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Drought Vulnerability in Cold-Climate Socio-Hydrological Systems

Exploring sectoral patterns, municipal contexts, and shifting perceptions

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ACTA UNIVERSITATIS
UPSALIENSIS
2026

ISSN 1651-6214
ISBN 978-91-513-2748-8
urn:nbn:se:uu:diva-578680

UPPSALA
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Dissertation presented at Uppsala University to be publicly examined in Hambergssalen, Geocentrum, Villavägen 16, Uppsala, Friday, 10 April 2026 at 10:00 for the degree of Doctor of Philosophy. The examination will be conducted in English. Faculty examiner: Professor Lindsey McEwen (University of the West of England Bristol, School of Architecture and Environment, Department of Geography and Environmental Management).

Abstract
Stenfors, E. 2026. Drought Vulnerability in Cold-Climate Socio-Hydrological Systems. *Exploring sectoral patterns, municipal contexts, and shifting perceptions*. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 2642. 83 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-513-2748-8.

In a changing climate, proactive risk management is increasingly advocated to reduce the complex and costly nature of drought impacts. Modern disaster-risk approaches conceptualize risk as a function of hazard, exposure, and vulnerability. Yet, vulnerability is in itself complex, varying across contexts and shifting over time. Across five interlinked studies, this thesis explores how drought vulnerability is shaped in forest or tundra dominated cold climate regions, using a combined top-down and bottom-up research design.

Papers I–III integrate a systematic literature review for the broader study region with a confirmatory survey of Swedish water-dependent sectors, assessing how these sectors perceive the influence of literature-derived vulnerability factors on drought risk. Papers IV and V use a repeated survey distributed to Swedish municipalities in 2018 and 2023 to analyze how municipal experiences, risk perceptions, and management approaches evolve over time and in relation to observed drought conditions.

The results demonstrate that drought vulnerability in forested cold climates is shaped more by biophysical and governance related factors than by socioeconomic factors tied to basic needs or human development. Vulnerability in the study region differs across sectors and water-dependence profiles, while foundational cross-sectoral vulnerability factors emerge from biophysical characteristics and governance capacities such as drought-related policies, planning, coordination, and awareness. The thesis also highlights persistent misalignments among sectors, researchers, and authorities, including limited policy implementation, inconsistent terminology, and perceptual dynamics that complicate proactive drought risk management. The repeated survey further reveals the temporal complexity of drought risk perception, which the results indicate is shaped more by event magnitude than by simple exposure frequency.

Together, these findings support a cold-climate conceptual framing that integrates biophysical vulnerability, governance capacity, and sector-specific vulnerabilities shaped by water dependencies. Its implications for policy and practice include i) specifying drought type and associated sectoral vulnerabilities in assessments and risk management, ii) developing drought indicators aligned with local realities, and iii) strengthening drought related governance capacities and science-authority-stakeholder exchanges within socio-hydrological systems. Overall, these findings also underscore the need for vulnerability assessments to account for context and water-type dependencies, rather than relying on generic indicator sets.

Keywords: Drought vulnerability, Risk management, Risk perception, Multi-sectoral perspectives, Boreal, Cold climate

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ISSN 1651-6214
ISBN 978-91-513-2748-8
URN urn:nbn:se:uu:diva-578680 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-578680)

For my family, those whose love still surrounds me,
and those whose loving memory will always be with me

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I. **Stenfors, E**., Blicharska, M., Grabs, T., & Teutschbein, C. (2024). Droughts in forested ecoregions in cold and continental climates: A review of vulnerability concepts and factors in socio-hydrological systems. WIREs Water, 11(2), e1692. https://doi.org/10.1002/wat2.1692

II. **Stenfors, E.**, Blicharska, M., Grabs, T., & Teutschbein, C. (2025). Multi-sectoral and systemic drought risk in forested cold climates: Stakeholder-informed vulnerability factors from Sweden. Hydrology and Earth System Sciences, 29, 3809-3832. https://doi.org/10.5194/hess-29-3809-2025

III. **Stenfors, E.**, Blicharska, M., Grabs, T., & Teutschbein, C. (2025). Sectoral vulnerability to drought: exploring the role of blue and green water dependency in mid- and high-latitude regions. Natural Hazards and Earth System Sciences, 25, 3381-3395. https://doi.org/ 10.5194/nhess-25-3381-2025

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

V. **Stenfors, E.**, Mickelsson, M., Landström, C., & Teutschbein, C. (2026). Evolving Perceptions of Drought Risk and Management: Insights from a Repeated Survey of Swedish Municipalities. [Preprint], http://dx.doi.org/10.2139/ssrn.6282651. *Under review*

Additional Papers

In addition, during my doctoral studies I contributed to the following papers:

Biella, R., Shyrokaya, A., Ionita, M., Vignola, R., Sutanto, S.J., Todorovic, A., Teutschbein, C., Cid, D., Llasat, M.C., Alencar, P., Matanó, A., Ridolfi, E., Moccia, B., Pechlivanidis, I., Van Loon, A., Wendt, D.E., **Stenfors, E.**, Russo, F., Vidal, J.-P., Barker, L., De Brito, M.M., Lam, M., Bláhová, M., Trambauer, P., Hamed, R., McGrane, S.J., Ceola, S., Bakke, S.J., Krakovska, S., Nagavciuc, V., Tootoonchi, F., Di Baldassarre, G., Hauswirth, S., Maskey, S., Zubkovych, S., Wens, M., Tallaksen, L.M. (2025). The 2022 drought needs to be a turning point for European drought risk management. Natural Hazards and Earth System Sciences, 25, 4475–4501. https://doi.org/10.5194/nhess-25-4475-2025

Biella, R., Shyrokaya, A., Pechlivanidis, I., Cid, D., Llasat, M.C., Wens, M., Lam, M., **Stenfors, E.**, Sutanto, S., Ridolfi, E., Ceola, S., Alencar, P., Di Baldassarre, G., Ionita, M., De Brito, M.M., McGrane, S.J., Moccia, B., Nagavciuc, V., Russo, F., Krakovska, S., Todorovic, A., Tootoonchi, F., Trambauer, P., Vignola, R., Teutschbein, C. (2024). The 2022 Drought Shows the Importance of Preparedness in European Drought Risk Management. https://doi.org/10.5194/egusphere-2024-2073 (*Accepted*)

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

Contents

Abbreviations

CAB	County Administrative Board
EDO	European Drought Observatory
IPCC	Intergovernmental Panel on Climate Change
PAR	Pressure and Release Model
PDSI	Palmer Drought Severity Index
SES	Social-Ecological System
SGI	Standardized Groundwater Index
SGU	Geological Survey of Sweden
SMHI	The Swedish Meteorological and Hydrological Institute
SMRI	Standardized Snow Melt and Rain Index
SPI	Standardized Precipitation Index
SWSI	Surface Water Supply Index
UNDRR	United Nations Office for Disaster Risk Reduction

Introduction

Droughts in Forested Cold Climates: An Emerging Challenge

Droughts are among the costliest and most complex natural hazards, causing billions of dollars in impacts for a range of sectors worldwide annually (Cammalleri et al., 2020; OECD, 2025; WMO & GWP, 2016). While they are naturally occurring phenomena for all climates (Wilhite, 1996), research suggests climate change is causing an acceleration in drought trends, with intensified drought events and increases in the global land area being exposed (OECD, 2025). Broadly defined as periods with regional water deficits compared to normal conditions, droughts can occur in all climates and are a recurring and often slow onset natural phenomena (Wilhite, 1996; WMO & GWP, 2016). Their impacts can be both direct and indirect (Blauhut et al., 2016; Freire-González et al., 2017; Gil et al., 2013; Rossi et al., 2023; Venton et al., 2019), and can emerge gradually (Mishra & Singh, 2010; Tijdeman et al., 2022) and accumulate over time (Tijdeman et al., 2022), causing some of the highest economic losses among natural hazards (Kim et al., 2015). While drought conditions are often associated with dry climates (Smakhtin & Schipper, 2008; Weitkamp et al., 2020), partly due to the common confusion between drought (temporary deviation from normal conditions) and aridity (a permanent climatic state) (Smakhtin & Schipper, 2008), recent events have shown that regions with forested and cold climates (Figure 1) can also be subject to drought conditions (Bakke et al., 2020; Meilutytė-Lukauskienė et al., 2024; Teutschbein et al., 2022, 2025).

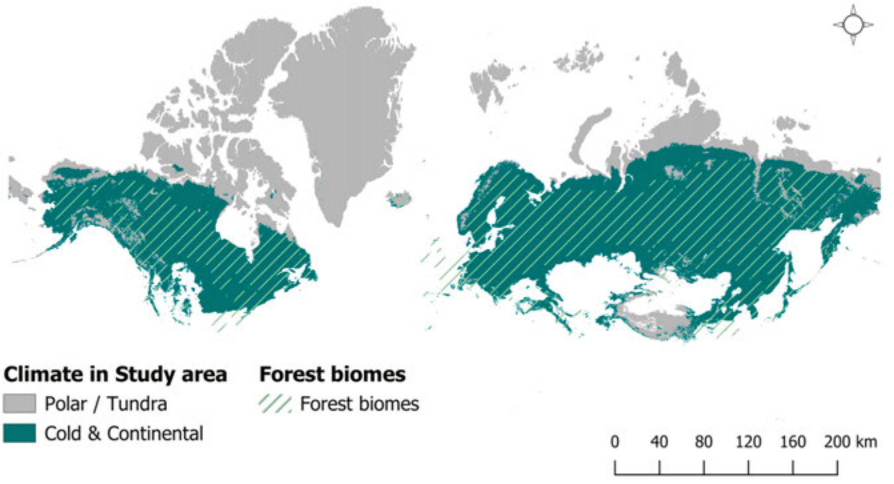

Figure 1. Climate regions exhibiting polar or cold climates (Beck et al., 2018) in the northern hemisphere, and existing forest cover in these regions (Dinerstein et al., 2017).

These regions rely on water resources for several sectors such as agriculture, energy production, industry, ecosystem services, forestry, and drinking water supply, sectors that have been significantly affected during recent drought events. For example, in 2022, the European continent saw some of the worst drought conditions in the continent's history (Faranda et al., 2023), affecting approximately a third of the continent (OECD, 2025), and in 2018 large parts of Europe, including Scandinavia were hit by a large scale drought event (Bakke et al., 2020; Teutschbein et al., 2022). The 2018 drought had significant impacts on the region. In Sweden, crop yields were significantly lowered compared to the five-year average (Jordbruksverket, 2018), and inflow to hydropower reservoirs were reduced, resulting in substantial increases in electricity prices (Sjökvist et al., 2019). More than 500 forest fires were registered in Sweden during the drought period, which together burned more than twenty thousand hectares of forest (MSB, 2018). In the summer of 2025, large parts of Canada experienced drought conditions ranging from moderate to extreme (Agriculture and Agri-Food Canada, 2025b). Reported impacts included low streamflow, declining surface water levels, wildfires, and official declarations of agricultural drought disasters (Agriculture and Agri-Food Canada, 2025b, 2025c, 2025a). In the Atlantic region of Canada, the wildfires prompted evacuations to be enforced, and one town declared a state of emergency after its water reservoir ran dry, necessitating manual pumping to maintain supply (Agriculture and Agri-Food Canada, 2025a).

As forested cold climates host a majority of the world's boreal forest (Brandt et al., 2013), drought effects on these ecosystems can affect both local economies and sectors of national economic importance such as timber production (Anderegg et al., 2013) as well as impact a vital global carbon sink (Anderegg et al., 2013, 2020; Q. Liu et al., 2023; Martínez-García et al., 2024; Pan et al., 2011). Boreal forests cover approximately a third of the global forest area (FAO, 2020), and the uptake of carbon dioxide by boreal forest are essential for moderating climate change (Q. Liu et al., 2023; Martínez-García et al., 2024; Pan et al., 2011, 2024). Meanwhile, the global boreal carbon sink is exhibiting a declining trend in recent decades as a result of intensified disturbances such as droughts (Q. Liu et al., 2023; Ma et al., 2012; Pan et al., 2024).

The many impacts seen from recent drought events in forested cold climates highlight the need to understand drought risk for local, national and regional resilience as well as global climate regulation. In this regard, drought vulnerability assessments can act as important analytical tools to understand the specific configurations that contribute to drought risk in these regions. By systematically assessing drought risk, decision-makers can move from reactive crisis management toward proactive planning in order to reduce the effect of future drought events.

Understanding Drought Risk: A Multi-Dimensional Problem

Modern disaster risk approaches follow the Sendai Framework for Disaster Risk Reduction (2015 - 2030) (UNDRR, 2015). The framework was adopted by the UN General Assembly in 2015, and is a central international agreement that aims to advance the understanding of complex disaster risks and emphasizes the need for proactive disaster risk reduction (UNDRR, 2015, 2019). The framework forms the basis of modern drought risk assessments, and divides risk into three dimensions: hazard, exposure, and vulnerability (Figure 2). The three dimensions of risk demonstrate that a hazard alone does not create a disaster (Birkmann, 2013; UNDRR, 2019; UNISDR, 2007). Rather, a disaster arises when a hazard coincides with exposed entities that are also vulnerable to its effects (Cardona et al., 2012; Meza et al., 2020; Rossi et al., 2023; UNDRR, 2019).

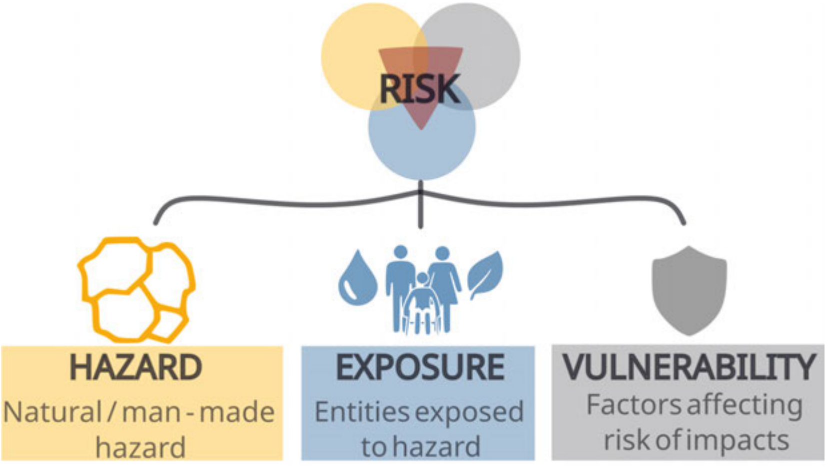

Figure 2. The three-component risk framework, incorporating hazard, exposure, and vulnerability.

From a drought risk perspective, hazard assessments focus on parameters of the drought phenomenon, such as the frequency, duration, severity or spatial extent (UNDRR, 2021). Meanwhile, drought exposure and vulnerability assessments study the entities exposed to the hazard and their characteristics (IPCC, 2014, 2023). The resulting risk of negative impacts from a drought event is therefore affected not only by the hazard, but also by the vulnerabilities of the socio-hydrological systems exposed, including the human actions taken in response to a drought both proactively and reactively (Birkmann, 2013). Consequently, human actions and the characteristics of exposed entities can both exacerbate or alleviate the effects of a drought event. By combining hazard, exposure and vulnerability assessments, an overview of drought risk at different scales can be studied (Rossi et al., 2023).

Drought as a hazard

Broadly defined as periods with regional water deficits compared to normal conditions, droughts can occur in all climates and are a recurring and slow onset natural phenomena (Tallaksen & Lanen, 2023; Wilhite, 1996). Drought events generally start with climatological variability causing deficiency in precipitation, sometimes combined with other factors such as increased temperature or high winds. These climatic variabilities limit the input of water into the hydrological system and deficits propagate through the hydrological cycle (Barker et al., 2016), often seen first as deficits in soil moisture (Tallaksen & Lanen, 2023; Teutschbein et al., 2025) and subsequent anomalies on ground- and surface water supplies (Figure 3) (Barker et al., 2016; Tallaksen & Lanen, 2023; Teutschbein et al., 2025). However, drought propagation is complex (Barker et al., 2016; Rajsekhar et al., 2015), with feedback loops between different parts of the sociohydroclimatic system (Van Loon, 2015; Van Loon et al., 2024). As a result, the drought signal will in reality differ depending on the specific situation (Barker et al., 2016; Laaha et al., 2017; Tallaksen & Lanen, 2023; Teutschbein et al., 2025). Nevertheless, depending on where in the hydrological system it occurs, droughts are typically categorized into four types: (1) meteorological (precipitation deficit, sometimes combined with increase in evapotranspiration), (2) soil moisture (soil moisture deficit), (3) hydrological (deficit in surface- or subsurface water), and (4) socioeconomic drought (deficit/impact on water as an economic good) (Mishra & Singh, 2010; Van Loon, 2015). While these drought types affect different parts of the hydro-meteorological system (Mishra & Singh, 2010) and can vary in characteristics such as propagation times (Tallaksen & Lanen, 2023; Teutschbein et al., 2025), risk assessments frequently fail to specify which drought type is studied (Hagenlocher et al., 2019).

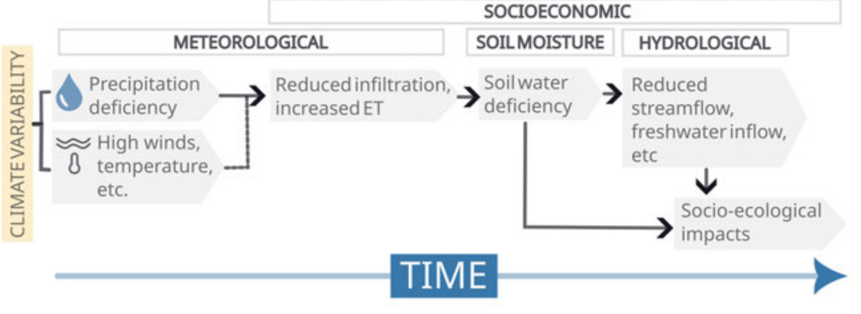

Figure 3. The four commonly used drought types and simplified schematic of their propagation through the hydrological system moving from left to right in the figure.

Drought hazards are often analyzed using drought indices in order to understand underlying mechanisms or quantify and identify drought conditions (Farahmand & AghaKouchak, 2015; Mishra & Singh, 2010; Teutschbein, Jonsson, et al., 2023). One of the most commonly used indices is the Standardized Precipitation Index (SPI) (Farahmand & AghaKouchak, 2015). It reflects meteorological drought conditions by assessing the precipitation anomaly compared to historical precipitation data (McKee et al., 1993; Mishra & Singh, 2010). Negative SPI values reflect drought conditions, whereas positive values mean above normal precipitation. The SPI can be calculated monthly or for longer time periods depending on the drought type or trend that is being investigated (McKee et al., 1993). For example, SPI3 is calculated for a three-month period and showcases seasonal trends providing indications on short- to medium term soil moisture conditions (Lloyd-Hughes & Saunders, 2002). Calculating SPI for longer time periods, such as SPI6 or SPI12 provides insight on seasonality and drought propagation in the medium to long term (Lloyd-Hughes & Saunders, 2002). The normalization approach adopted by the SPI has been expanded into other indices, such as the Standardized Groundwater Index (SGI) that estimates groundwater deficits compared to historical data (Bloomfield & Marchant, 2013), the Standardized Snow Melt and Rain Index (SMRI) that accounts for deficits in both rain and snow melt (Staudinger et al., 2014), and the Standardized Precipitation Evapotranspiration Index (SPEI) that includes evapotranspiration (or temperature as a proxy) in order to use a cumulative water balance (precipitation - potential evapotranspiration) in the distribution (Vicente-Serrano et al., 2010). As the SPEI incorporates both precipitation and evapotranspiration, it can serve as a proxy for deviations in soil water availability compared to normal conditions (Rossi et al., 2023). Other examples of drought indicators include the Palmer Drought Severity Index (PDSI) (Palmer, 1965) that is also based on the water balance, but fails to account for snow (Mishra & Singh, 2010; Wilhite & Glantz, 1985) and the Surface Water Supply Index (SWSI) that incorporates snowpack, streamflow, precipitation and storage to assess surface water resources (Wilhite & Glantz, 1985).

Drought hazards in a changing climate

Many regions located in polar or cold climates have traditionally been associated with water abundance (Ahopelto et al., 2019; Lindqvist et al., 2021; Praskievicz, 2019; Veijalainen et al., 2019). Yet recent drought events have shown that even these regions can experience significant drought conditions (Bakke et al., 2020; Biella et al., 2025; Markonis et al., 2021; Moravec et al., 2021; Semenova & Vicente-Serrano, 2024; Wheaton et al., 2008).

Both temperature and precipitation are projected to increase in high latitude regions following climate change, where the warming trend is expected to be more than twice that of the global warming rate (IPCC, 2023). In addition, climate change is expected to drive shifts in hydrological regimes, particularly in areas such as Northern Europe (Spinoni et al., 2018) and Canada (Tam et al., 2019). These shifts are characterized by a redistribution of water availability, with for example increasing surface water deficits during spring and summer combined with increasing surface water surplus during winter months (Tam et al., 2019). While the overall water availability in high latitudes suggests an overall wetting trend (when studied on an annual basis), for regions such as northern Canada (Asong et al., 2018; Tam et al., 2019), northern Sweden

(Chen et al., 2021; Teutschbein et al., 2022, 2025; Wilson et al., 2010), and south-western Norway (Wilson et al., 2010) increased variability, such as decreases in summer precipitation, have still been shown to increase the projected frequency of meteorological droughts, even in regions where mean precipitation is projected to increase (Zhao et al., 2020). Similarly, some studies argue that increases in precipitation may be outbalanced by projected warming trends and their associated increase in evaporative demands during warm seasons in humid regions (Vicente-Serrano et al., 2025) including high-latitude regions such as Northern Europe and Scandinavia (Markonis et al., 2021; Spinoni et al., 2018). Concurrently, these wetting trends have also been shown to diverge in regions such as Scandinavia, where northern Sweden is generally seeing a wetting trend, whereas southern regions are seeing drying trends in future projections (Chen et al., 2021).

Historically, Sweden, together with Denmark, Finland, and Norway generally saw a decrease in drought severity and frequency during the past decades (Markonis et al., 2021; Spinoni et al., 2015). However, in future projections this trend seems to shift toward increasing or more severe drought trends, especially during spring, summer, and autumn (Spinoni et al., 2018; Wilson et al., 2010) . Under high emissions scenarios, future projections indicate an increased probability of dry conditions comparable to the 2018 drought in Sweden (Sjökvist et al., 2019), and northern and northeastern Scandinavia is expected to see increases in both drought frequency and severity under both extreme (RCP8.5) and moderate (RCP4.5) climate scenarios (Spinoni et al., 2018).

In the climatic transition zones of Central Europe and European Russia, historical drought trends have been mixed (Markonis et al., 2021; Spinoni et al., 2018), yet future scenarios suggest projected increases in summer droughts, with rising temperatures (rather than changes in precipitation) appearing to be the key driver (Bakke et al., 2023; Markonis et al., 2021; Semenova & Vicente-Serrano, 2024; Spinoni et al., 2018).

However, the chosen observational datasets (Asong et al., 2018) as well as the drought index used can strongly influence both observed and projected drought trends, because including or excluding variables such as evapotranspiration can affect results in a warming climate (Bakke et al., 2020; Chen et al., 2021; Teutschbein, Jonsson, et al., 2023; Vicente-Serrano et al., 2010). Thus, reported trends diverge, with some studies not detecting any significant changes in mean annual discharge (Korhonen & Kuusisto, 2010), drought hazards (Rossi et al., 2023; Yang et al., 2020) or propagation behavior (Teutschbein et al., 2025).

This sensitivity to methodological choices remains a challenging aspect of risk management, but it does not diminish their importance for risk assessments. Nevertheless, to clarify why similar hydroclimatic conditions can lead to markedly different impacts across regions and sectors, such assessments need to move beyond hazard characterization and explicitly consider vulnerability.

Defining drought vulnerability

Drought vulnerability can broadly be described as the predisposition to be negatively impacted by an external stressor, such as a drought (Adger, 2006; Cardona et al., 2012). The concept is context dependent, varying across different types of physical environments (Borden et al., 2007; Cutter, 1996; O'Brien et al., 2004), among or within social groups (Borden et al., 2007; Brooks et al., 2005; O'Brien et al., 2004), and across scales (Fekete et al., 2010; O'Brien et al., 2004). It is also dynamic, and will change over time depending on the evolution of its underlying drivers (Cutter, 1996; O'Brien et al., 2004) as well as feedback mechanisms between and within the socio-natural system (Fekete et al., 2010).

Due to the complexity of the term, a universally applicable definition is lacking (Fuchs & Thaler, 2018; Lanlan et al., 2023; O'Brien et al., 2007; Rufat & Metzger, 2024). Traditionally, the study of vulnerability has been shaped by disciplinary boundaries, with varying interpretations depending on the scientific field (O'Brien et al., 2007). Reflecting the historical evolution of the concept, some vulnerability definitions emphasize the impact of external hazards on a system, while others adopt a systems-based approach, focusing on how internal characteristics influence the extent of potential loss (Ciurean et al., 2013; Thywissen, 2006). One widely accepted interdisciplinary definition is outlined in the United Nations Office for Disaster Risk Reduction's (UNDRR) disaster terminology (Table 1) (Ciurean et al., 2013). This definition integrates aspects from both natural and social sciences across multiple scales (UNDRR, 2017). Meanwhile, one of the most commonly used definitions of vulnerability comes from the Intergovernmental Panel on Climate Change (IPCC) (Hagenlocher et al., 2019). In its assessment reports, the IPCC offers definitions for the term vulnerability; however, these have changed over time. In the Fourth Assessment Report, AR4, vulnerability is defined as a function of exposure, sensitivity, and adaptive capacity (IPCC, 2007). Consequently, exposure was treated as an element of vulnerability rather than a standalone concept. The definition was later updated in AR5, where the exposure component was replaced by coping capacity. Hence, in its latest assessment report, the IPCC defines vulnerability as encompassing components such as susceptibility, adaptive capacity, and coping capacity (IPCC, 2014, 2023). Nevertheless, the definition proposed in AR4 is still widely used in vulnerability and risk assessments, despite the updated definition being available (Hagenlocher et al., 2019).

Table 1. Common definitions of vulnerability

Source	Definition of vulnerability
UNDRR, 2017	*"The conditions determined by **physical, social, economic** and **environmental** factors or processes, which increase the **susceptibility** of an individual, a community, assets, or systems to the impacts of hazards".*
IPCC AR4	*"function of the character, magnitude, and rate of climate change and variation to which a system **is exposed**, the **sensitivity** and **adaptive capacity** of that system."*
IPCC AR5 & AR6	*"vulnerability encompasses a variety of concepts and elements including **sensitivity or susceptibility** to harm and **lack of capacity to cope and adapt**"*

Building on these definitions, researchers have developed diverse conceptual framings that reflect disciplinary perspectives (O'Brien et al., 2007). For example, the natural and engineering sciences have historically viewed vulnerability primarily as a consequence of a hazard, and vulnerability assessments were often impact-oriented, placing the hazard as the focal point where risk-reduction alternatives often took the form of structural/engineered approaches (Cutter, 1996; UNDRO, 1980; White, 1945). By comparison, social sciences began to view vulnerability as a state of the system that exists before the hazard occurs (Birkmann, 2013; Ciurean et al., 2013; Wisner et al., 2010). Still today, vulnerability is studied across a range of scientific disciplines (Fuchs & Thaler, 2018). This is mirrored in the wide range of conceptualizations that exist, from viewing vulnerability as human-centered to considering coupled human-environment systems (Adger, 2006; Birkmann et al., 2013; King-Okumu et al., 2020).

Common conceptualizations of vulnerability include the Pressure and Release model (PAR) , the holistic social-ecological system (SES) framework as well as the early conceptualization of vulnerability by Chambers (1989) as a double-sided concept, with an external and an internal side (Figure 4). The external side relates mainly to the exposure of an entity to an external stressor, while the internal side relates to the entity's defenselessness to the stressor, expressed as its ability to cope. This double-sided framework was later further developed by Watts & Bohle (1993) and Bohle (2001) to refine the two sides by, for example, acknowledging interactions between the external and internal sides of vulnerability, the importance of access to coping resources, and how conflict and crisis conditions shape the effectiveness of coping assets and agency.

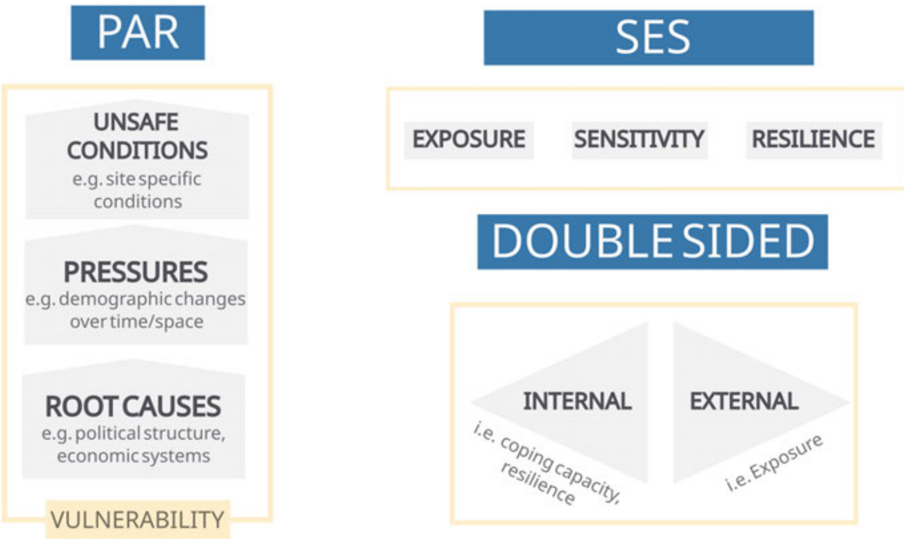

Figure 4. Common conceptual frameworks such as the Pressure and Release model (PAR), the Social-Ecological System (SES) framework, and the double-sided conceptual framing of vulnerability.

The PAR model stems from the notion that a disaster occurs at the intersection between vulnerability processes and a hazardous event. In order to release pressure, vulnerability must be reduced (Wisner et al., 2010). In the PAR model, vulnerability is framed as being inherent in a studied system and made up of three dimensions: (1) root causes (i.e. economic systems, political structures and available resources), (2) pressure dynamics (demographic changes over time and space), and (3) unsafe conditions (site-specific conditions connected to for example the physical environment, local economy, or political actions) (Birkmann et al., 2013; Ciurean et al., 2013; Turner et al., 2003; Wisner et al., 2010). The model proposes that understanding disasters requires examining how hazards interact with socially produced vulnerability (Wisner et al., 2010). In response to the human-centered focus of the PAR model, Turner et al (2003) built on the framework and developed the SES vulnerability framework, which was more geared toward sustainability science, aiming to incorporate the coupled human-environmental interactions within a studied system. In the holistic SES vulnerability framework, vulnerability is made up of hazard-dependent exposure, sensitivity of the socio-natural system, and the lack of resilience to cope and recover from a hazard (Birkmann et al., 2013; Turner et al., 2003). As shown by the vulnerability definitions as well as its conceptualizations, vulnerability incorporates numerous interrelated and often complex concepts and terminology. This further adds to the complexity of the term, and the difficulty in forming a consensus on how to describe it (Gallopín, 2006; Miller et al., 2010).

Factors Shaping Vulnerability in Socio-Hydrological Systems

In this work, we adopted the latest definition of vulnerability as expressed by IPCC AR6 (IPCC, 2023), which introduces several additional terms that bear importance for vulnerability studies. *Susceptibility,* or sometimes *sensitivity,* is often used in connection with vulnerability and relates to the predisposition of an element to suffer harm (Birkmann et al., 2013). The term can be viewed from several perspectives. Environmental susceptibility focuses on the characteristics of the natural environment that can influence its sensitivity to drought stress (Birkmann et al., 2013; X. Liu et al., 2013; Rossi et al., 2023). This can, for example, include aspects such as soil characteristics (Felton et al., 2020; González Tánago et al., 2016) or species drought tolerance (Albert et al., 2015; Bosela et al., 2021), which in turn can be affected by a wide range of aspects such as age, size, root depth, etc. Social susceptibility, on the other hand, relates to the characteristics within a social system (Birkmann et al., 2013; Karagiorgos et al., 2023; Turesson et al., 2024; Wainger et al., 2025). Examples of such characteristics include health and well-being of individuals or populations (Birkmann et al., 2013), access to clean water (González Tánago et al., 2016), gender (in)equality (Alcamo et al., 2008), social inclusion or marginalization (Alcamo et al., 2008; Dumitrascu et al., 2018).

The concepts of *coping capacity* and *adaptive capacity* refer to the ability of the studied entity to moderate the potential impacts of a drought, adapt to its effects, or make use of any opportunities it may offer (Cammalleri et al., 2020; IPCC, 2023). *Coping capacity* has been described as focusing on the capacity of a studied entity to respond to, manage, and recover from drought events using available knowledge and resources (IPCC, 2023). The concept primarily focuses on responses taking place in the short to medium term during and after a drought event (Berman et al., 2012; Smit & Wandel, 2006).

On the other hand, *adaptive capacity* revolves around the ability to transform (Berman et al., 2012) and modify the exposure to risk (Adger & Vincent, 2005), and to take advantage of opportunities that arise in the adaptation process regarding drought events (Adger & Vincent, 2005; IPCC, 2023). Adaptive capacity is often applied to longer time frames and sustainable adjustments (Berman et al., 2012; Gallopín, 2006; Smit & Wandel, 2006) that enable or enhance the ability of a system to cope with future drought events (Berman et al., 2012). However, the two terms have occasionally been used interchangeably, and the distinction between them is not always clearly defined (Berman et al., 2012; Gallopín, 2006; OECD, 2006).

Moving from Reactive Responses to Proactive Drought Risk Management

All components of vulnerability, from susceptibility to coping and adaptive capacity, can be affected by how humans and social systems respond to droughts through human-nature feedback mechanisms (Di Baldassarre et al., 2018; Van Loon et al., 2024). Such responses can be short-term, reactive responses implemented during a drought event in order to manage the crisis, or longer-term strategies focused on sustainable measures to reduce vulnerability and manage disaster risk before a drought occurs. The former often involves reactive management actions taken in immediate response to a drought event in order to provide emergency relief (Wilhite et al., 2000), such as deploying emergency water trucks to drought-affected areas. This approach has been criticized for producing inefficient emergency actions and for failing to address underlying mechanisms that drive potential drought impacts (Biella et al., 2025; UNDRR, 2021), often resulting in limited reduction of risk (Wilhite et al., 2000). The latter, in contrast, adopts a proactive management approach with the aim of minimizing vulnerability and managing drought risk before an event takes place (UNDRR, 2021). In this sense, proactive risk management seeks to address the underlying risk drivers and to implement measures that can increase societal resilience to drought in both the short and long term. Proactive risk management is widely advocated for drought impact reduction and resilience building (HFA, 2007; UNDRR, 2015, 2021; UNISDR, 2007; World Bank, 2012). Proactive risk management responses revolve around risk identification and reduction and can, for example, include drought monitoring and forecasting systems or drought management plans at local, regional or national levels (Masih, 2025; UNDRR, 2021; World Bank, 2012). Such drought plans typically define roles and responsibilities, coordination mechanisms, inventories of the water system, drought stages and their identification, mitigation and preparedness measures, and procedures for activating responses during drought events, making them a cornerstone of proactive drought management (De Assis Souza Filho et al., 2023; Fatulová et al., 2015; Iglesias et al., 2021; Masih, 2025; Ministry of Water, Land and Resource Stewardship, 2025; UNISDR, 2007; Wilhite et al., 2014).

Governance and Risk Perception: A Critical Gap

How individuals and institutions react and respond to risk is shaped by their perceptions (Di Baldassarre et al., 2018; Stefanski et al., 2025; Van Loon et al., 2024). The concept of risk perception broadly refers to how individuals and institutions interpret signals about uncertain impacts and form judgments about the risks posed by hazardous events such as drought (Slovic, 1987; Wachinger et al., 2013). Risk perception plays a critical role in determining whether and how action is taken before, during, or after a drought (Wens et al., 2019), as it influences, for example, drought preparedness, management strategies (Miceli et al., 2008), and long-term adaptation (Wens et al., 2019; Zhang et al., 2018). It is therefore pivotal in shaping societal responses in the face of drought risk (Zhang et al., 2018). However, elevated risk perception does not necessarily lead to preventive or proactive action (Becker et al., 2014; Lindell & Prater, 2002), because responses are also conditioned by aspects such as resources and capacity, legal mandates, coordination structures, and political priorities (Dookie et al., 2024; Haigh et al., 2023; Henstra, 2010; Nohrstedt, 2022; Nohrstedt & Parker, 2024; Solecki & Michaels, 1994). Here, the focus is on practitioners and local authorities, where risk perception has been shown to shape institutional responses and can act as a catalyst for initiating proactive measures aimed at strengthening adaptive capacity and reducing future vulnerability (Cavalcante et al., 2023; Haigh et al., 2023; Zhang et al., 2018).

Accordingly, drought risk perception has been shown to be a determinant of proactive drought risk management across organizations and places. Equally important is examining how drought perceptions evolve over time in response to droughts of varying severity, as such changes can influence both institutional preparedness, long-term adaptation strategies, and the prioritization of drought risk management on the policy agenda (Cavalcante et al., 2023; Kingdon, 2014; Zhang, 2022). Integrating these insights into drought risk assessments and management approaches enhances their relevance and accuracy by grounding them in the lived experiences and decision-making contexts of local authorities (Bachmair et al., 2016; Cardona et al., 2012; Kohl & Knox, 2016; McNeeley et al., 2016; Stefanski et al., 2025).

Assessing vulnerability

Reflecting the multidimensional and complex nature of drought vulnerability, a range of methodological approaches have been developed to assess it (Cardona et al., 2012; González Tánago et al., 2016; Zarafshani et al., 2016). Most drought risk and vulnerability assessments rely on quantitative methods to evaluate various components of drought risk (González Tánago et al., 2016; Hagenlocher et al., 2019). This is commonly achieved either through analysis of the underlying vulnerability factors or by examining the impacts of past drought events (Blauhut et al., 2016; González Tánago et al., 2016). The former aims to assess or quantify the factors present within the studied system or entity that affect its vulnerability to a drought or other hazards. Impact-based approaches, in contrast, assume that historical observable drought impacts reflect pre-existing vulnerability, thereby serving as a proxy for assessing systemic weaknesses (Blauhut et al., 2016). Vulnerability assessments often use indicators aimed at transforming factors of vulnerability into quantifiable measures. Index-based approaches then try to capture the multifaceted dimensions of vulnerability and risk by integrating multiple indicators into composite indices (Blauhut et al., 2016; Borden et al., 2007; González Tánago et al., 2016; Pandey et al., 2010). Depending on the study's focus and spatial scale, vulnerability indicators may be weighted, ranked, and aggregated to reflect the dynamic characteristics of the system (Blauhut et al., 2016; Ciurean et al., 2013; Hagenlocher, 2019). Weighting procedures frequently draw on expert judgment or stakeholder input to ensure contextual relevance, although equal weighting remains common in many studies (Blauhut et al., 2016). Research has however shown that index-based assessments often apply indicators without consideration of context (Hagenlocher et al., 2019).

There are also qualitative approaches to assessing vulnerability. Such approaches often involve qualitative tools to describe and investigate vulnerability, such as storylines (Liguori et al., 2021; Roberts et al., 2022) or narratives (McEwen et al., 2021).

Research Gap

Moving from reactive crisis management to proactive risk management requires a clear understanding of the underlying vulnerabilities that drive drought risk. While it is widely accepted that drought vulnerability is context specific, there is a limited understanding of what shapes drought vulnerability in socio-natural systems in polar and cold climates. These regions cover more than a third of the global landmass (Keenan et al., 2015) and host important socioeconomic sectors (UNECE, 2024) and biomes (Watson et al., 2018) that are critical for both economic activity (Saarikoski et al., 2015; UNECE, 2024) and climate-change mitigation through their role as a global carbon sink (Pan et al., 2024).

Existing vulnerability assessments and reviews often adopt a primarily human-centered perspective (González Tánago et al., 2016). As a result, several current vulnerability frameworks and multi-sectoral approaches do not adequately capture forest vulnerability or the cross-sector dependencies that may be particularly relevant for forest- or tundra- dominated cold-climate regions. In addition, drought risk and vulnerability assessments frequently do not specify the analyzed drought type (Hagenlocher et al., 2019). This matter because drought vulnerability may differ substantially depending on a system's water-type dependencies and, as a result, also the drought type to which is exposed. However, such differences and interdependencies have received limited attention in polar or cold climates.

Finally, human actions and risk perceptions are known to influence drought vulnerability (Di Baldassarre et al., 2018). While the mechanisms linking risk perception and risk management have been investigated in organizational contexts (Bin-Husayn et al., 2024) there is still limited understanding of how local authorities in areas traditionally perceived as water-abundant interpret recent drought events, how these perceptions align with observed drought conditions, how drought risk is perceived, and what drought management practices are currently in place. Repeated cross-sectional insights into how drought awareness and management evolve over time within municipalities is especially scarce. Addressing these gaps is critical for developing context-specific, forest-inclusive drought vulnerability assessments and effective management strategies in cold-climate regions.

Research aims

This thesis investigates the contextual nature of drought vulnerability by examining how it manifests across multiple dimensions and scales, specifically focusing on socio-hydrological systems located in polar and cold-climate settings dominated by forests or tundra (hereafter referred to as forested cold climates). These dimensions include climatological and ecological conditions, functional and organizational structures, and spatial and temporal variability. The thesis further assesses how vulnerability is shaped by both systemic factors and human responses, bridging theoretical perspectives with practical management realities. By integrating insights from the literature, stakeholder-informed surveys, and repeated cross-sectional data, the research seeks to understand how vulnerability differs across regions, sectors, water dependencies, organizations, and experiences within the study region. Particular attention is paid to risk perception (recognizing its influence on preparedness) and drought management. This multi-perspective approach provides the foundation for the research questions that guide the analysis of vulnerability factors, risk perceptions, and institutional responses that shape drought vulnerability in forested cold-climate regions.

The five papers included in this thesis collectively aim to address the following research questions:

- How is drought vulnerability conceptualized and defined across disciplines, sectors, and within governance structures in forested cold-climate regions?
- What dimensions and factors shape drought vulnerability in forested cold climates?
- How do contexts such as place, water dependencies, and sectoral and institutional perspectives influence the relevance and prioritization of different drought vulnerability factors?
- How do drought experiences, perceptions, and management practices among local authorities evolve over time, and how do past drought experiences shape current assessments of drought risk?
- How do governance systems, scientific understandings, and stakeholder needs interact in shaping drought vulnerability?

Methodological Framework

The thesis applies a quantitative research approach in order to investigate socio-hydrological drought vulnerability, drought risk management and drought risk perception in forested cold climates. A combination of a structured literature review, survey study and repeated cross-sectional survey study was employed to achieve the overall research aims.

To capture the complexity of vulnerability, this study integrates two methodological strands focusing on its key influential aspects: contextuality and temporal dynamics. The former employs a confirmatory survey based on literature-derived factors to investigate how vulnerability differs across regions, sectors, organizations, and water dependencies. The latter utilizes a repeated cross-sectional survey study to examine how vulnerability-related perceptions and actions change over time within stakeholder groups. This integrated design enables exploration of how vulnerability is simultaneously context-dependent and temporally dynamic. In this regard, the confirmatory survey represents a top-down approach, testing literature-derived vulnerability constructs with stakeholders, while the repeated cross-sectional survey embodies a bottom-up perspective, capturing evolving stakeholder experiences and management strategies over time (Figure 5). Together, these approaches balance theoretical guidance with grounded, context-sensitive insights.

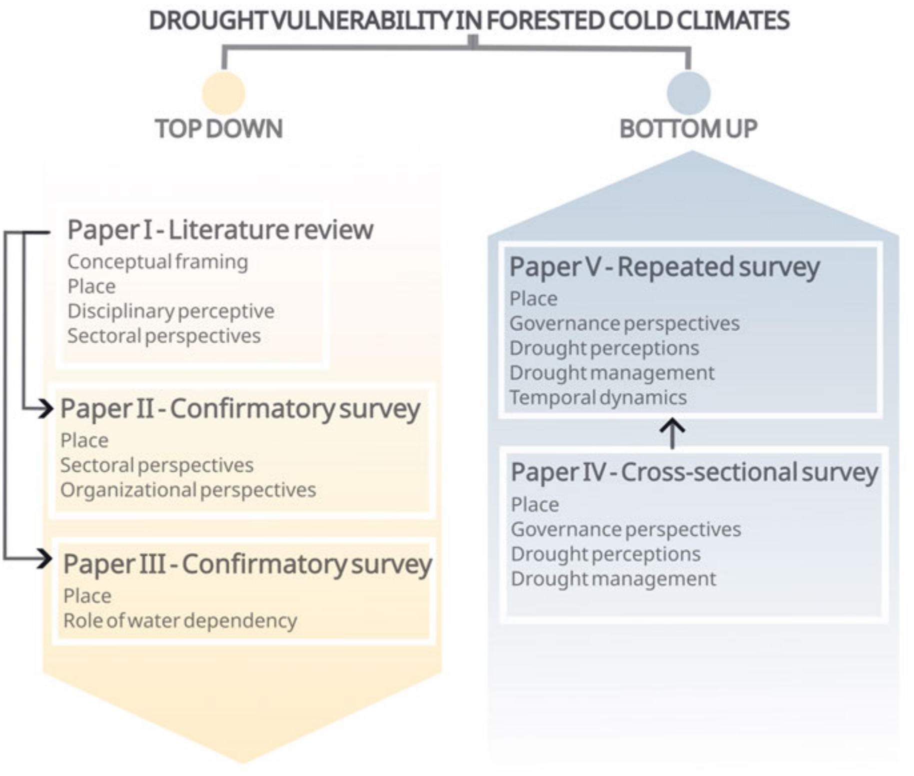

Figure 5. Overview of the methodological approach used, highlighting the top-down approach applied in papers I, II, III and the bottom-up approach used in papers IV and V. The main methodological approach and key contextual focus of the individual works are shown in their respective "box".

The following section offers an overview of the study area, methodological choices, data sources, and analytical strategies employed across the thesis and is structured around key components of the research process.

Detailed descriptions of the study design, survey distribution, and analysis methods are provided in each individual article.

Study area

The research focused on assessing drought vulnerability in regions with polar or cold climates, and with a majority of its landmass covered by forest or tundra (here: forested cold climates). For the literature review in **Paper I**, the study region was selected following the Köppen–Geiger climate classification system focusing on countries and regions located in polar (Köppen–Geiger group E) or cold/continental (group D) climate zones (Figure 6a). Following arid climate zones, cold climate (group D) is the second-largest climate type globally, dominated mainly by areas with humid cold climate without a dry season (Df climate subtype) (Peel et al., 2007). The review was further refined to only include countries predominantly covered by forest or tundra biomes within these climate zones (Figure 6b).

The contextual validation of theory (**Paper II & III**) and the repeated cross-sectional survey (**Paper IV & V**) was then carried out in Sweden, a country in northern Europe with a population of approximately 10.5 million. Sweden is divided into three climate zones according to the Köppen–Geiger classification (Figure 6c). A majority of the country is classified as humid cold with no dry season (Dfb, warm-summer hemiboreal; and Dfc, subarctic boreal). The Scandinavian Mountains in north-western Sweden are classified as polar/tundra (ET)(Beck et al., 2018). As a country situated entirely within the target climate zone and characterized by extensive forest cover (over 65% of land area) (SLU, 2025) (Figure 6d), Sweden offers an ideal setting for investigating drought vulnerability in forested socio-hydrological systems located in polar and cold climates.

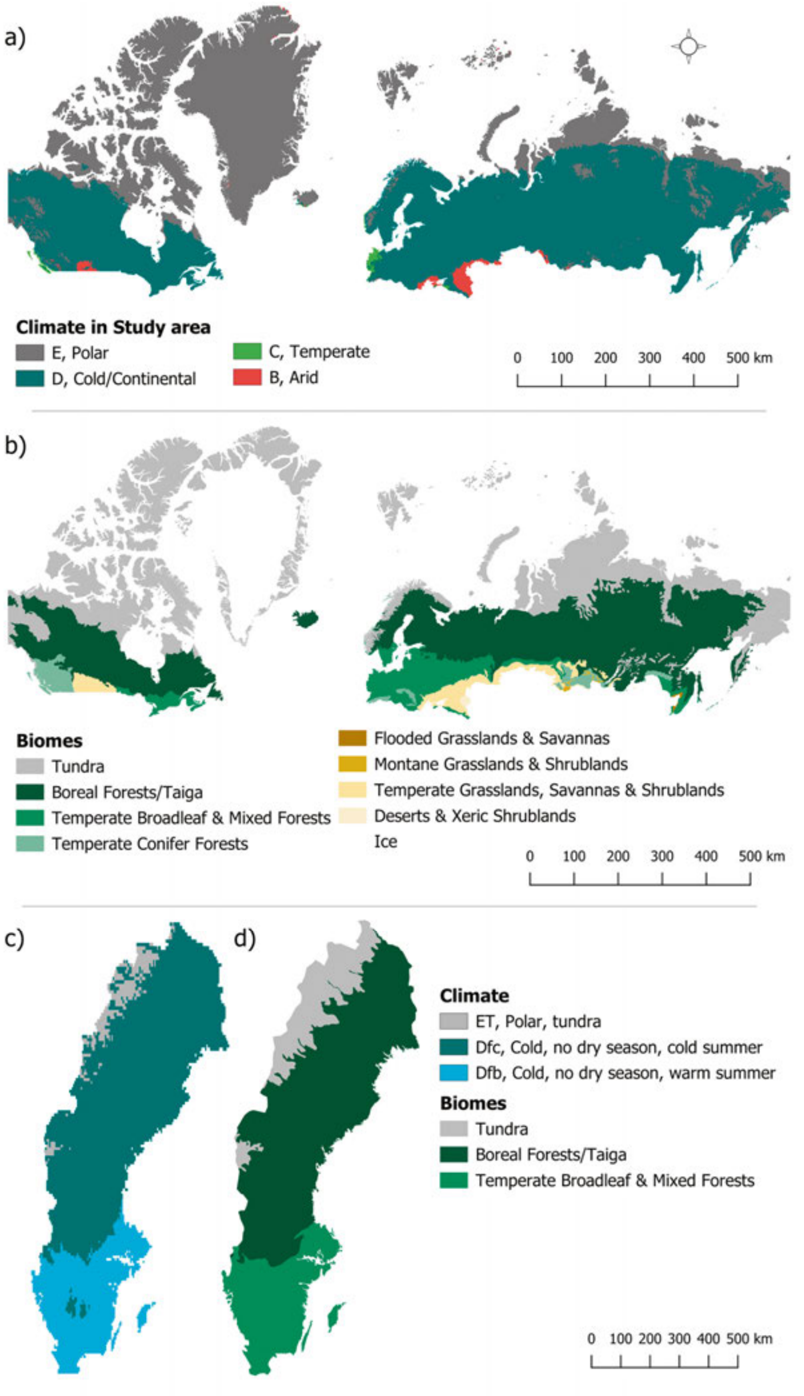

Figure 6. Main climate groups (a) according to the Köppen–Geiger classification (Beck et al., 2018) and biomes (b), within the countries included in the study (Dinerstein et al., 2017). Swedish climate subtypes (c) according to the Köppen–Geiger classification (Beck et al., 2018), and biomes in Sweden (d) (Dinerstein et al., 2017).

Contextual validation of theory

Structured literature review (Paper I)

A structured literature review was undertaken to identify drought vulnerability factors relevant to the study region. The review included both qualitative and quantitative studies across multiple disciplines, including disaster risk management, environmental governance, psychology, and urban planning. It pursued two aims: (1) to synthesize current conceptualizations and descriptions of vulnerability in these contexts, and (2) to inform the development of an analytical framework.

Searches were conducted in Scopus and Web of Science between December 2021 and March 2022 using broad, systematically combined search strings that targeted articles containing "drought" and "vulnerability" in specified metadata fields and referencing a relevant country or region. Only peer-reviewed, English-language studies that addressed drought vulnerability beyond the drought hazard were included, with a primary focus on the selected countries or regions. Eligible studies spanned local, national, or cross-national scales, but excluded research focused solely on species-level or highly localized ecological processes.

A predefined search protocol was used to screen and extract information consistently across studies. For each eligible publication, the review recorded definitions and conceptualizations of vulnerability, spatial scope, thematic focus, methodological approach, temporal framing, and the specific vulnerability factors addressed. Identified factors were then thematically classified by their relationship to blue water (surface and groundwater), green water (soil moisture), or universal relevance. Overlapping factors were consolidated into broader categories. For example, factors relating to water stress were grouped under baseline water stress; factors describing species or stand-level drought tolerance (e.g., tree age, growth rate) were grouped under drought tolerance; and factors relating to economic status, access to resources, and social conditions were grouped under socioeconomic susceptibility. Likewise, indigenous knowledge, identified in the literature as a relevant vulnerability factor, was operationalized through broader categories capturing local adaptation knowledge and public participation in drought management. This approach reflects the functional role attributed to indigenous knowledge in the reviewed literature and maintains consistency with the aggregation applied to other multidimensional factors.

The synthesis produced a set of regionally relevant vulnerability factors that formed the basis for the design of the confirmatory stakeholder survey.

Stakeholder informed vulnerability factors (Paper II & III)

To assess the practical relevance of vulnerability factors identified in the literature, a confirmatory stakeholder survey was conducted in Sweden in 2023. The survey targeted representatives from seven water-dependent sectors: energy, agriculture, environment & ecosystems, water supply, water resource management, forestry, and water-intensive industry. It incorporated stakeholders from governmental, research, private, and civil society organizations across local, regional, and national scales. As the confirmatory survey only received one response from respondents representing water-intensive industries, the sector was omitted from the sectoral analysis in **Paper II.**

Using a five-point scale, respondents evaluated the perceived impact of each literature-derived factor on drought risk in relation to sectoral or societal vulnerability. Some factors were rated for both sectoral and societal risk, whereas others were rated only in one context. Additional questions invited respondents to identify missing factors and provide contextual information about their professional role and experience. This design enabled the exploration of vulnerability's contextuality across regions, sectors, and organizational types. Respondents had the possibility to opt out of rating any factor by selecting "I don't know", allowing them to indicate insufficient knowledge rather than making uninformed guesses. These responses were treated as not applicable and excluded from statistical analyses, which reduced the number of valid observations for some items.

The subsequent identification of key factors and ranking of vulnerability factors followed the methods applied by Meza et al. (2019). As Meza et al. (2019) studied the relevance of vulnerability factors for agricultural and water-supply drought vulnerability at the global scale, following their methodology provided an opportunity to assess scale-dependent contextuality of vulnerability. Differences in vulnerability factor ratings by sector, employment context, and geographical location (**Paper II**) were analyzed using Kruskal-Wallis test by ranks (Kruskal & Wallis, 1952), followed by Wilcoxon rank sum test for pairwise comparisons between group levels (Asadzadeh et al., 2014; Mann & Whitney, 1947). These non-parametric statistical tests allow analysis of ordinal (non-parametric) data, and have previously been applied in participatory research studies to identify differences among groups (Cuesta et al., 2022; Mızrak & Aslan, 2020). The same analytical approach as in **Paper II** was applied in **Paper III**, but with respondents categorized by their main water-type dependency. Respondents working in energy, water supply, water resources, water intensive industries, or with aquatic ecosystems were categorized as dependent on blue water (i.e. ground- or surface water). Those working in forestry or with terrestrial ecosystems were categorized as dependent on green water (i.e. soil water). Respondents working in agriculture, or with both aquatic and terrestrial ecosystems were categorized as universal water consumers (i.e. dependent on ground-, surface-, and soil water)

Repeated cross-sectional Stakeholder Survey on context-specific practices, management, and perceptions (Paper IV & V)

The confirmatory analysis (**Papers II & III**) highlighted the importance of drought management strategies and drought awareness from a top-down perspective, yet provided limited insights into how these aspects are operationalized in municipal practice and how they change over time. To address this gap, a repeated survey of Swedish municipalities was conducted following two drought events of differing severity. The survey design enabled investigation of spatial and temporal dynamics of drought management and the perceptions of drought and drought risk in practice and over time.

The first survey round was conducted in December 2018, following the 2017 and 2018 drought years. An online questionnaire was distributed to the official email addresses of 290 Swedish municipalities. The questions revolved around how local authorities perceived the recent drought events, what measures were taken in response to the drought years, whether a drought plan existed, and how future drought risk was assessed. The questionnaire combined rating-scale items, multiple-choice questions, as well as open-ended questions. In the 2018 survey round, questions on recent events were asked separately for both the summer drought of 2017 and 2018.

The results of this baseline survey were analyzed using descriptive statistics and frequency distributions to allow analysis of overall patterns among the surveyed municipalities (**Paper IV**). Differences in responses between groups were tested using the Wilcoxon rank sum test (Mann & Whitney, 1947). Spearman rank correlations (Spearman, 2010) were used to unravel links between management and risk perception, and Fisher's exact test (Fisher, 1922) was used to compare dichotomous categorical responses (e.g., yes/no). Together, these analyses provided insights into the perceived perception and management of drought events among local authorities (**Paper IV**).

The second survey round was distributed in 2023, following the less severe drought event in Sweden in 2022. The survey was conducted as part of a Europe-wide study on drought management (Biella et al., 2024, 2025) and included both the core items from the baseline survey and additional questions. As in 2018, the online questionnaire was distributed to the official email addresses of Sweden's municipalities, asking respondents to assess recent events, municipal management practices, and future risks.

Responses from the second round were analyzed using descriptive statistics and frequency distributions, with additional emphasis on changes between the two survey rounds. Statistical analysis used non-parametric tests: Kruskal-Wallis tests for group-wise comparisons (Kruskal & Wallis, 1952), Pearson's chi-square test of independence (Agresti, 2007) for associations, and Wilcoxon rank-sum tests for pairwise comparisons (Asadzadeh et al., 2014; Mann & Whitney, 1947). This design and analysis framework supported the assessment of temporal dynamics in vulnerability-related perceptions and management practices among municipalities (**Paper V**).

Relating empirical data with observed hazard indicators (Paper IV & V)

In both survey rounds, empirical survey data regarding perceived hazard severity was compared with observation-based drought indices. This comparison helps assess how perceived severity aligns with observed hydroclimatic conditions, perceptions that may, in turn, affect subsequent management actions.

Perceived drought severity was assessed by the survey respondents on a six-point scale: flood, normal conditions, mild drought, moderate drought, severe drought, or extreme drought. If respondents were unsure, they could select the option "I don't know".

Observed drought severity was characterized using the Standardized Precipitation Index (SPI) (**Paper IV & V**) and the Standardized Groundwater Index (SGI) (**Paper IV**). In **Paper IV,** precipitation and groundwater deficits were quantified using the SPI6 and SGI6 based on data from the Swedish Meteorological and Hydrological Institute (SMHI) and Geological Survey of Sweden (SGU), with drought severity classified from normal to extreme. The 2017 and 2018 droughts were further evaluated using univariate and copula-based multivariate empirical return periods for precipitation deficits and summer temperature anomalies to represent compound drought risk.

In **Paper V**, observed SPI3 and SPI6 data capturing precipitation deficits for spring and summer 2022 were obtained from the European Drought Observatory (EDO) (EDO, 2025a, 2025b). Municipality-level mean and median SPI values for August 2022 were derived using zonal statistics in QGIS (version 3.40.6) (Dawson et al., 2025) and translated into drought severity classes ranging from normal to extreme.

Methodological reflections

The dual approach adopted in this thesis allows for an examination of vulnerability dynamics from two complementary perspectives, combining a top-down theory-driven approach with a bottom-up, practice-oriented analysis. Together, these methods enabled the exploration of vulnerability's complexity and provided insights into how it may be assessed and tackled. At the same time, the study design also entails some limitations.

First, the broad scope of the literature review enabled a wide range of inputs into vulnerability. However, drawing on diverse bodies of literature also increases the risk of misinterpretations, because terminology, methodological conventions, and epistemic cultures differ across fields, including those beyond my primary expertise. The confirmatory survey offered a means to minimize the effect of these limitations, by involving practitioners and domain experts, to "validate" this information's relevance for their field of expertise. The survey also generated added value by presenting a shared set of vulnerability factors across sectors, allowing participants to reflect on factors that are not commonly discussed within their own sector. However, attention must still be paid when translating the results of **Paper II** and **Paper III** into measurable vulnerability indicators, as epistemic terminology will play a role.

A further limitation of the confirmatory survey is that stakeholders rated each vulnerability factor by its perceived impact on drought risk (from no impact to high impact), without indicating the direction of the effect (risk-increasing versus risk-reducing). This design choice was done to maintain comparability with the global survey by Meza et al. (2019), which used the same response format, but it constrains interpretation for factors that may plausibly operate in both directions depending on context.

The repeated cross-sectional survey **(Paper IV & V)** offers bottom-up insights into vulnerability-related practices, perceptions, and management responses. Revolving the study around a survey enabled broad coverage across all 290 Swedish municipalities and opened up for the possibility to repeat the survey over time. Yet the use of online questionnaires also come with limitations. The role of terminology and the risk of misinterpretation plays a role here. The survey was answered by a range of municipal practitioners, many working with water and wastewater services, as managers, engineers, strategist or similar. This variation may influence responses due to role-specific perspectives, priorities, and levels of access to information. As a result, observed differences between municipalities may partly reflect differences in respondent roles rather than solely municipal-level characteristics. In the present data, however, responses did not differ significantly by job title, suggesting that this source of bias may be limited in practice.

Summary of Articles

Vulnerability in forested cold climates (Paper I)

The literature review showed an increasing attention to drought vulnerability over time, where a distinct increase in drought vulnerability research was seen from 2011 onward. It also highlighted the lack of unified definitions and conceptualizations, with many articles failing to define the term and no articles adhering to the latest definitions provided by IPCC AR5 & AR6. Interestingly, articles with a thematic focus on forestry were the least common to provide a definition for the term, where over 70 % of the reviewed articles lacked a definition. The forestry sector also stood out regarding methodological approaches for assessing vulnerability, often adopting simulation models. Meanwhile, the most commonly adopted approach was index-based (31% of the reviewed literature) (Figure 7).

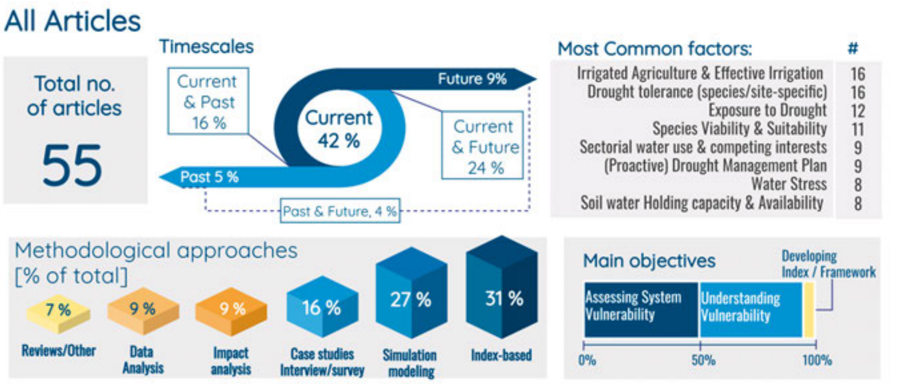

Figure 7. Overview of key literature review insights, highlighting timescales, frequently mentioned vulnerability factors, methodological approaches, and article main objectives (Stenfors et al., 2024)

Yet the literature review revealed the prominence of forestry in the region, as 31 % of the articles were focusing on these aspects. This was followed by agriculture and water resources and supply, sectors commonly addressed in global vulnerability assessments. Taken together, this distribution underscores the sectoral relevance of forestry, agriculture and water management in these climate- and biome contexts.

Context dependence of vulnerability was also evident in the rather limited number of socio-economic or socio-cultural factors identified in the review. Vulnerability factors used in global-scale assessments (such as under-nourishment, life expectancy, or access to improved water sources) did not appear in the reviewed literature. Likewise, vulnerability factors concerning poverty or gender inequality were rarely included, only appearing in the joint cross-national drought vulnerability assessments for Russia, India, and Portugal.

Based on the vulnerability factors described or used in the literature, a conceptual framework for drought vulnerability in the region could be developed (Figure 8). The framework organizes vulnerability factors as relating to one of three categories: 1) direct water consumers 2) indirect water consumers 3) governance processes and plans. The framework introduces a simplified way to identify vulnerability factors and guide vulnerability research designs. It further aims to visualize the main perspectives of vulnerability in the study region.

A majority of vulnerability factors relate to direct water consumers. A direct water consumer can for example be a sector that is directly reliant on stable water supply, such as agriculture or drinking water production. A second set of factors concerns indirect water consumers, that indirectly rely on water through the consumption of goods and services. Indirect consumers, for example, may be vulnerable to rising energy or food prices, or to employment losses in water-dependent sectors. A third, cross-cutting category captures governance processes and planning, which can shape the vulnerability of both direct and indirect water consumers. This includes characteristics of governing system as well as the availability of drought or water management plans or drought monitoring systems.

Figure 8. Conceptual framework for forested cold climates in Paper I, which categorized vulnerability factors as relating to governance (grey), indirect water consumers (yellow), or direct water consumers (blue) (Stenfors et al., 2024)

By making these perspectives explicit, the conceptual framework enables the identification of vulnerability factors that match a specific study's scope and analytical boundaries. It also allows for identification of potentially conflicting drought vulnerability factors. As an example, the literature revealed the conflicting nature of irrigation for drought vulnerability, where it is seen as a factor lowering vulnerability in rainfed agriculture by buffering soil water deficits. Simultaneously, vulnerability assessments focusing on baseline water stress or competing water interests sometimes incorporate irrigation as a factor putting pressure on water resources, thereby increasing overall vulnerability. With the framework, by clarifying which parts of the socio-hydrological system are being assessed, such trade-offs and inconsistencies become easier to detect and discuss.

Multisectoral vulnerability and systemic drought risk (Paper II)

The second paper explored the findings of **Paper I** through a stakeholder-informed confirmatory survey. The results showed that each of the surveyed sectors exhibited a distinct vulnerability profile. Meanwhile, the responses also indicated that some vulnerability factors tend to be more universally important, rated as impactful for several sectors. Such factors related to for example biophysical properties, such as the geographical characteristics, and the soil water holding capacity which were seen as impactful for drought risk in all surveyed sectors. Approximately 90 % of the vulnerability factors found in the literature (**Paper I),** were seen as relevant for drought vulnerability by at least one sector.

The results also highlighted the importance of drought risk management and the capacity of authorities to offer drought-related support (Figure 9). Notably, respondents emphasized institutional competence, coordination and cooperation among authorities as more influential than institutional financial resources alone. This supported the conceptualization proposed in **Paper I,** as governance-related factors were frequently rated as impactful for both sector-specific as well as for societal drought risk. Likewise, the important role of drought awareness appeared as a key factor: respondents found both drought awareness within authorities as well as among water consumers as important vulnerability factors for both sectoral and societal drought risk. Meanwhile, factors relating to socioeconomic susceptibility and demographics were not seen a relevant for societal drought risk in a Swedish setting. Instead factors reflecting societal human-water interdependencies, such as access to public drinking water services, economic dependency on water-consuming industries, and drought awareness among water consumers were identified as relevant for societal drought risk.

A key strength of the survey design was that all sectors assessed the same set of literature-derived factors. It provided an opportunity to find vulnerability factors that were impactful for more than one sector. It also expanded the evidence base for the environment and ecosystems sector, where the literature review (beyond forest ecosystems) identified relatively few vulnerability factors (**Paper I**). Respondents from this sector identified several factors from the list as relevant for their field and also proposed several additional vulnerability factors not captured in the literature review.

Paper II further illustrates the contextuality of vulnerability by studying identified vulnerability factors in relation to sectoral relevance. Respondents from the agricultural sector rated factors relating to access to irrigation and effective irrigation systems highly. They also emphasized water availability, both specifically for irrigation and in general, as highly impactful. Water availability was also highlighted as important by the environmental, water resources, and water supply sectors, which rated factors such as baseline water stress or having a reliable water resource highly.

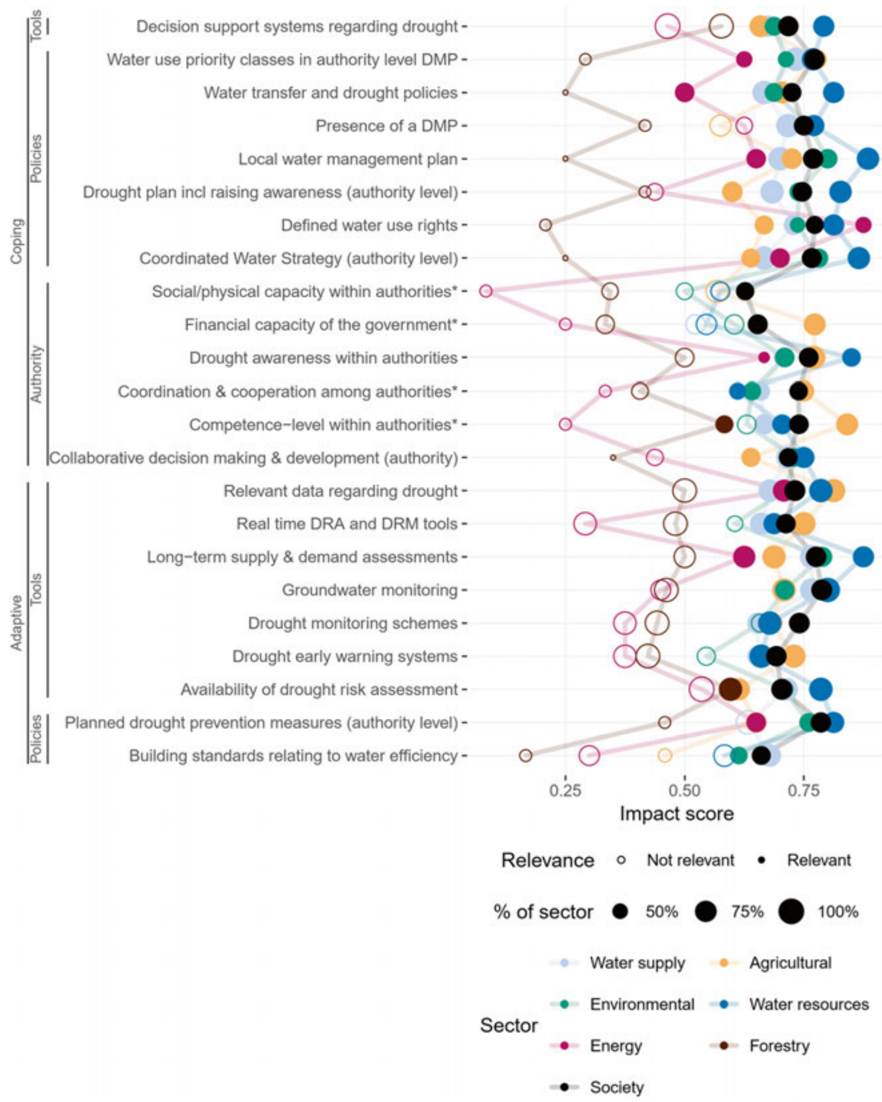

Figure 9. Perceived influence of governance-related vulnerability factors on drought risk across sectors. Filled points denote factors deemed relevant; hollow points denote those not considered relevant for a sector. Point size indicate the share of respondents who rated each factor. (Stenfors et al., 2025a).

In contrast, respondents from the forestry sector rated species drought tolerance and drought resilience particularly highly, together with soil water-holding capacity. Soil water-holding capacity was among the most highly rated vulnerability factor for the forestry, environmental, agricultural and water resources sector. It was also one of the two vulnerability factors that were seen as relevant for drought vulnerability by all included sectors, along with the geographical characteristics. The latter was one of the highest rated factors for the energy sector, along with the presence of wetland, lakes, and ponds, possibilities for developing water storage and the distribution of hydropower plants.

The results provided important information into both sectoral vulnerabilities, but also cross-sectoral or systemic drought risk. For example, several vulnerability factors previously discussed in relation to one sector were also perceived to be relevant for others. The analysis also showed that significant differences in ratings exist for several vulnerability factors. In this regard, the forestry sector especially stood out with significant differences in ratings for several vulnerability factors compared to the agricultural, environmental, water supply, and water resources sector. Likewise, significant differences in vulnerability factor ratings were also observed between the agricultural sector and the energy and water supply sector.

When comparing societal- and governance-related factor ratings by geographical location (i.e. north versus south Sweden), no statistically significant differences were detected. However, respondents located in southern Sweden tended to identify more factors to be relevant (4 societal, 23 relating to governance) compared to respondents located in northern Sweden (1, 20).

Overall, these results align with the climatological and biome contexts explored in **Paper I**. They again point to a comparatively limited role of socioeconomic factors in this context, while underscoring the cross-cutting importance of certain more “universal” biophysical factors across sectors.

The role of water dependency (Paper III)

The analysis of drought vulnerability from the perspective of water type dependency revealed new patterns of vulnerability (Figure 10). First of all, the main type of water dependency resulted in clear differences in respondents’ ratings for the included vulnerability factors. Especially when comparing ratings for sectors reliant on blue water versus green water. The blue water-dependent sectors found some aspects relating to the surrounding settings, such as the geographical characteristics and the presence of wetlands, lakes, and ponds, and consistently aspects relating to policies and plans as highly impactful. In addition, the blue water-dependent groups also found factors relating to water availability as highly impactful, such as baseline water stress, having reliable water resources, and the availability of long-term supply and demand assessments. On the contrary, green water-dependent respondents had a primary focus on factors relating to the setting and species characteristics. Factors included having growth-limiting conditions, or the soil water-holding capacity, as well as the drought tolerance of species, stand mixtures and seedlings. Interestingly, almost no vulnerability factors categorized as relating to policies and plans were seen as relevant for green water consumers. The agricultural sector's classification as "universal", or dependent on both blue and green water types, could be seen in the ratings, as it became a "middle ground" sharing relevant vulnerability factors with both water type consumption groups. Among the universal water-dependent respondents, the most highly rated factors related to water availability (including baseline water stress, competing water interests, and reliable water resource) as well as drought tolerance of species, and the soil water holding capacity.

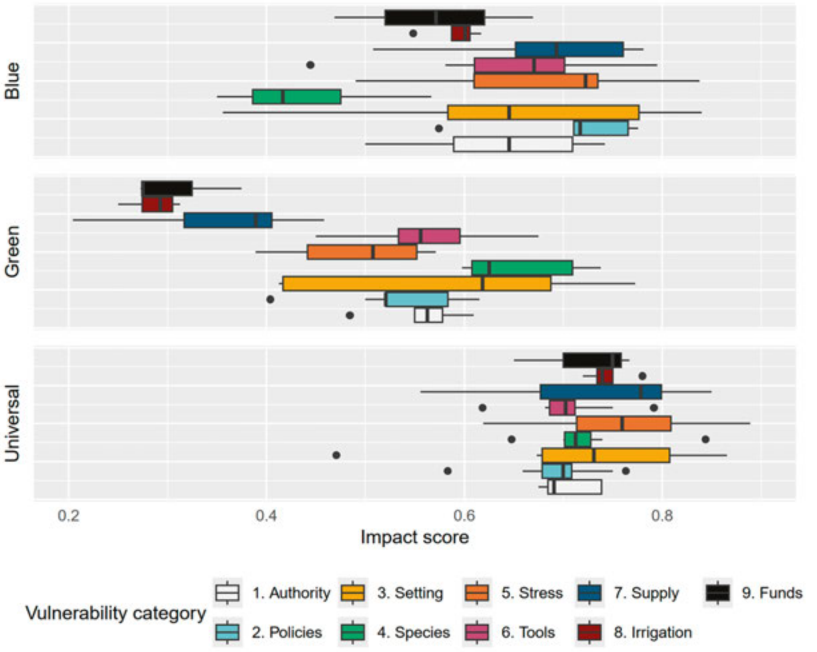

Figure 10. Distribution of impact ratings for the nine overarching categories of vulnerability factors included in the survey, divided by blue water consumers (top), Green water consumers (middle), and universal water consumers (bottom) (Stenfors et al., 2025b)

Even though clear differences in ratings emerged between the groups, some factors were also considered relevant across all water-dependency types. These included soil water holding capacity, presence of wetlands, lakes and ponds, and the availability of a drought risk assessment. Consequently, the results underscore the contextuality of vulnerability, whilst also highlighting the commonality of some vulnerability factors.

These findings also reinforce the importance of linking vulnerability assessments explicitly to drought hazard type. Droughts that primarily affect green-water availability, and consequently green water consumers, require a different set of vulnerability factors than droughts that primarily affect blue-water availability. Yet, many drought risk assessments do not specify the drought type under analysis (Hagenlocher et al., 2019), which can obscure these distinctions and limit interpretability.

Drought experiences, risk perceptions, and management in 2018 (Paper IV)

The bottom-up approach produced important insights into drought management and associated perceptions. For example, the first survey round showed that municipalities perceived the 2018 drought to be more severe than the 2017 drought year. Respondents reported impacts on drinking water supply (with a main focus on impacts on private wells), agriculture, livestock, as well as industry, tourism, and forestry. A majority of the respondents associated drought conditions with low groundwater levels or dry individual wells (over 70 %), whereas forest fires (33%) and low soil moisture (21%) were less frequently mentioned. The severity of the impacts followed a poleward gradient, where respondents in southern Sweden reported everything from no impacts to very strong impacts, whereas respondents in the North saw no impacts in the two drought years. This pattern was, however, not seen when studying perceived municipal preparedness or management, which generally received high ratings from all the respondents.

The survey also highlighted that 97 % of the respondents perceived that drought risk would increase in future climates. Meanwhile, few municipalities reported having an operational drought definition or a drought management plan in place. Municipalities that reported having a drought management plan also reported to have implemented 2 to 2.5 times more measures in response to the drought years compared to those lacking such plans. The most commonly reported measures taken in response to drought related to information campaigns to the public, monitoring, contact with relevant authorities, reducing water withdrawals, or other forms of measures. The most frequently reported strategy to cope with climate change or population dynamics involved increasing water supply, while measures to reduce demand were less frequently mentioned. A small number of respondents (3%) answered other measures, including efforts to increase competence within the municipality.

While not statistically significant, the results showed that municipalities that reported experiencing strong or very strong impacts from the drought years tended to have higher intentions to develop a drought management plan, compared to other municipalities.

Comparing the perceived drought severity from the observed drought severity showed limited correlation. Consistent significant correlations were only seen for SPI6 and perceived drought severity in 2018. Simultaneously, the results revealed a pattern, where municipalities experiencing moderate to extreme drought conditions tended to underestimate the drought severity compared to observed conditions.

Evolving perceptions of drought management and risk (Paper V)

According to the respondents, the 2022 drought was on average perceived as milder than the 2018 event in several municipalities. More than half did not consider drought conditions to be present in 2022, and nearly one third reported taking no measures in response to the drought event. Clear differences emerged when compared with 2018, a year in which significantly more municipalities reported experiencing drought impacts. While the perceived management of the drought years was consistently rated positively by the respondents in both survey rounds, the management of the 2018 drought was most highly rated. The perceived preparedness on the other hand, seemed to increase over time and received the highest share of positive ratings in 2022.

Among the respondents, drought-related terms such as *water scarcity* and *drought* were the most frequently used in both survey rounds (Figure 11). Yet, the share of respondents reportedly often or very often using the term *drought* in their day to day work had decreased from 39 % to 28 % between the two survey rounds. Terms connected to one of the four drought types commonly used in drought research were very rarely, or never used by a majority of the respondents, in both survey rounds. Meanwhile, a significant increase in the number of municipalities having an operational drought definition was seen. However, the number of municipalities adopting an operational drought definition, or having a drought management plan was still low.

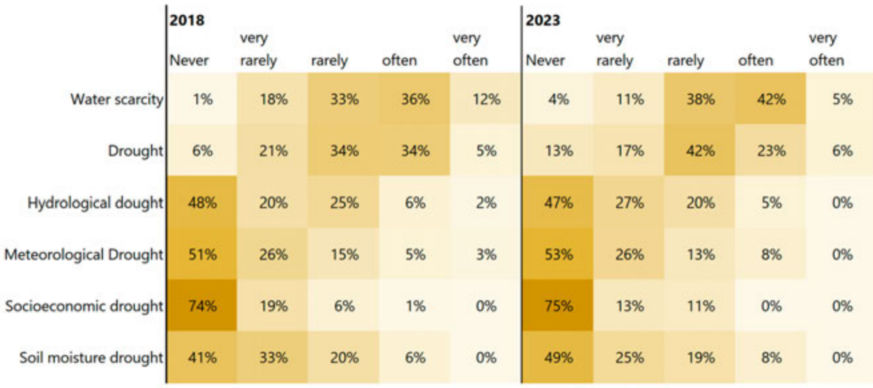

Figure 11. Heatmap depicting the distribution of response frequencies regarding how often respondents report using particular drought-related terms in their everyday work. The frequency scale ranges from “Never” to “Very Often”, with darker colors representing higher numbers of responses within each category (Stenfors et al., 2026).

Similar to the results in **Paper IV**, no association between perceived severity and observed drought severity (SPI3 and SPI6) could be seen for the 2022 drought year (Figure 12). Furthermore, the results indicated a slight decline in drought risk perception. In the latest survey round, a significantly larger proportion of respondents anticipated either no change or a decrease in drought risk in the future. The level of drought risk perception was not associated with the perceived or observed drought conditions in 2022. Meanwhile, in northern municipalities, the drought risk perception was significantly associated with the observed drought severity (SPI6) experienced in 2018, where more severe drought conditions in 2018 were associated with higher risk perception in the follow-up survey. The same association could be seen when comparing observed SPI6 drought conditions in 2018 with reported drought risk perception in the latest survey across all responding municipalities, however, this association was not statistically significant.

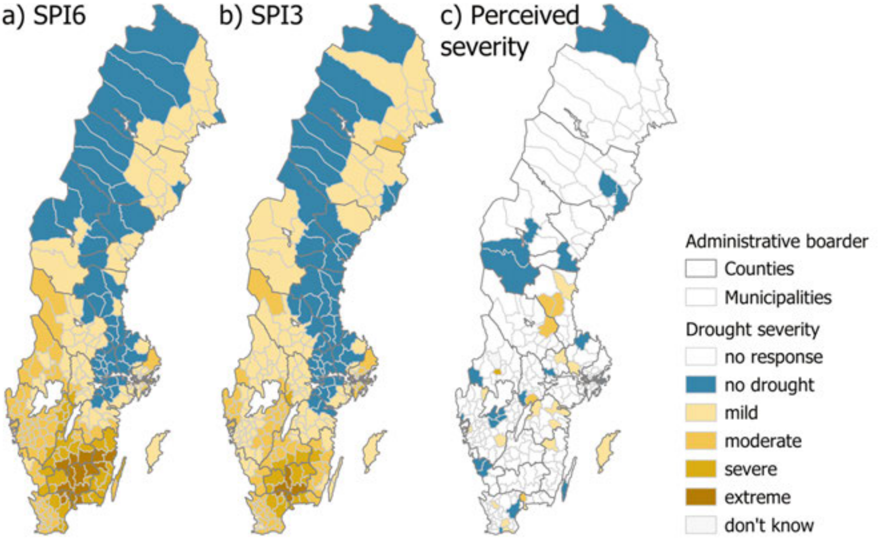

Figure 12. Observed and perceived drought conditions during 2022 for each municipality. a) depicts median SPI6 for August 2022, b) median SPI3 for September 1st 2022, and c) perceived drought severity reported by the respondents (Stenfors et al., 2026).

Synthesis of Findings

Drought vulnerability in forested cold climates

This thesis examines how drought vulnerability is formed in forested cold climates. The results indicate that region-specific characteristics shape vulnerability dynamics. These characteristics are more strongly linked to biophysical conditions and governance arrangements than to social vulnerability dimensions such as basic needs or human development. The analysis also identified both commonalities and differences in vulnerability drivers across sectors and water dependencies. The combination of a top-down and a bottom-up approach to drought vulnerability highlights how misalignments, both within governance systems and between the scientific community, sectors, and governing institutions, can strongly shape vulnerability and its evolution over time. The following sections provide an overview of the key findings derived from the study.

The importance of context

From the top-down analysis of vulnerability, drought vulnerability emerges as a product of a broad range of biophysical and governance related factors, and human-water interdependencies (**Papers I–III**). What constitutes drought vulnerability is determined by several contextual considerations such as climate (**Paper I**), sector (**Papers I & II**), and water dependency (**Paper III**). As a large share of vulnerability factors identified in the literature review (**Paper I**) were judged relevant by at least one sector in the confirmatory survey (**Paper II**), the results underscore the value of multi-factor vulnerability assessments that are specifically adapted to context-specific conditions.

Socioeconomic dimensions of vulnerability in forested cold climates

One of the key findings in the top-down approach was how the use (**Paper I**) and applicability (**Paper II)** of vulnerability factors relating to basic needs (e.g. under-nourishment, or access to improved water sources), or other forms of socioeconomic susceptibility or demographic conditions differed between the study region and global studies and assessments. Instead the factors most relevant for societal vulnerability in this context, apart from governance related factors, were those shaping how society interacts with and depend on hydrological systems, including access to drinking water services, financial reliance on water-dependent sectors, and water users' drought awareness (**Paper II**).

Several mechanisms may explain this pattern. First, socioeconomic or demographic variables may have less explanatory power for drought vulnerability in high-income welfare states such as Sweden, where baseline living conditions and service provision reduce sensitivity to basic-needs impacts. In that case, transferring such indicators into the study region should be done with caution, and explicit attention should be paid to ensure that they reflect local conditions and impact pathways. Second, the results are consistent with a vulnerability profile that is more strongly shaped by sectoral vulnerability, water dependencies, and governance arrangements than by poverty- or development-related metrics.

The limited relevance of socioeconomic susceptibility and demographics revealed in the confirmatory study (**Paper II**) may, however, also reflect how the survey questions were framed (e.g., focusing on society's drought vulnerability as a whole), which could have potentially been interpreted as connected to factors more relating to governance, processes and plans. Another potential reason for their limited relevance is the intrinsic perspectives and priorities of the surveyed stakeholder, that may not be connected to factors relating to social and societal vulnerabilities. Whilst the employment context (e.g. academia, enterprise, authority, etc.) did not significantly influence the vulnerability ratings for societal drought vulnerability (**Paper II**), respondents were largely affiliated with water-dependent sectors rather than welfare-sector organizations, which may have influenced which vulnerability drivers were seen as most salient. Nonetheless, the results suggest that the conditions of forested cold climates shift the vulnerability profile away from socioeconomic factors and toward biophysical and governance-related factors, combined with human-water interdependencies (**Papers I & II**).

Sectoral context

Another key finding is the pivotal role of forestry in vulnerability studies within the study region: more than one-third of the reviewed articles focus on vulnerability in forestry (**Paper I**). Meanwhile, the vulnerability profile for the forestry sector stands out compared to other sectors included in the confirmatory study, with significant differences in ratings compared to other

sectors across several vulnerability factors (**Paper II**). These results underline forestry's dual significance: it is both a uniquely vulnerable sector in the region (**Paper II**) and a core component of the socio-hydrological system in forested cold climates (**Paper I**). The results also indicate that multisectoral drought vulnerability assessments in forested cold climates should consistently incorporate forestry-specific processes, practices, and impact pathways when assessing drought risks associated with sector-relevant drought types.
Through the confirmatory survey, unique sectoral vulnerability configurations emerged for all surveyed sectors (**Paper II**), shaped by their operational and ecological context and dependencies. One notable finding is that some factors previously not used in the context of certain sectors (**Paper I**) were found to be relevant for these sectors (**Paper II).** This was particularly evident for the environmental and energy sectors, where respondents identified a broader range of vulnerability factors than those commonly referenced in previous research. This highlights a knowledge gap between research and operational realities and stresses the need to continually re-assess and re-evaluate sectoral and systemic drought vulnerability, both to improve sector-level accuracy and to support robust assessments of systemic risk across the socio-hydrological system. If such systemic assessments overlook vulnerability factors that operate across multiple sectors, they may miss potential cascading or systemic impact mechanisms and understate compound impacts.

These findings underscore that vulnerability assessments should be both sector-specific and reflexive: capable of capturing distinct sectoral configurations while remaining open to emergent or previously underrecognized vulnerability factors. At the same time, the presence of cross-sectoral vulnerability factors suggests that effective drought governance requires both tailored strategies and a system-level perspective on shared risks.

Water dependencies

Both the literature review as well as the confirmatory survey highlight water dependency as a central determinant of drought vulnerability (**Papers I & III**). This finding reinforces that vulnerability patterns are intrinsically connected to the type of drought a system experiences (e.g., meteorological, agricultural/soil moisture, hydrological, or socioeconomic drought). In light of evidence that risk assessments often fail to specify the drought type under study (Hagenlocher et al., 2019), this finding underscores a substantial methodological deficiency that can bias vulnerability assessments and lead to poorly informed conclusions.

The findings also have practical implications for drought risk management planning. Plans should explicitly define which drought types are important for the system and which dependencies are most critical, because different vulnerability factors play different roles depending on the drought characteristics. Here, drought management plans should during initial screening of the water system aim to identify the different water dependencies present in the system. This should be done before evaluating potential drought definitions, thresholds or drought indicators.

Assessing drought vulnerability using vulnerability factors

The confirmatory study provided the opportunity to see how the same list of vulnerability factors, found in the literature (**Paper I**), differs in relevance across distinct water-dependent sectors (**Paper II)**. The results indicate that vulnerability factors within the region can be distinguished as foundational versus sector- or drought-specific factors (**Papers II & III**). This adds valuable information into systemic vulnerability: some factors of vulnerability are impactful for several societal sectors whereas others are tightly linked to specific sectoral or drought contexts and operational constraints. A key implication is that multi-sector drought vulnerability assessments can be distorted when they rely on generic indicator sets without adapting them to sectoral context and water dependency. The confirmatory survey shows significant differences in the rated impact of individual vulnerability factors across sectors (most notably for forestry) and across water-dependency types. This points to unique vulnerability profiles within socio-hydrological systems that risk being blurred when generic indicators are applied regardless of context.

Foundational vulnerability factors

The confirmatory study reveals several vulnerability factors that appear foundational from a cross-sectoral perspective. These specifically relate to the biophysical setting and recur as high impact factors across all, or a majority of, surveyed sectors (**Paper II**). Examples include geographical characteristics, soil water holding capacity, baseline water stress, and the presence of wetlands/lakes/ponds. The results suggest that these factors could serve as a core component of multi-factor and multi-sectoral vulnerability assessments in the study region, complemented by sector-specific vulnerability factors to capture differences in vulnerability.

Just as was seen with cross-sectoral drought vulnerability, some biophysical vulnerability factors related to the landscape characteristics were also seen as relevant across water dependencies, further supporting their foundational nature for systemic drought vulnerability.

The confirmatory survey also shows that governance capacity is central to drought vulnerability across most sectors. Factors such as having authority level drought management plans, long-term supply and demand assessments, drought monitoring, and the drought awareness, coordination, and competence within and across authorities were shown to by impactful for several sectors as well as society as a whole. However, one particularly important insight is that green-water-dependent sectors identified only a limited number of policy instruments and governance capacities as relevant for drought risk. This pattern needs to be further explored, as it highlights a potential gap between current policy instruments and how they serve green-water industries.

Sector- & drought-specific vulnerability factors

The emergence of water dependency as an important contextual consideration controlling which vulnerability factors matter provides a direct entry point for systemic drought vulnerability assessments, highlighting the role of drought type for sectoral drought vulnerability. Here, significant differences between blue- and green-water-dependent sectors show how drought type affects the socio-hydrological system in different ways. For example, green-water-dependent sectors were mainly concerned with biophysical characteristics of settings and species, whereas blue-water-dependent sectors place greater weight on factors such as water-supply reliability and the presence of water-/drought-related policy and plans.

From a sectoral perspective, assessments including agricultural systems, could involve factors relating to for example access to and efficiency of irrigation systems, or baseline water stress depending on the specific drought type used for the analysis. For the water supply and energy sectors this could involve presence of alternative water sources or the potential for water storage development. And for terrestrial ecosystem services and forestry, factors relating to drought tolerance, or growth limiting conditions could be included (**Paper II**).

Transferability

The confirmatory study shows broad alignment between vulnerability factors identified across the wider study region (**Paper I**) and those considered relevant from a national perspective within the region (**Paper II**). This supports the interpretation that drought vulnerability in these climate-biome settings has a coherent structure, and it points to opportunities to harmonize drought vulnerability factors and assessment approaches across comparable forested cold climate regions. The similar water dependencies and forest-intensive regions of countries such as Norway, Finland, and Canada suggest that the overall vulnerability profiles found for sectoral actors and water-dependencies in Sweden could be transferable, with the important distinction that variations in governance structures, mandates and planning will shape their local realities. The overall importance of governance is stressed both regionally and in the Swedish context showcasing its important role for drought vulnerability in forested cold climates.

Temporal Dynamics & Risk Perception

The temporal dynamics of vulnerability have long been argued by scholars (Fekete et al., 2010; O'Brien et al., 2004). Most of the vulnerability factors identified in literature (**Paper I**) and in the confirmatory survey (**Papers II & III**) are not stationary over time. For example, one of the highest rated vulnerability factors across all respondents was baseline water stress (**Paper II**), which is not static, but will rather change over time, following aspects such as competing water interests, changes in population, or introduction of water efficient technologies. This implies that even when factors are important for drought vulnerability in forested cold climates, an assessment based on them represents a time-specific snapshot that mirrors the conditions at the time of data collection.

The results also show that different sectors have different temporal drought vulnerability frames. For example, the agricultural sector has shorter crop rotation times than stakeholders working in other sectors. For example, the forestry sector will work with long rotation periods, spanning several decades (Bréda & Brunette, 2019; Roberge et al., 2016). These differences shape assessment choices: forest-sector drought vulnerability assessments more often use simulation modelling rather than static index-based approaches (**Paper I**) to capture vulnerability over time.

Temporal nature of perception

The temporal dynamics of vulnerability is further exemplified by the complex nature of risk perception. While respondents across multiple organizations emphasized that maintaining drought awareness within authorities is essential for addressing drought vulnerability (**Paper II**), the repeated cross-sectional survey indicates that drought risk perception diminishes over time (**Paper V**). Such a decline in perception may undermine the ability of authorities to remain drought aware and proactive, potentially resulting in insufficient long-term planning thereby affecting drought vulnerability over time. Addressing this gap requires institutional mechanisms that sustain both awareness and perception over time, ensuring that drought remains salient in decision-making even in periods without severe drought events.

At the same time, in municipalities in northern Sweden, observed drought severity in 2018 seemed to be moderately associated with the drought risk perception five years after the event. The same association could not be seen between observed or perceived drought severity in 2022 and drought risk perception in 2023. This provides some insight into how more severe drought events can have the potential to influence drought risk perception years after the event took place, whilst more recent but less severe events seem to play a weaker role in such perceptions.

In addition to the role of hazard severity on risk perception, several other mechanisms may be involved in the dynamics of institutional risk perception. While not directly analyzed within the scope of the repeated survey, aspects such as media coverage, organizational culture and structure, and the gradual and hard-to-discern nature of slow-onset droughts may also shape organizational sensemaking and play a role in the changes in risk perception seen in the repeated survey (Zhang, 2022). For example, the 2018 drought was an extraordinary event (Teutschbein, Albrecht, et al., 2023) that resulted in large impacts on several sectors (Jordbruksverket, 2018; MSB, 2018; Sjökvist et al., 2019) and was accompanied by extensive media coverage. Meanwhile the 2022 drought prompted less public resonance regarding its effects on water availability, as suggested by a Google Trends comparison of search activity related to water shortage (Google Trends, 2025).

Science-authority-stakeholder misalignments

Across all papers, misalignments between research, sectoral practitioners, and authority emerge as impactful systemic drivers of drought vulnerability in forested cold climates. Aspects such as limited governance capacity (**Papers I–III**), unclear or insufficient implementation of management tools (**Papers I–V**) and drought definitions (**Papers IV & V**), declining drought awareness and risk perceptions (**Papers I–V**) and incoherency between perceived and observed drought conditions (**Papers IV & V**) all play a role in drought vulnerability in the study region. While such misalignments are difficult to quantify, they underscore pivotal challenges that need to be addressed in order to strengthen whole-of-society drought risk management.

Misalignment in perceived and observed drought conditions

One clear example is the role of hazard perception, which is complicated by the misalignment between perceived and observed drought severity (**Papers IV & V**). This indicates that perceived drought severity may be influenced by other factors than solely the experienced drought conditions. Meanwhile, respondents in the first survey round of the repeated cross-sectional study mainly associated drought conditions with effects on blue water sources, less frequently associating it with low soil moisture, i.e., green water (**Paper IV**). Simultaneously, soil water holding capacity was one of only two vulnerability factors that was considered highly impactful on drought risk in all surveyed sectors (**Paper II**). This could be an indication of an overrepresentation of blue water consumption and dependencies in relation to drought, which risks downplaying vulnerabilities in green-water-dependent sectors such as ecosystem services, forestry, or agriculture (**Paper III**). However, the results of the repeated cross-sectional survey reflect the responsibilities of Swedish local authorities. As municipalities are responsible for drinking water supply according to Swedish law, a primary focus on drought conditions affecting blue water sources is, to some extent, expected.

Yet, the results indicate that the hydrologically observed drought conditions do not always translate into corresponding perceived severity in practice. This implies that meteorological or hydrological hazard severity alone does not determine the on-the-ground perceived severity. One potential explanation for this is that aspects such as drought vulnerability come into play, where observed moderate to severe drought conditions are attenuated in municipalities with a low drought vulnerability. Consequently, the results could be an indication that municipal operations in Sweden have some built-in robustness to such events. However, the 2018 drought was still shown to affect several municipalities to various degrees, highlighting that vulnerability still exists. The question also involves the issue of water dependency and drought type (**Paper III**), as drought impacts on municipal operations will be dependent on the drought type that they face, and their corresponding vulnerabilities. For example, municipalities dependent on deep groundwater or large surface water aquifers for drinking water production may see weaker effects from a short meteorological drought, than a municipality with a large share of inhabitants reliant on private (potentially shallow) wells, where the possibility to attenuate precipitation deficits is less. However, during severe and prolonged drought events such municipal operations may still see exceptional impacts. In this context, the indication that current municipal operations to a large extent are unfamiliar with the different drought types (**Papers IV & V**) becomes particularly important.

Misaligned governance: Sectoral needs versus practical implementation

The important role of governance is highlighted in the confirmatory survey (**Papers II & III**). Respondents found all vulnerability factors relating to governance to be impactful for drought risk in Swedish society, and most vulnerability factors were also impactful for drought risk in the agricultural, environmental, water resources, and water supply sector. However, whilst several sectors rated the presence of a drought management plan highly (**Paper II**), such plans are still rarely adopted in practice (**Papers IV & V**).

Meanwhile, the repeated cross-sectional study provides evidence that formal planning can matter when it exists. Municipalities with drought management plans reported a larger number of measures implemented in response to past drought events in Sweden (**Paper IV**) highlighting the potential of proactive planning to improve authoritative drought responses during drought events to support sectors and society as a whole. Concurrently, the findings also highlight the importance of efforts that reduce water demand (as indicated by factors such as baseline water stress and competing water interests) (**Paper II**) yet municipalities seem to primarily focus on measures that increase supply with much less attention given to efforts aimed at reducing consumption (**Paper IV**).

Beyond formal plans, several sectors pointed out the role of competence within authorities to offer drought related support as an impactful vulnerability factor for drought risk (**Paper II**). The results show that not only the existence of policy tools such as drought plans are important for drought risk management. Instead, several sectoral stakeholders repeatedly stressed that drought plans and risk-management efforts should also be accompanied by stronger coordination and cooperation among authorities, and systematic efforts to build drought-related competence within institutions. Meanwhile, such measures were rarely mentioned in the repeated cross-sectional survey (**Papers IV & V**). This suggests that while sectoral actors emphasize the importance of institutional competence and coordination for effective drought risk management, these aspects may be underprioritized by local authorities in their current approaches to securing water supply. The findings highlight a need for governance efforts that go beyond the development of formal drought plans, by also prioritizing inter- and intra-authority coordination and internal capacity-building. Strengthening institutional knowledge and communication around drought-related issues could enhance authorities' ability to support local actors and sectors more proactively and effectively.

Misaligned drought terminology and stakeholder interpretations

The repeated cross-sectional survey underscores the limited adoption of drought terminologies and typologies commonly used and referred to in scientific literature (**Papers IV & V**). Terminology such as "*water scarcity*" and "*drought*" were more commonly used among local authorities than terms associated with different drought types. Meanwhile, how a drought is perceived and understood can vary depending on the perspective of the stakeholder (Kohl & Knox, 2016; McEwen et al., 2021), and could influence the measures taken in response to drought events or its perceived urgency (Cavalcante et al., 2023; Kohl & Knox, 2016). For example, if drought is perceived as primarily associated with a lack of rainfall, one might underestimate hazard or risk appraisal associated with rising temperatures and increasing evaporative demands. One way to achieve common understanding of what constitutes a drought on a local level can be by establishing operational drought definitions in municipal operations. However, while the number of municipalities adopting such definitions seems to increase over the study period, the number of municipalities with operational definitions in place is still low (**Paper V**). This is also an important insight for the scientific community, as much of the extensive research performed regarding drought hazards, vulnerability and risk is performed in order to guide policy and future risk management approaches. Meanwhile, if scientific drought typologies are not commonly understood in practice, this may result in misinterpretations and communication gaps between the scientific community and its intended audience. This is further complicated by the infrequent and incoherent use of drought hazard and vulnerability definitions in scientific drought risk literature (**Paper I**).

Implications for whole-of-society risk management

The results across all papers stress the central role of drought management and drought-related awareness and capacities within and across authorities. They further show that when implementing drought plans, objective triggers or drought indicators need to reflect local realities (**Papers III–V**), such as the water dependencies present within the target water system (**Paper III**) that are relevant for institutional responsibilities. Here it is crucial to study how the chosen indicator align with local perceptions (**Paper IV & V**), or to integrate local drought thresholds into drought monitoring and trigger systems. Furthermore, as drought monitoring and forecasting tools are argued as pivotal for drought risk management (**Papers I–III**), tracking their alignment with local realities and perceptions is crucial.

The results also highlight that scientific drought terminology is rarely applied in practical realities. This provides important information for risk communication strategies between scientific research and its intended audience. Scientifically informed communication to authorities and policy practitioners should explicitly situate drought-type-specific findings within the broader framings of drought and water scarcity (**Papers IV & V**), ensuring that the audience can correctly interpret both the capacities and limitations of the results.

Papers II and **III** also stress the importance of drought management plans or other water related policies and to pair these with capacity-improving measures. Such measures should aim to strengthen for example inter- and intra-governance coordination, collaboration and drought awareness.

The identified misalignments among and across sectors, research, and authorities, showcase the need for harmonizing vulnerability experiences and perspectives across sociohydrological systems. This should be done at different governance levels, for example through development of an EU-level drought framework (as stressed by Biella et al. (2025)), establishing national drought responsibilities and frameworks for collaboration and coordination, requiring incorporation of drought risk assessments in legally mandated crisis and risk assessments, and establishing science-authority-stakeholder exchanges to harmonize drought risk and vulnerability perceptions across sectors and institutions.

Finally, future drought risk assessment in the study region must recognize the unique vulnerabilities connected to different drought types (**Paper III**) and be specific in the applied vulnerability indicators to ensure that they reflect the drought type studied, thereby improving the accuracy of the assessments. Such assessments, if incorporating multi-sectoral perspectives, should also aim at combining foundational biophysical vulnerability factors (**Paper II & III**) with sector- and drought-specific vulnerabilities (**Paper II & III**) in order to capture systemic vulnerability patterns within the studied system.

Conceptual framework

The literature review shows that conceptualizations of drought vulnerability in forested cold climates are fragmented across sectors and disciplines, but can be unified through a systemic framing, as articulated in the conceptual framework for drought vulnerability in forested cold climate regions developed in **Paper I**. The framework categorizes vulnerability depending on three dimensions of vulnerability, the indirect or direct water consumers, and the governance processes and capacities that affect them. This approach is a simplification of a system's vulnerability to drought, that serves as a guide for initial screening of drought vulnerability or the design of a drought vulnerability assessment. It also shows the dynamics of vulnerability within a socio-hydrological system where an individual can be vulnerable both as a direct water consumer as well as an indirect water consumer, and the shifting perspectives of drought vulnerability in a societal sector versus for society as a whole. However, the conceptual framework also highlights the central role of governance, as a dimension that will affect the vulnerability of both direct and indirect water consumers. This was also seen in **Papers II and III**, as stakeholders found several vulnerability factors relating to governance as relevant for drought risk in sectors as well as society. **Paper IV** also shows that governance-related policy tools lead to an increase in implemented measures in response to drought.

The framework is intended as a complement to established approaches rather than a replacement. For example, the PAR model differentiates vulnerability into root causes, dynamic pressures, and unsafe conditions. Such distinctions can be mapped onto the three dimensions of vulnerability present in the proposed framework. The main novelty here is the explicit guidance it provides for identifying *who* is exposed in a given drought context (direct versus indirect water consumers), and for linking those exposed entities to relevant vulnerability factors in forested cold climates. In practice, the framework can help researchers or policy makers clarify whether an assessment targets individual vulnerability (often with a focal point on indirect water consumers), sectoral vulnerability (direct water consumers), or adopts a holistic view that combines both aspects (**Paper I**).

The framework also enables the identification of potentially conflicting vulnerability factors across sectors and drought hazard types. This is illustrated by the role of irrigation, which may reduce vulnerability to soil-moisture droughts in rainfed agriculture, while simultaneously increasing vulnerability to hydrological droughts (**Paper I**), particularly in areas with competing water uses or limited blue-water resources.

By combining the insights from **Papers I–V**, this thesis proposes a conceptual framing of drought in forested cold climates that specifically integrates biophysical vulnerability characteristics, sector specific vulnerabilities distinguished by water dependencies for direct water consumers, governance capacities and risk perception dynamics. Importantly, the framing also underscores that integrating the vulnerabilities of indirect water consumers requires a focus on human-water interdependencies while being cautious when integrating factors relating to socioeconomic susceptibility or demographics to ensure region-specific relevance. Through the conceptual framing it is shown that drought vulnerability in forested cold climates is strongly shaped by biophysical susceptibility and governance, combined with science-authority-stakeholder misalignments and risk perceptions.

Stakeholder-Informed Methodologies

The top-down and bottom-up approach applied in this thesis provided insights into both the strengths and limitations of incorporating participatory approaches in vulnerability research. The confirmatory survey enabled an assessment of how vulnerability factors used regionally correspond to national perspective. It furthermore allowed for identification of sectoral/consumer discrepancies as well as commonalities from a multi-sectoral point of view (**Papers II & III**). Having the possibility for respondents to offer their own suggestions of vulnerability factors further enriched the overall understanding of vulnerability in these regions (**Paper II**).

Linking the top-down approach with the bottom-up repeated cross-sectional study added further detail on the many nuances of drought vulnerability. Vulnerability factors emphasized by sectoral practitioners (**Paper II**) were not consistently reflected in measures reported by local authorities (**Papers IV & V)**, pointing to potential implementation gaps**.** The repeated cross-sectional survey also highlighted potential barriers for proactive drought risk management such as diminishing drought risk perceptions, and limiting adoption of drought typologies (**Paper V**).

Meanwhile, participatory approaches also come with limitations. The methodology applied in this thesis incorporates knowledge from a range of scientific disciplines and sectoral domains. This increases the risk of misinterpretations based on disciplinary boundaries. Furthermore, the large number of vulnerability factors identified in the literature review called for factor aggregation into broader categories in order to limit the (already substantial) number of vulnerability factors presented to the stakeholder in the survey. However, this also results in a loss of information about the individual impact of vulnerability factors incorporated in the aggregated categories.

Conclusion and Future Directions

This thesis set out to explore drought vulnerability in forested cold climate regions as a multi-dimensional puzzle, where each piece, such as drought type, biome and climatological conditions, sectoral characteristics, temporal dynamics, and governance structures, offers a distinct but interconnected perspective (Figure 13). The result showcase how vulnerability in forested cold climates, is fundamentally shaped by biophysical vulnerability and governance, influenced by science-authority-stakeholder misalignments, risk-perception dynamics, and human-water interdependencies.

The results show that the conceptual framing of drought vulnerability in these regions is still highly fragmented. The findings also highlight the complex issue with drought perception and risk, and its evolution over time: even when recent (but milder) drought events occur, drought risk perception tends to diminish as time passes.

The results also underscore both the sector-specific nature of drought vulnerability and the existence of systemic factors that are relevant across diverse ecological, hydrological, and organizational contexts in the study region. This highlights the limitations of using generic vulnerability indicators across diverse contexts. While some vulnerability factors (namely biophysical factors) seem to be more generally applicable to drought vulnerability across most sectors and water dependencies, careful attention should be paid during the selection of vulnerability factors and their consequent indicators to ensure their relevance for local realities.

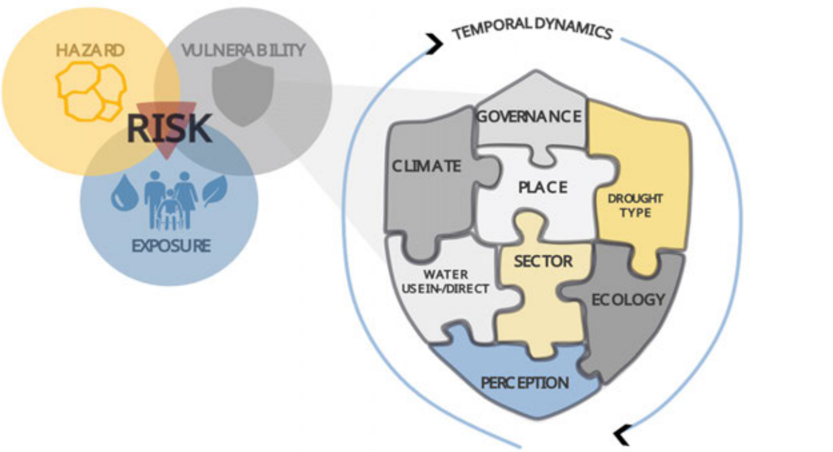

Figure 13. Schematic showcasing some of the characteristics of drought vulnerability that shape its contextuality.

Vulnerability definitions and conceptualizations differ across disciplines as well as between academic researchers and local authorities. Such disconnect requires new efforts in order to improve multiscale synchronization if system vulnerabilities are to be addressed. It also highlights the need for clearly defined terms for risk communication and awareness raising measures. The disconnect between perceived and observed drought severity also indicates the need for the risk framework, combining hazard analyses with vulnerability and exposure studies, to fully grasp how observed hazard conditions translates into impacts and perceived severity.

As recent drought events have shown, forested cold climates are not exempt of experiencing severe drought conditions. With impacts on water supply, agricultural production and the health of the boreal forest ecosystem, understanding context specific drought vulnerability is key. Both the confirmatory as well as the repeated cross-sectional study revealed vulnerability profiles from both an eco-/climatological, sectoral, and water dependency perspective, providing new insights for moving from crisis management to proactive drought risk management. This research has also shown the importance in engaging stakeholders in order to improve accuracy as well as legitimacy in providing context-specific vulnerability assessments.

Future directions.

This thesis aimed to explore the context specificities of drought vulnerability in forested cold climates. The findings show that the vulnerability in the region is dependent on several aspects, such as climate, sectoral focus, and water dependency. Yet the findings also uncover new potential research questions that would further our understanding of how vulnerability is shaped in this region. The following section provides some possible directions for future research on the topic.

Exploring contextual conflict

Papers II and **III** showed how sectoral focus and water type dependency affected the relevance and impact of different vulnerability factors. Each sector and water consumer group had their own unique selection of vulnerability factors and associated size of impacts. Simultaneously, the results also showed how several vulnerability factors were seen as relevant and highly impactful for drought vulnerability across more than one sector. This provides indication that some vulnerability factors are highly relevant on a cross-sectoral scale. However, the direction of this impact is unknown, and a factor that has a large positive impact on drought risk in one sector can have a large negative impact on another sector. This was to some extent seen in **Paper I** for factors such as irrigation, which can decrease vulnerability in rainfed agriculture whilst increasing vulnerability in areas with baseline water stress and competing water interest. Furthering this research by investigating such conflicting factors would increase the understanding of the dynamics of vulnerability in the region. Such information is also crucial when designing and interpreting holistic vulnerability assessments.

Translating factors into indicators and factor validation

Whilst this research identifies relevant vulnerability factors for several societal sectors and water consumers, further work is needed to translate such factors into measurable vulnerability indicators, if they are to be used in indicator-based assessments. This can for some factors prove challenging as some factors are affected by data limitations or are difficult to measure by nature. This could be the case for some of the governance related vulnerability factors, where aspects such as competence and coordination among authorities to offer drought related support can be difficult to quantify.

If the vulnerability factors were to be translated into indicators and applied in practical vulnerability assessments, a next step could also be to validate the results with recorded impact data from recent drought events. Whilst such data has its limitations, such as biases relating to hazard or event type, geographic coverage, and a reliance on reported or monetized losses (often overlooking indirect or non-economic losses, and delayed impacts appearing gradually over time) (Gall, 2015; Gall et al., 2009; Joshi et al., 2025), it could provide an indication on whether the identified vulnerability factors seem to translate into observed impacts. If a drought vulnerability assessment of Sweden would be combined with a hazard analysis to form an overall drought risk assessment, such results could then be compared with the perceived drought severity and risk perception seen in the repeated cross-sectional study. This could further our understanding of whether risk perception and hazard appraisal is indeed more connected to the risk as framed in the Sendai Framework, rather than solely connected to the observed drought hazard severity.

Exploring risk perception at different levels of government

Papers IV & V showed how risk perception among Swedish municipal water managers seem to be misaligned with observed drought conditions. This poses new questions as to why this could be. One potential reason could be the stakeholder's perspective, that may be mainly focused on water security, rather than on overall impacts on the socio-environmental system in their municipality. By expanding such repeated survey research to incorporate other levels of government, the role of societal perspectives could be explored. For example, Swedish County Administrative Boards (CAB) have an overall coordination responsibility regarding crisis preparedness and climate adaptation (HaV, 2022). They are also the regional supervisory authority for regional water activities (Sydvatten, 2019), nature conservation and environmental protection and are responsible for developing plans for regional water supply and green infrastructure. Five of the CABs also serve as water district authorities, responsible for the implementation of the water framework directive (HaV, 2022). As a result, their view of drought impacts and severity may differ from those primarily responsible for water supply. Incorporating more perspectives, among authorities at different governmental levels could further deepen our understanding about risk perception among drought related authorities, and how it may affect drought risk management.

Under-studied sectors & knowledge gaps

Within the literature review, sectors such as the energy sector and the environment and its ecosystem services were underrepresented among the reviewed articles. Whilst the current thesis developed the understanding of how drought vulnerability is expressed in these sectors, further advancement of drought vulnerability for these sectors for inclusion in systemic drought vulnerability is pivotal. The literature review also identified the specific perspectives of indigenous communities and the important role of indigenous knowledge in the broader study region. However, as its role cannot be fully captured through aggregated factors in cross-sectoral surveys, future research should examine the role of indigenous knowledge for drought vulnerability in the study region in greater depth through context-specific and participatory approaches. One possible way to enable the inclusion of indigenous perspectives in systemic vulnerability assessments could be by including indigenous groups as their own distinct sector. Indigenous communities often hold unique place-based knowledge and may experience vulnerability through pathways that differ from those of administrative or economic sectors. Therefore, by treating indigenous groups as a separate sector would allow their perspectives, priorities, and strategies to be examined on their own terms, rather than indirectly through aggregated indicators or external stakeholder assessments.

Further exploring the role of social vulnerability

The top-down approach applied in this thesis indicates that social vulnerability, tied to basic-needs, human developments, socioeconomic susceptibility and demographics seem to play a weak role in drought vulnerability in the broader study region as well as in Sweden. This finding contrasts the results reported by, for example, Englund et al. (2023) and Turesson et al. (2024) which show that social vulnerability is an important driver of vulnerability to climate risks in Sweden. While their results focus on other climate hazards, and not specifically on droughts, the role of social vulnerability in drought risk in Sweden and the broader study region should be further assessed.

Designing holistic vulnerability assessments

This thesis has shown how drought vulnerability differs depending on context, and across different sectors. For example, the forestry sector stands out when it comes to relevance and impact of vulnerability factors compared to many other sectors (**Paper II**). We also saw that the sector often uses other approaches for their vulnerability assessments, such as applying simulation models to study vulnerability or impacts over time in relation droughts. The differences in time scales between different sectors impose challenges when performing vulnerability assessments taking several sectors into account. Meanwhile the forestry sector is not only an integral part in the social systems in forested cold climates, but also plays a pivotal role for climate regulation. Hence excluding this sector in holistic vulnerability assessments may skew the results, and affect accuracy and legitimacy of such assessments. Here, efforts should be put at exploring how forestry can be integrated with other water dependent sectors in order to produce holistic vulnerability assessments.

Populärvetenskaplig sammanfattning

Torka är en av de mest kostsamma och svårhanterliga klimatextremerna i världen. Den utvecklas ofta långsamt, kan drabba alla typer av klimat och kan ha stora konsekvenser för både natur och samhälle. De senaste åren har visat att även områden som traditionellt förknippats med rikliga vattenresurser kan påverkas av torka. År 2018 såg till exempel Sverige stora konsekvenser av torrperioden, med negativa effekter på exempelvis jordbruk, energiproduktion, och skogsbruk. Likaså såg Kanada kraftiga effekter av torråret 2025 i form av låga vattennivåer, skogsbränder och undantagstillstånd.

I dagens arbete med klimatextremer och naturfaror ligger fokus mer och mer på att hantera och förebygga riskerna att uppleva negativa effekter av faran. I sammanhanget talar man ofta om att risk är en produkt av en *naturfara* (i detta fall torka), *exponering* för naturfaran, och *sårbarheter* hos de som påfrestas. För att effektivt kunna arbeta förebyggande med risk behövs därför en förståelse av alla dessa tre komponenter.

Denna avhandling fokuserar på den tredje riskkomponenten, sårbarhet. Att studera sårbarhet är svårt, då begreppet saknar en gemensam och allmänt accepterad definition. En vanlig definition för sårbarhet baseras på IPCC definition i deras senaste rapport, AR6. Där beskrivs sårbarhet som en kombination av känslighet mot påfrestningar, förmågan att på kortare sikt hantera störningar och kapaciteten att anpassa sig över tid. Sårbarhet är därför starkt kopplat till sammanhanget som det studeras i, och kan förändras över tid.

Hur människor och organisationer uppfattar risk spelar också en viktig roll för sårbarhet. Riskuppfattning påverkar hur vi människor reagerar på påfrestningar såsom en torka, både på kort och lång sikt, och kan påverka hur organisationer och myndigheter väljer att arbeta med riskhantering. En viktig del i att studera samhällsårbarheter innefattar därför att studera hur involverade aktörer upplever torka eller andra påfrestningar.

För att kunna ta fram effektiva strategier för riskhantering krävs en förståelse för de underliggande sårbarheter som påverkar den övergripande risken. Samtidigt saknas en övergripande förståelse över hur sårbarhet formas i skogbeklädda kalla klimat som ofta traditionellt förknippats med rikliga vattentillgångar. Likaså fattas kunskap om hur riskuppfattningar och riskhantering i dessa områden ser ut i praktiken och över tid.

Metod

Denna avhandling undersöker samhällsårbarheter för torka i områden som domineras av skogsmark eller tundra i kalla klimatområden. Genom fem delstudier analyseras hur sårbarhet varierar mellan olika klimat, ekoregioner, sektorer, organisationer och erfarenheter.

Delstudie I var en litteraturstudie med syftet att undersöka hur sårbarhet studeras och beskrivs i länder och regioner inom studieområdet. Identifierade faktorer kopplat till sårbarhet för torka samlades systematiskt in och kategoriserades. De identifierade sårbarhetsfaktorerna låg sedan till grund för en nationell svensk enkätstudie utförd i Delstudie II. Enkäten involverade svenska aktörer verksamma inom olika vattenberoende sektorer, och hade som syfte att studera hur bedömningen av sårbarhetsfaktorer varierade mellan sektorer. Deltagarna fick bedöma hur mycket de olika sårbarhetsfaktorerna påverkar risken för torka, både inom sin egen sektor och för samhället i stort, sett ur ett svenskt perspektiv. Delstudie III använde samma enkätmaterial och undersökte skillnader i bedömningen av sårbarhetsfaktorer baserat på typ av vattenberoende, dvs om sektorerna främst var beroende av grund- och ytvatten eller markfuktighet.

I Delstudie IV och V användes en upprepad enkätstudie (utförd 2018 och 2023). Syftet var att förstå hur kommunernas riskhantering, erfarenheter och riskuppfattning utvecklats över tid, särskilt i ljuset av torrperioderna 2017-2018 och 2022. Kommunernas upplevelser jämfördes även med observerade data från SMHI, SGU och EDO.

Centrala resultat

Litteraturstudien visade att forskning kring torka idag är splittrad och ofta saknar tydliga definitioner för vad sårbarhet är. Samtidigt framkom det att sårbarhet i dessa områden skiljer sig från globala narrativ, där sociala faktorer och mänskliga grundläggande behov ofta får större utrymme. I resultaten framträdde istället andra faktorer som centrala för sårbarhet, exempelvis biogeofysiska egenskaper och styrningsrelaterade aspekter.

Den nationella enkätstudien visade att olika samhällssektorer bedömer sårbarhetsfaktorer olika. Samtidigt lyftes flera sårbarhetsfaktorer upp som relevanta för mer än en sektor. Styrning, planering och verktyg framstod till exempel som centrala faktorer för flertalet sektorer, liksom tillgången på vatten. Däremot syntes även i denna studie en begränsad relevans för socioekonomiska sårbarhetsfaktorer för torka sett för samhället i stort.

Resultaten i delstudie III understryker hur typen av torka man exponeras för har en central roll för sårbarhet. Tydliga skillnader kunde ses mellan sektorer beroende av grund-och/eller ytvatten gentemot sektorer främst beroende av markfuktighet. Sektorer beroende av grund- eller ytvatten betonade vattentillgång, omgivningens egenskaper och styrningsrelaterade faktorer, medan sektorer beroende av markfuktighet till stor del fokuserade på ekosystemens och omgivningens egenskaper. Denna grupp ansåg inte heller styrningsrelaterade faktorer som relevanta för gruppens sårbarhet.

Den upprepade enkätstudien gav en tydlig bild över hur riskuppfattning, erfarenheter, och hantering rörande torka inom svenska kommuner förändrats över tid. Den första enkätomgången visade att kommunerna upplevde torkan 2018 som betydligt allvarligare än 2017, med rapporterade effekter på flera olika typer av verksamheter. Trots detta bedömdes den kommunala beredskapen som god för en majoritet av kommunerna. Nästan alla ansåg att risken för torka kommer att öka i framtiden, men få kommuner hade en operativ definition eller handlingsplan.

När undersökningen upprepades 2023 visade resultaten att kommunerna uppfattade torkan 2022 som mildare, och fler än hälften angav att de inte upplevt torka alls. Resultaten visade på en nedgång i hur kommunerna uppfattar risken för torka i framtiden. I jämförelse med första enkätstudien ansåg nu fler kommuner än tidigare att risken för torka i kommunen kommer att vara oförändrad eller minska i framtiden. Användningen av begreppet ”torka” i dagligt arbete hade också minskat. Trots att fler kommuner än tidigare nu rapporterade att de hade en operativ definition för torka, var antalet kommuner med formella planer eller definitioner fortfarande låg. I båda enkätomgångarna fanns en tydlig skillnad mellan upplevd och observerad torka.

Diskussion & Slutsats

Sammanfattningsvis visar avhandlingen att sårbarhet i kalla klimat dominerade av skogsmark eller tundra till stor del formas av en kombination av biogeofysiska egenskaper och styrningsprocesser och verktyg, I jämförelse med globala narrativ tycks social sårbarhet ha en mindre framträdande roll för risker förknippade med torka i dessa områden. Tydliga sektorspecifika skillnader kan ses, särskilt inom skogsbruket, samtidigt som flera tvärsektoriella faktorer identifieras som ett gemensamt fundament för sårbarhet inom klimat- och ekoregionen. Likaså är vattenberoende och typ av torka centrala för sårbarhet, där sektorer som använder grundvatten eller ytvatten påverkas av andra sårbarheter än de som är beroende av markfuktighet

Avhandlingen visar också att riskuppfattningen inom svenska kommuner tycks minska över tid, trots återkommande torrperioder. Implementeringsgraden av operativa definitioner tycks öka över tid, men andelen kommuner med formella handlingsplaner och definitioner är fortfarande låg. Samtidigt lyfts styrning och planering upp som viktiga sårbarhetsfaktorer för flera sektorer och samhället i stort, vilket pekar på ett glapp mellan vad som uppfattas som viktigt och vad som faktiskt implementeras.

Sammantaget visar denna avhandling att effektiva riskbedömningar och riskhanteringsstrategier i kalla klimat med stor andel skog eller tundra kräver en kombination av sektorspecifika analyser, systemförståelse, och stärkt institutionell kapacitet. I detta arbete krävs även en kontinuerlig anpassning till lokala förhållanden, erfarenheter och uppfattningar där fokus även läggs på att skapa en samstämmig lokal bild över vad torka innebär ur ett lokalt perspektiv.

Acknowledgements

I am incredibly grateful to have gotten the opportunity to conduct my PhD studies at Uppsala University, studying drought vulnerability in forested cold climates. Looking back, I couldn't have done it without the wonderful people around me who have been there as support, encouragement, and inspiration.

The first person to come to mind is my main supervisor, **Claudia**, the level of support you've given me during these years has been absolutely incredible. You've always been there to offer valuable advice, constructive comments and inputs, and to guide me in the realms of academia. But you have also been an immense support for me personally. Lending an ear when needed, or spending hours discussing life and science in the LUVAL kitchen. I also want to thank my co-supervisors **Thomas and Malgorzata -** having your guidance and support throughout my PhD has meant so much. Your advice, encouragement, and insights have been invaluable. Together with Claudia, you have shaped my PhD into an amazing experience.

To all my fantastic colleagues at LUVAL and CNDS; you've made these years unforgettable. I especially want to thank my wonderful roommates I've shared these years with: **Laura, Makoto, Greta, Koffi,** and **Meriem**. You have really brightened my days at the office throughout these years.

A special thank you to my amazing Water Nature for Future-teammates: **Andrijana, Elise, Faranak, Greta, and Sara C**, it's been wonderful to work alongside you all.

I also want to thank my parents. Your endless support and your way of encouraging me to meet the world with curiosity have shaped who I am today. I'm so incredibly proud to have you as my parents. Your strength, courage, and incredibly warm hearts guide me, now and always. And to my amazing sister: your creativity inspires me, and I'm constantly amazed by the energy and imagination you bring into everything you do.

And finally, my amazing husband, thank you for *everything*. Thank you for always being there. You are the most incredible person I've ever met and I look up to you in everything I do. This journey wouldn't have been possible without your support, love and encouragement throughout the years. And to our children, for showing me what research is all about: learning about the world through exploration, wonder, and trial and error. I love you so much.

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