, and **(c)** governance factors rated on their impact on societal drought risk. The letters in parentheses indicate vulnerability factors concerning adaptive capacity (A), coping capacity (C), or susceptibility (S).

(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 and demand assessments	0.788	(C) Competence level within authorities*	0.583
(C) Coordinated water strategy (authority level)	0.781		
(A) Planned drought prevention measures (authority level)	0.760		
(C) Presence of a DMP	0.760		
Water resources		Water supply	
(C) Local water management plan	0.885	(A) Long-term supply and demand assessments	0.767
(A) Long-term supply and 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
(S) Access to public drinking water service	0.750	(A) Planned drought prevention measures (authority level)	0.786
(C) Drought awareness among water users	0.747	(A) Long-term supply and demand assessments	0.776
(S) Size of population	0.695	(C) Defined water-use rights	0.773
(S) Size of town	0.668	(C) Water use priority classes in authority level DMP	0.772

The asterisk (*) indicates "to offer drought-related support".

Sweden. Respondents from both the north and south of Sweden found the societal financial dependency on direct water-consuming industries to be relevant for societal drought risk. However, no significant differences in societal factor ratings were seen between respondents working in enterprises or 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 involve the sector. Respondents from the water resources and environmental sector gave significantly different ratings compared to the forestry sector (for seven and five factors, respectively), where a majority of the factors were water- and drought-related policies and plans. When comparing governance factor ratings from a societal perspective per place of employment (Fig. 4b), significant differences in factor ratings were found between respondents from authorities and enterprises (2) and research (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 Table S7a and S7b.

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 the south of Sweden for ratings for individual sectors or society. Significant differences in factor ratings depend-

(a) Sectoral vulnerability

	Water supply (1)	Agricultural (2)	Environmental (3)	Water resources (4)	Energy (5)	Forestry (6)
Sectoral						
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

	Authority (1)	Research (2)	NGO (3)	Enterprise (4)	Trade association (5)
Governance					
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 a pairwise Wilcoxon rank sum test were observed. Differences in vulnerability factor 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 colored 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 Tables S6 and S7 in the Supplement.

ing on reported drought experience were only seen for the governance factor *presence of groundwater monitoring* (p value 0.042). The factor was generally rated as impactful by respondents regardless of the level of drought experience. However, respondents that reported having moderate to moderately significant drought experience (indicating a drought experience rating of 2 or 3) seemed to have a larger spread in their ratings for that factor.

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 (Fig. 5). 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 around the area used for production forest and natural forests and the presence of forest damage. For the agricultural sector, several of the additional factors suggested revolved around the presence or availability of information on adaptation strategies and knowledge- or evidence-based policies. Financial factors were also mentioned, such as the profitability of investments.

Societal factors included a combination of biophysical and socioeconomic factors. For example, forest fires, geography, and the 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 mentioned the importance of understanding the actual responsibility of different authority levels during drought.

4 Discussion

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 NGOs 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 a 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 the 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. For instance, Moshir Panahi et al. (2023) found 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 systems, and agricultural systems had some of the largest numbers 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 and water supply as important for the sector. This emphasizes the role of terrestrial ecosystem 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), and 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 and plans, degree of land degradation and 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 did receive high impact scores by the respondents working in the water supply sector. Still, these findings highlight the importance of locally relevant vulnerability factors and that the relevance of vulnerability factors can differ depending on climatological and ecological context.

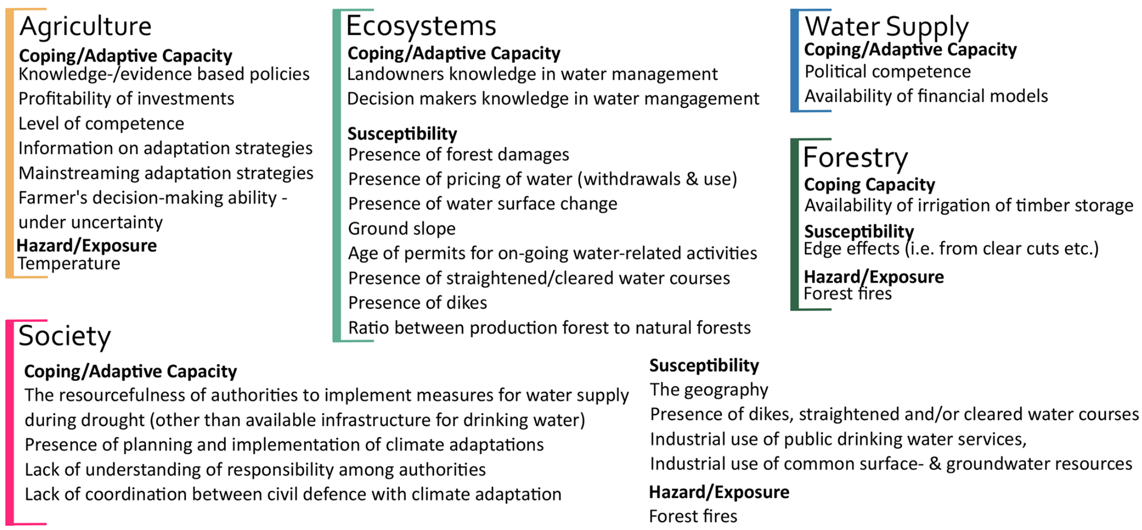

Figure 5. New factors that were mentioned by the respondents divided by sector (as expressed by respondents from the agricultural – yellow, environmental – light green, forestry – dark green, and water supply –blue) and societal factor (pink).

This information is crucial, as indicator-based assessments often use the same set of vulnerability indicators, regardless of sectoral, contextual, and scale-dependent differences (Hagenlocher et al., 2019). The contextual nature of drought vulnerability becomes clearer when comparing our findings with the most commonly used vulnerability indicators globally. For example, factors related to poverty and income are some of the most commonly used vulnerability factors in people-centered drought risk assessments globally (Hagenlocher et al., 2019). Yet, 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 the socioeconomic susceptibility of the population (Acosta and Galli, 2013; Hurlbert and Gupta, 2016; Pappné Vancsó et al., 2016; Raikes et al., 2021), were considered relevant for societal drought vulnerability by the respondents. This contrasts with the findings of Englund et al. (2023), who, through participatory approaches, found that several aspects connected to social susceptibility (e.g., illness and disability, age, income, unemployment, housing) and social integration were important for social vulnerability to floods in the Swedish municipality of Halmstad. Likewise, Turesson et al. (2024) concluded that social vulnerability to climate extreme exists in Nordic countries, finding factors related to, for example, demographics, income, and social cohesion as contributing to social vulnerability to climate risk in the study region. However, as these studies are not specifically focused on drought hazard but on flood and climatic hazards in general, our results could be an indication that aspects such as social integration and socioeconomic susceptibility are less impactful for drought risk in welfare states such as Sweden. Another potential reason for this disconnect could lie in whether societal vulnerability is addressed as an individual condition or a societal one (Orru et al., 2022). In our survey, respondents were asked to rate the societal vulnerability factors regarding their impact on drought risk in society as a whole. Whilst social integration and socioeconomic susceptibility may play an important role for drought risk for the individual, the respondents may view such factors as having less impact on overall societal drought risk. Alternatively, the low rated relevance for these factors can be a reflection of an unwillingness to categorize certain groups or individuals as more vulnerable than others (Orru et al., 2022), instead putting an emphasis on structural pressures and institutional tools for societal vulnerability. Looking at the factors considered relevant for societal drought risk, these could be seen as relating more to factors exerting pressures on a society, such as the size of the population, size of the town, and societal dependency on water-dependent sectors. Nevertheless, further research is needed to understand the role of social susceptibility for drought vulnerability in the region.

Local differences in stakeholder perceptions of societal vulnerability were also seen. 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. There could be several reasons for the low number of relevant societal vulnerability factors in the north of Sweden. 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 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; 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 no or very weak impacts from the 2 drought years 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 in 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 into drought vulnerability

Letting all sectors rate the same list of factors 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 of water management, the 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. 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 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, 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 sociohydrological systems on both 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 and 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 impact scores not only show the impact of the factors within a specific sector, but also 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. 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, regarding both sectoral and 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.

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, and 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 water 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 for 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 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 to, for example, minimize water consumption (to reduce baseline water stress) and source 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, as well as 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 also on 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 as well as coordination and cooperation across authority levels.

4.4 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, and authorities (Fleming et al., 2023). Our study addressed this by incorporating stakeholders working in authorities, academia, industry, trade associations, and NGOs. Whilst significant differences in sectoral factor 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 the 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 respondents' subjective opinions than the characteristics of the respondents, such as work or drought experience (Moreira et al., 2023). However, since a majority of stakeholders 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.

4.5 Further work

Our drought vulnerability survey found several vulnerability factors relevant for drought vulnerability in water-dependent sectors and 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 number of responses attained. The study provides a comprehensive list of context-specific drought vulnerability factors, as well as their relative impact on drought risk depending on 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 northeastern Europe), and future research should aim to incorporate the factors in applied assessments to deepen the understanding of drought risk in the region.

5 Conclusions

To confirm and investigate 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 the sectoral focus of the respondents, as well as place of employment for sectoral and societal vulnerability factors, 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 with droughts compared to respondents with more reported experience were 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 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 to be 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 from 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 ways 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 forested cold countries such as Sweden, efforts should be made to further analyze the results obtained in this study for operationalizing the factors through the development of relevant drought indicators and identification of suitable data sources. In this context, our study provides a valuable guide for drought vulnerability in six water-dependent sectors as well as for society as a whole to effectively lower drought vulnerability in water-dependent societies.

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 is provided within the paper. For any inquiries regarding the data, please contact the corresponding author.

Supplement. The supplement related to this article is available online at https://doi.org/10.5194/hess-29-3809-2025-supplement.

Author contributions. ES: 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). MB: supervision (supporting), visualization (supporting), writing – review and editing (supporting). TG: conceptualization (supporting), methodology (supporting), supervision (supporting), visualization (supporting), writing – review and editing (supporting). CT: conceptualization (supporting), funding acquisition (lead), methodology (supporting), project administration (lead), supervision (lead), visualization (supporting), writing – review and editing (supporting).

Competing interests. The contact author has declared that none of the authors has any competing interests.

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Special issue statement. This article is part of the special issue "Drought, society, and ecosystems (NHESS/BG/GC/HESS inter-journal SI)". It is not associated with a conference.

Financial support. This research has been supported by the Svenska Forskningsrådet Formas (grant-nos. FORMAS 2015-01123 and FORMAS 2023-00515) and the Royal Swedish Academy of Sciences (grant-no. LN2016-0101). Access to an online survey platform and training in survey analysis were funded by the Interdisciplinary Grant from the Centre of Natural Hazards and Disaster Science (CNDS).

The publication of this article was funded by the Swedish Research Council, Forte, Formas, and Vinnova.

Review statement. This paper was edited by Anne Van Loon and reviewed by three anonymous referees.

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