Built Environment

Drought in Water Abundant Finland

Data and Tools for Drought Management

Lauri Ahopelto

Aalto University

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Abstract

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Abstract

Droughts pose a risk to all societies, even those with abundant water resources. Climate change will affect this risk, and societies should adapt accordingly. Though Finland has a low drought risk, recent droughts have had a clear impact, especially on agriculture and water supply, but also forestry, hydropower, and ecosystems. While Finland's water governance and water security are generally at a good level, drought has so far gained little attention and operative drought management plans and strategies are absent.

This dissertation studies drought risks in Finland and provides recommenda-tions on how to improve drought management. Drought risk can generally be understood as a combination of three factors: vulnerability, exposure, and haz-ard. Several drought indices, models, and weather data generation are used in the dissertation to better understand drought hazard and to quantify drought frequency, severity, and other characteristics of drought events in Finland. The dissertation also considers how drought hazard might change due to climate change. The results are discussed in relation to different sectors and within the broader water governance context in Finland.

The results from the drought index analyses provide detailed information on drought characteristics in Finland. The findings show that choosing the best drought indices for different contexts is difficult, emphasizing the need to use several indices. For the Sirppujoki basin case study (a river basin in southwestern Finland), 20 different standardized drought indices were calculated for two drought events of 2002–2003 and 2018 as well as for the years 2040–2069. In addition, weather data generation coupled with hydrological modeling was tested for the basin.

This dissertation reveals that drought risks will likely increase due to climate change, predominantly in the south and southwest Finland. Based on evapo-transpiration-dependent indices, drought events are predicted to increase espe-cially during the growing season. This is particularly worrying for the agricultural sector, since only a few percent of fields have irrigation systems. However, the climate scenarios have a large variation, emphasizing the need for more research as well as flexible climate change adaptation.

To address the growing drought risk in Finland, adaptation measures against drought impacts are suggested. A national drought strategy, together with bot-tom-up drought management plans, would mitigate the increasing drought risks. These should be accompanied with a systematic drought management process with an early warning system.

Keywords water resources management, water governance, climate adaptation, drought indices, drought management, Finland

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Tiivistelmä
Kuivakaudet aiheuttavat riskejä kaikille maille, myös niille, joilla on runsaat vesivarat. Ilmastonmuutos vaikuttaa tähän riskiin ja yhteiskuntien tulisi siksi sopeutua muutokseen. Vaikka Suomessa kuivuuden riski on pieni, viimeaikaisilla kuivakausilla on ollut merkittävät vaikutukset erityisesti maatalouteen ja vesihuoltoon, mutta myös metsätalouteen, vesivoimaan ja ekosysteemeihin. Vaikka Suomessa vesivarojen hallinta ja vesiturvallisuus ovat yleisesti ottaen hyvällä tasolla, kuivuuteen ei ole toistaiseksi kiinnitetty syvemmin huomiota eikä operatiivisia kuivuuden hallintasuunnitelmia tai -strategioita ole olemassa.

Tämä väitöskirja tutkii kuivuuden aiheuttamia riskejä Suomessa ja tarjoaa suo-situksia kuivuuden hallinnan parantamiseksi. Kuivuuden riski voidaan yleisesti ymmärtää kolmen tekijän yhdistelmänä: haavoittuvuus, altistuminen ja vaaratekijä (eli varsinainen kuivakausi). Väitöskirjassa käytetään useita kuivuusindeksejä, mallinnusta ja säädatan generointia lisäämään ymmärrystä kuivuusvaarasta ja mittaamaan kuivuuden toistuvuutta, vakavuutta ja muita kuivakausien keskeisiä ominaisuuksia. Väitöskirja tarkastelee myös, miten kuivakaudet saattavat muuttua ilmastonmuutoksen myötä. Tuloksia käsitellään eri sektoreiden näkökulmasta ja ne liitetään laajempaan vesivarojen hallinnan kontekstiin Suomessa.

Kuivuusindeksianalyysien tulokset esittelevät yksityiskohtaista tietoa kuiva-kausien ominaisuuksista Suomessa. Tulokset osoittavat, että eri alueille parhaiten sopivan kuivuusindeksin valitseminen on vaikeaa. Tämä korostaa useiden indeksien käytön tarvetta. Sirppujoen valuma-alueelle (Lounais-Suomessa sijaitseva tapaustutkimusvesistö) laskettiin 20 erilaista standardoitua kuivuusindeksiä kahdelle kuivakaudelle vuosilta 2002–2003 ja 2018 sekä vuosille 2040–2069. Lisäksi valuma-alueella testattiin säädatan generoimista yhdessä hydrologisen mallin kanssa.

Väitöskirja osoittaa, että kuivuuden riskit todennäköisesti kasvavat ilmaston-muutoksen myötä, erityisesti Suomen etelä- ja lounaisosissa. Haihduntaan perustuvien indeksien perusteella kuivakaudet vaikuttavat lisääntyvän etenkin kasvukaudella. Tämä on erityisen huolestuttavaa maataloussektorille, sillä vain harvoilla pelloilla on kastelujärjestelmiä. Ilmastonmuutosskenaarioissa on kuitenkin suurta vaihtelua, korostaen tarvetta lisätutkimukselle sekä joustavalle ilmastonmuutokseen sopeutumiselle

Kasvavan kuivuusriskin hallitsemiseksi väitöskirjassa ehdotetaan sopeutumistoimia kuivuuden. vaikutuksien varalle. Kansallinen kuivuusstrategia yhdessä paikallisella tasolla laadittavien kuivuusriskien hallintasuunnitelmien kanssa hillitsisi kasvavia kuivuusriskejä. Näiden rinnalle tarvitaan myös systemaattinen kuivuusriskien hallinnan prosessi sekä ennakkovaroitusjärjestelmä kuivakausille.

Avainsanat vesivarojen hallinta, sopeutuminen, kuivuusindikaattorit, kuivuusriskien hallinta, Suomi

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Helsinki, March 2024
Lauri Ahopelto

Contents

List of Abbreviations

DMP	Drought Management Plan
EDO	European Drought Observatory
EU	European Union
GWP	Global Water Partnership
IDM	Integrated Drought Management
IDMP	Integrated Drought Management Programme
IPCC	International Panel for Climate Change
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
NDMC	National Drought Mitigation Center
OECD	Organisation for Economic Co-operation and Development
PET	Potential evapotranspiration
P	Precipitation
Q	Discharge
RH	Relative Humidity
RCP	Representative Concentration Pathway
RQ	Research Question
SM	Soil moisture
SMA	Soil Moisture Anomaly
SPI	Standardized Precipitation Index
SPEI	Standardized Precipitation and Evapotranspiration Index
SRI	Standardized Runoff Index
SSI	Standardized Streamflow Index
T	Temperature
UNDRR	United Nations Office for Disaster Risk Reduction
UK	United Kingdom
UN	United Nations
WFD	Water Framework Directive
W	Water Level
WSFS	Watershed Simulation and Forecasting System
WMO	World Meteorological Organization

List of Publications

This doctoral dissertation consists of a summary and the following open access publications, which are referred to in the text by their numerals (e.g., Paper I),

1. **Ahopelto, L.**, Veijalainen, N., Guillaume, J.H.A., Keskinen, M., Marttunen, M. and Varis, O. Can There be Water Scarcity with Abundance of Water? Analyzing Water Stress during a Severe Drought in Finland. *Sustainability,* **2019**, *11*, 1548. https://doi.org/10.3390/su11061548

2. Veijalainen, N., **Ahopelto, L.**, Marttunen, M., Jääskeläinen, J., Britschgi, R., Orvomaa, M., Belinskij, A. and Keskinen, M. Severe Drought in Finland: Modeling Effects on Water Resources and Assessing Climate Change Impacts. *Sustainability,* **2019**, *11*, 2450. https://doi.org/10.3390/su11082450

3. **Ahopelto, L.**, Kallio, M., Veijalainen, N., Kouki, R. and Keskinen, M. Drought hazard and annual precipitation predicted to increase in the Sirppujoki basin, Finland. *Climate Services,* **2023**, 31, 100400, https://doi.org/10.1016/j.cliser.2023.100400

4. **Ahopelto L**., Sojamo S., Belinskij A., Soininen N. and Keskinen M. Water governance for water security: analysing institutional strengths and challenges in Finland, *International Journal of Water Resources Development*, https://doi.org/10.1080/07900627.2023.2266733

5. Blauhut, V., Stoelzle, M., **Ahopelto, L.**, Brunner, M. I., Teutschbein, C., Wendt, D. E., Akstinas, V., Bakke, S. J., Barker, L. J., Bartošová, L., Briede, A., Cammalleri, C., Kalin, K. C., De Stefano, L., Fendeková, M., Finger, D. C., Huysmans, M., Ivanov, M., Jaagus, J., Jakubínský, J., Krakovska, S., Laaha, G., Lakatos, M., Manevski, K., Neumann Andersen, M., Nikolova, N., Osuch, M., van Oel, P., Radeva, K., Romanowicz, R. J., Toth, E., Trnka, M., Urošev, M., Urquijo Reguera, J., Sauquet, E., Stevkov, A., Tallaksen, L. M., Trofimova, I., Van Loon, A. F., van Vliet, M. T. H., Vidal, J.-P., Wanders, N., Werner, M., Willems, P., and Živković, N.: Lessons from the 2018–2019 European droughts: a collective need for unifying drought risk management, Nat. Hazards Earth Syst. Sci., 22, 2201–2217, https://doi.org/10.5194/nhess-22-2201-2022 , 2022.

Author's Contribution

The authors have contributed to the articles accordingly:

1. Conceptualization, L.A. and N.V.; methodology, L.A., N.V., and J.H.A.G. (global models); software, L.A., N.V., and J.H.A.G. (global models); formal analysis, L.A., N.V., and J.H.A.G. (global models); investigation, L.A.; resources, L.A., N.V., and J.H.A.G.; data curation, L.A., N.V., and J.H.A.G.; writing—original draft preparation, L.A.; writing—review and editing, all; visualization, L.A. and J.H.A.G.; supervision, M.K., M.M., and O.V.; project administration, L.A. and M.M.; funding acquisition, M.M., M.K., and O.V.

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3. Conceptualization: L.A., Methodology: L.A., M.Ka. and N.V., Hydrological modeling N.V., climate scenarios: N.V. and L.A., coding: L.A. and M.Ka. Data generation: L.A. and R.K. Analysis of results: L.A., visualization: L.A. and M.Ka, Writing–Original draft preparation: L.A., Writing—review and editing: L.A., M.Ka. N.V. and M.Ke.

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1. Introduction and objectives

1.1 Introduction

Droughts cause major negative impacts to societies and affect nation's water security, food security and energy security (Cook and Bakker, 2012; Jääskeläinen et al., 2018; UNDRR, 2021). It is also one of the most expensive natural hazards, with estimates of average annual losses of 9 billion euros in the EU and UK alone (Cammalleri et al., 2020; Smith, 2020). For example, the 2022 drought in Europe was the most severe in decades and caused massive impacts across the region (Toreti et al., 2022). Other examples of recent severe drought events include the 2012–2016 drought in California (Lund et al., 2018) and the 2017 day-zero event in Cape Town (LaVanchy et al., 2019).

A functional society should try to manage drought impacts. In the past, droughts were primarily handled in a reactive manner; in the last decade, however, focus has generally shifted from reactive to proactive drought management (UNDRR, 2021, 2015). Proactive drought management (i.e., managing the risk in advance) is cheaper in the long term than reactive drought crisis management (Cammalleri et al., 2020; Howarth, 2018). It also alleviates the societal impacts of drought more effectively (Cammalleri et al., 2020; Wilhite and Pulwarty, 2017).

To promote proactive drought management, the International Drought Management Programme (IDMP) was launched in 2013 by the World Meteorological Organization (WMO) and the Global Water Partnership (GWP). The objective of the IDMP was to provide policy and management guidance, as well as to share scientific information and best practices for Integrated Drought Management (IDM). The IDM framework can be considered as the main approach for proactive drought management and the related risk-based national drought management policy.

Drought risk is defined generally in the IDM as a combination of exposure to a drought hazard and vulnerability (WMO and GWP, 2014). This definition is well in line with the risk framework used by the Intergovernmental Panel on Climate Change (IPCC, 2014); the IPCC risk framework views risk as a combination of three main components: hazard (e.g., drought), exposure (e.g., field hectares) and vulnerability (e.g., how vulnerable the crop is to drought). Acknowledging and assessing these three distinct but interrelated components is needed to ensure an analytical understanding of drought risk, making it easier to develop targeted mitigation measures and build resilience in the areas that are most susceptible to drought. In this dissertation, this process of assessing and mitigating drought risk is called 'drought risk management'. This forms a part of general drought management, which also incorporates other aspects such as monitoring, early warning systems, preparedness, and response.

Climate change is expected to exacerbate drought risk globally, with potential negative impacts on, for example, agriculture and forestry sectors. Although annual precipitation is predicted to increase in Finland (Ruosteenoja and Jylhä, 2021), changing precipitation patterns, higher evapotranspiration, and more intense drought events are expected to increase drought risk, particularly in the growing season (Ruosteenoja et al., 2018). Adaptation to climate change is thus an essential element of proactive drought management.

While the IDM framework provides a general structure for drought management, it still needs to be implemented to be effective. Local or regional Drought Management Plans (DMP) can be an effective tool for implementing proactive drought management, where DMP can be generally described as a preparedness and mitigation plan (GWP CEE, 2015). One important element of comprehensive DMPs is an early warning system. Drought indices are a key element of early warning systems, though DMPs can also utilize them when assessing current and future drought risk and estimating the start, severity, duration, and extent of a drought event (UNDRR, 2021; WMO and GWP, 2014).

Droughts are long lasting and affect large areas; as such, the direct and indirect impacts of drought on water security are extensive and difficult to quantify. Drought impacts also extend beyond water security – for example, by impacting food security and agriculture in particular, which is heavily reliant on water. Energy security is also affected, due to constraints of hydropower generation and cooling water availability.

Various parts of Europe have been affected by several severe, large-scale drought events, with ten events between 2003 and 2022 alone (Blauhut et al., 2022; Boergens et al., 2020; García-Herrera et al., 2019; Ionita et al., 2017; Laaha et al., 2017; Toreti et al., 2022). The European Commission has therefore established the European Drought Observatory (EDO), drafted guidelines, and conducted studies to support drought management in its Member States (van Lanen and Tallaksen, 2008; Vogt et al., 2018, 2011). Drought management is a topical theme in other parts of the world as well. The United States, for example, has a National Drought Mitigation Center (NDMC), which has actively developed tools, products, and services around drought monitoring and early warning, risk and vulnerability assessments, as well as mitigation, policy and planning activities across the globe (Svoboda, 2020).

1.2 Drought and drought management in Finland

Finland is a Northern European country with abundant water resources (FAO, 2020). It would therefore be easy to assume that Finland cannot suffer from drought, but this is not the case. Despite its abundance of water resources, the drought event of 2002–03 had clear impacts in Finland, and was estimated to cost 100 million euros in direct costs (Silander and Järvinen, 2004). The drought was meteorologically and hydrologically more severe than the 2018 drought event, which was estimated to cost 400 million euros just for the agricultural sector (YLE, 2018). These differing impacts are mainly due to the timing of the droughts; the 2002–2003 event started after the summer of 2002 and ended before the next summer, whereas the 2018–2019 drought was not as severe but started in spring 2018, which was a critical time for crop development (see figure 5 in the Results section).

In both events, several water supply companies had to restrict water use. After the 2002–2003 event, several companies built emergency connections to neighboring water supply companies, which were mostly compensated by the government. In 2018, the Government of Finland issued 86.5 million euros in compensation to the agriculture sector as a reactive relief measure (YLE, 2018).

Due to the low drought risk and thousands of lakes, Finland has practically no systematic national drought management policies in place. However, in the latest Water Framework Directive's (WFD) feedback, the European Commission recommended that Finland consider DMPs, since the country did not have any in place (European Commission, 2012). Hence, a DMP was tested in 2020 for the Sirppujoki basin in southwestern Finland, which has been identified as one of the most drought-prone areas in Finland (Ahopelto et al., 2019). This test was part of a larger project funded by the Ministry of Agriculture and Forestry (the ministry responsible for water resources management) and intended to study drought related climate resilience in southwestern Finland (Ahopelto and Veijalainen, 2020). The project also included the development of drought maps, as well as an early warning system and guide to draft local DMPs in Finland. A draft version of this DMP was finished, but it has not yet been implemented (implementation is planned to start in 2023).

Despite having no operational DMPs or a national drought strategy, Finland tries to mitigate drought impacts within some sectors. For example, some water supply companies have special action plans for drought, and some have built emergency connections to neighboring water supply companies. Water regulation dams and operations can reserve water in dry periods. Finland has a rather inconsistent climate and predominantly rain-fed agriculture, so farmers are used to dealing with alternating weather conditions every year.

A certain level of drought impact mitigation is an integral part of agriculture. However, the impact of drought to the society, economy, and ecology of Finland is evident. Drought risks and past drought events in Finland should therefore be studied further to advance the drought resilience of Finland, along with drought related climate change effects.

1.3 Research Objectives

The overarching aim of this dissertation is to understand drought risks in Finland and provide recommendations on how to improve the country's drought management, while providing insights into drought assessment and management more broadly. The suggestions on how to improve drought management in Finland are presented in the Results and Discussion chapters, based on the dissertation findings and the presented tools and frameworks. The present synthesis of the dissertation will function as a general introduction to the topic and to the appended articles. The synthesis will present highlights from the appended articles and draw conclusions from the perspective of the Research Questions (RQs) presented below. In addition to the synthesis, more detailed findings, methods, and discussion can be found within the appended articles.

The dissertation studies three RQs. RQ1 and RQ2 are based on the appended articles and are prerequisites for answering RQ3, which provides the broader theme of the dissertation.

RQ1: What kind of data and methods are needed to analyze drought risk in Finland?

RQ2: How is Finland affected by drought, and how will climate change affect this drought risk?

RQ3: How can drought management be improved in Finland?

The results are discussed from three perspectives: 1) a methodological perspective; 2) a practical and managerial perspective; and 3) a governance and water security perspective. All three perspectives are needed for functional and successful drought management. The connections between the RQs and research articles are illustrated in Figure 1.

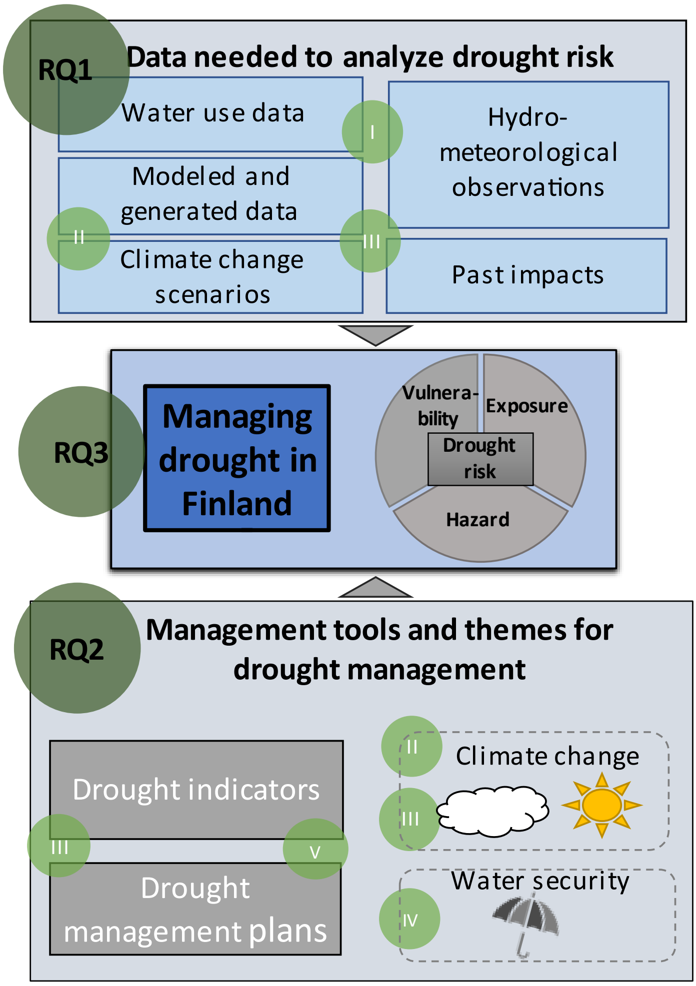

Figure 1. Research Questions (RQs) and appended research articles (I-V).

This dissertation applies a novel combination of various data and tools to understand and assess drought hazard and risk in Finland. Methodologically, the weather data generation presented in **paper III** is a novel method in this context. All other drought analyses carried out for Finland (**papers I, II, III and V**) have not been completed before in as high detail. Furthermore, the Pan-European survey in **paper V** of drought perceptions was the first of its kind. **Paper IV** presents a new application of the OECD water governance framework, linking it with the concept of water security. The scientific novelty of the present work is further discussed and reflected in relation to scientific literature in the Results and Discussion sections.

2. Research background

This chapter summarizes the theoretical background and key concepts used in this dissertation: 2.1) drought in general and how climate change affects drought; (2.2) drought management frameworks and management; 2.3) the concept of drought risk; 2.4) drought indicators and indices; and finally 2.5) water security.

2.1 Drought

Drought is one of the costliest natural hazards. These losses encompass a wide range of factors, including direct impacts, such as crop losses, and indirect impacts, such as higher food prices, economic instability, migration, and health effects. The annual cost of droughts globally can be significant but varies greatly from year to year depending on the severity and location of the droughts. The costs are therefore difficult to assess, since indirect costs are often not reported (Gerber and Mirzabaev, 2017).

Due to the complex nature of drought, it does not have one clear, approved definition (Van Loon et al., 2016). Though the term "drought" means different things to different people, many good definitions do exist. The Intergovernmental Panel on Climate Change (IPCC) defines drought as "*a period of abnormally dry weather long enough to cause a serious hydrological imbalance*" (IPCC, 2012). While the IPCC definition is valid, it is purely physical and lacks a social component covering the society a given drought is affecting – i.e., the impact of the drought. Schwalm et al. (2017) define drought more comprehensively as "*recurring slow-onset hazards that can potentially have major direct and indirect impacts on human and natural systems, including terrestrial and freshwater ecosystems, agricultural systems, public health, water supply, water quality, food security, energy, or economies*". This definition fits the scope of this research well and is therefore used in this dissertation.

As a water abundant country (FAO, 2020), it would be easy to assume that Finland cannot be impacted by drought, and to a certain extent this is correct. The general narrative of Finland and its nature is "the land of a thousand lakes" (Vuoristo, 2002), which of course does not underscore drought-related issues and may be partly the reason for the low level of drought management in Finland. Nonetheless, Finland has had significant economic and ecological impacts from lack of sufficient water in the past (Silander and Järvinen, 2004; YLE, 2018): Finland's society and nature are accustomed to certain levels of water, and a deficit from the average has an impact.

Droughts can be divided into five basic types: meteorological, hydrological, agricultural, socioeconomic, and ecological (Crausbay et al., 2017; Wilhite and Glantz, 1985). Each type refers to the object of the drought (i.e., where the impact is felt). Meteorological drought is always the first impacted, and in essence means clearly lower precipitation than normal. This, in time, leads to hydrological drought (lower discharge, groundwater, and runoff) and agricultural drought (low soil moisture). Socioeconomic drought (i.e., supply and demand of various commodities are affected) and ecological drought (i.e., natural ecosystems are affected) are more complex to determine. All these drought types can, and often do, co-exist in one drought event. Every drought event is unique and affects sectors differently. For example, the 2002–2003 in Finland – which started in the autumn of 2002 and ended in spring 2003 – barely affected agriculture but had a strong impact on water supply companies, with 15% of water supply companies having problems with water availability (Silander and Järvinen, 2004).

Globally, climate change is projected to increase the frequency and severity of droughts in the coming decades (Arias et al., 2021; Cammalleri et al., 2020). Though the degree of change to be experienced is heavily dependent on humanity's level of success in limiting greenhouse gas emissions in near future, there will nevertheless be negative impacts across society, the economy, and nature (Cook et al., 2018; Dai, 2013; Lesk et al., 2016; Seidl et al., 2017).

The changes of frequency and severity of drought vary greatly all over the globe (Arias et al., 2021; Cook et al., 2018). Previously, '*dry-areas-getting-drier and wet-areas-getting-wetter*' was often stated as a general principle for the global implications of climate change, but this has been seen as too simplistic (Polson and Hegerl, 2017; Trnka et al., 2018; Xiong et al., 2022). Finland is a wet country, and climate change has been estimated to increase annual precipitation in the region (Tuomenvirta et al., 2018). For Finland, previous studies about future changes in drought risk provide varying results with decreases (Spinoni, 2018), and no significant change in southern Finland (Roudier et al., 2016). The varying results originate from different methods and models. The projected rise in precipitation levels may lead to reduced drought risk; however, a longer summer season with elevated evapotranspiration could potentially increase drought risk, particularly in southern and central Finland (Dai, 2013; Forzieri et al., 2014).

2.2 Integrated Drought Management

Structured approaches are essential for deconstructing the complexity of drought into manageable units and systematic processes. For example. the United Nations Office for Disaster Risk Reduction (UNDRR) has conducted extensive work on drought management, as seen in their latest global assessment and special report on drought, which provides a comprehensive collection on the current understanding of drought management and drought risk assessment (UNDRR, 2021) and presents several approaches to drought management.

A well-known framework is the Sendai framework for Disaster Risk Reduction 2015-2030 (UNDRR, 2015). However, in this dissertation, the key approach used for drought management is therefore the Integrated Drought Management (IDM) framework, complemented by the IPCC's risk framework (presented in Chapter 2.3). The IDM forms an integral part of the WMO's and GWP's Integrated Drought Management Programme (IDMP), which presents a ten-step process for developing a national drought management policy (Figure 2).

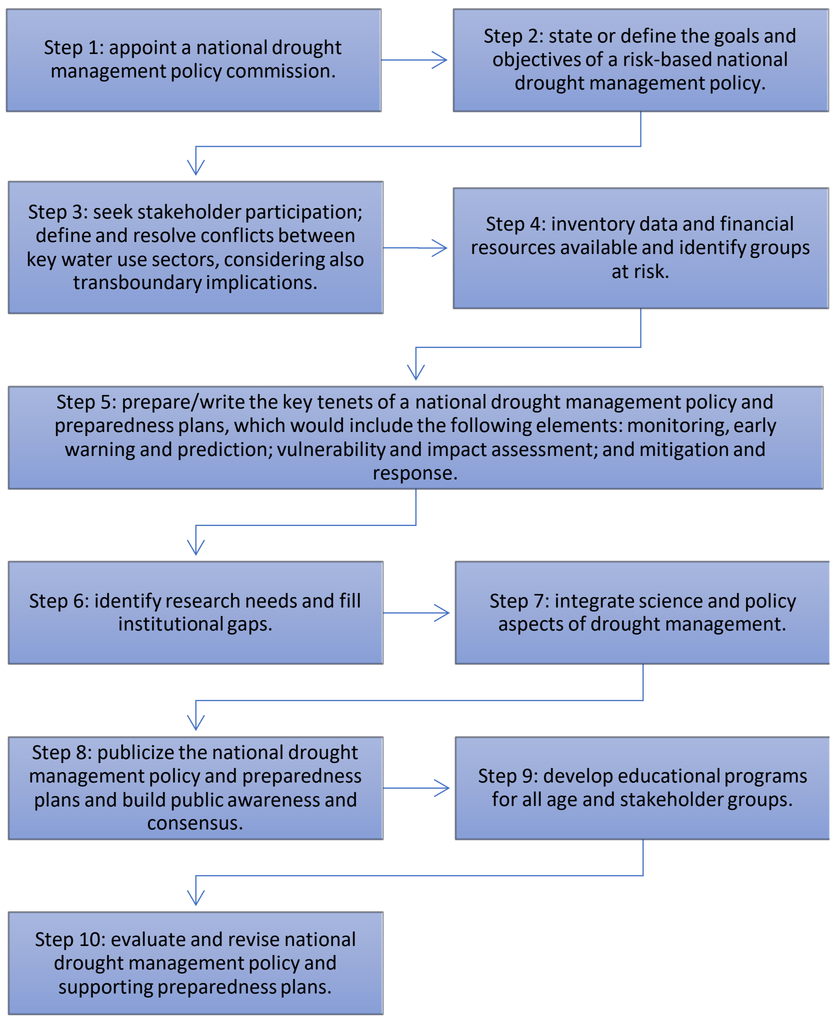

Figure 2. The 10 steps in the development of a National Drought Management Policy (adapted from WMO and GWP, 2014)

The ten-step process was originally presented by Wilhite (1991) and later evolved (Wilhite et al., 2000). It was then adapted by the IDMP into three pillars of IDM as a practical approach to drought management (Wilhite, 2019; WMO and GWP, 2014): I) Monitoring and Early Warning; II) Vulnerability and Impact Assessment (i.e., risk assessment); and III) Drought Risk Mitigation, Preparedness and Response (i.e., drought management plans). Figure 3 illustrates how these three pillars of the IDM link with the key components of risk, central drought management tools, and background themes. All pillars are essential and interconnected. Below are brief descriptions of each pillar.

Pillar I: Monitoring and early warning

Monitoring and early warning systems are essential for understanding the current drought situation in relation to risk analysis, answering questions such as: *How severe is the drought and when are early warnings given?* Climate scenarios and drought frequency and severity estimations (i.e., drought hazard) are included in this pillar.

Pillar II: Vulnerability and impact assessment

Vulnerability and impact assessments are conducted to gain a better understanding of the drought risks, which is fundamental for drought mitigation. Typical assessments include historical, current, and future impacts (impact assessment) and the cause(s) of these impacts (vulnerability assessment).

Pillar III: Drought risk mitigation, preparedness, and response

Drought risk mitigation, preparedness and response consists of all actions to mitigate identified current and future risks. This can be done by mitigating impacts or vulnerability, or by increasing resilience – or optimally, all three. One systematic way to do this is with drought management plans (as presented in Chapter 2.6).

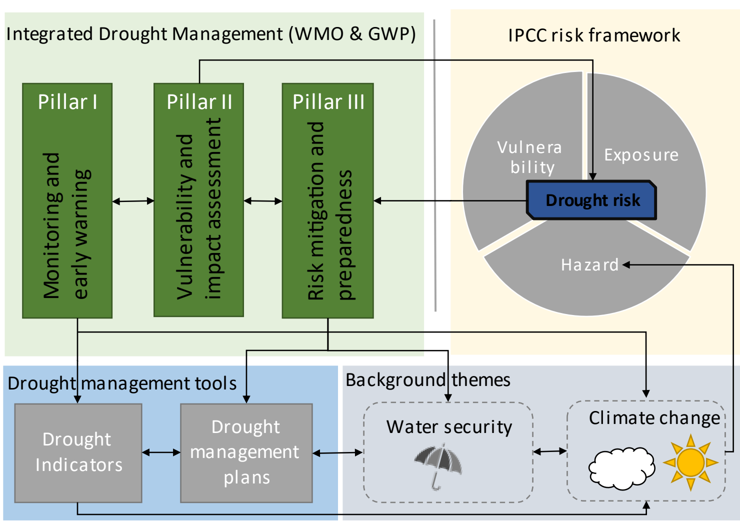

Figure 3. Frameworks and tools associated with drought management and how they are connected.

The IDM framework need to be properly applied in practice in order to be effective. A Drought Management Plan (DMP) can be an effective tool for proactive drought management, and usually includes climate change analyses and adaptation measures (Estrela and Vargas, 2012; GWP CEE, 2015; Wilhite and Knutson, 2008). In the IDM framework, the DMPs contain elements from all the three pillars, although they fall mostly under Pillar III: *Risk mitigation and preparedness*.

DMPs are a key institution in proactive drought management. According to UNDRR (2019), adding drought management to legislation is a fundamental part of functional drought management. A central challenge of DMPs is getting the right stakeholders involved from the beginning (Tsakiris, 2017).

Local DMPs usually include a drought risk assessment, engagement with key actors, and some mitigation measures for the planning area. There are several guides for drafting drought management plans (Bokal et al., 2014; GWP CEE, 2015; Vogt et al., 2018). Local DMPs are often linked with national drought management strategies and national early warning systems. Drought indices are a key element of functional DMPs, since they are often used in assessing the current and future drought risk, early-warning systems and estimation of the start, severity, duration, and extent of the drought (UNDRR, 2021). They are also used to trigger emergency drought mitigation measures.

2.3 Drought risk

Risk can generally be understood as the potential of an adverse outcome, while risk management is then the process of lowering the potential and mitigating the adverse outcomes. Unmanaged risks are more expensive and cause more humanitarian distress; proactive drought management is, on the other hand, proven to be cheaper than reactive drought crisis management, and also mitigates longer-term societal impacts (Cammalleri et al., 2020; Howarth, 2018; Wilhite and Pulwarty, 2017).

A thorough drought risk assessment can be a part of DMPs program of measures, or it can be done before the DMP drafting process. The most prominent risk assessment framework with natural hazard and climate change related assessments is currently the IPCC risk framework, which was presented in 2014 (IPCC, 2014; UNDRR, 2019, 2021), and is used in this dissertation. This framework was designed to help analyze climate-related risk, which deconstructs the risk to three components: Hazard, exposure, and vulnerability (figure 3). For the purposes of this dissertation, the three key components of the IPCC risk framework (IPCC, 2014) are defined as follows, also making use of the related definitions related to IDM (WMO and GWP, 2014):

Hazard is the frequency and severity of drought. However, the hazard analysis should also include seasonal and climate change predictions. Drought hazard is often calculated with drought indices related to different drought types (see Chapter 2.1 for definitions of five drought types).

Exposure is defined as the elements (e.g., factories, people, crop fields) located in areas that could be adversely affected by the drought (IPCC, 2014). Droughts often affect large areas over a long period of time and far from rivers, and thus drought exposure can be high over large distances (in contrast to flood risk exposure, which is typically concentrated around rivers and floodplains).

Vulnerability can be understood as the susceptibility to drought (e.g.., drought-prone crop), but also as the resilience to cope with or mitigate drought impacts should be analyzed (e.g., irrigation system). The UN defines vulnerability as the conditions determined by physical, social, economic, and environmental factors or processes that increase the susceptibility of an individual, a community, assets, or systems to the impacts of hazards. Vulnerability is often difficult to quantify due to complex nature of drought and its impact chains. Local knowledge is essential when assessing vulnerability on a local scale. One way to pin-point where the drought risk has materialized into impacts is to look backwards; past impacts indicate which places are most vulnerable to drought. There is currently no drought impact database in Finland, but an impact assessment was done for the drought of 2002–2003 (Silander and Järvinen, 2004). For other droughts (e.g., 2018–2019), no similar studies have been conducted.

Drought risk is the function of all three components (hazard, vulnerability and exposure). Mitigate one, and the overall drought risk is mitigated as well. On a local level, the drought hazard component of risk cannot be altered, but exposure and vulnerability components can. Nevertheless, drought risk remains theoretical until it transforms into actual drought impacts during a drought event.

In this thesis two essential tools are presented, which help to understand and manage drought risk:

(1) DMPs, which help to manage and mitigate drought risk in a systematic and collaborative way, and

(2) drought indicators and indices (presented in Chapter 2.4), which make it possible to understand the drought better and in a quantitative format.

The second pillar of the IDM, *vulnerability and impact assessment*, is essentially about risk assessment. If a certain level of water deficit is reached, certain impacts will follow, and the drought frequency and severity can be calculated. In other words, risk is the possibility of an adverse effect in the future. In this context, drought can be defined as a phenomenon that creates a water deficit (meteorological, hydrological or any other deficit) which has an impact on society or nature.

Understanding and addressing drought risks is getting an increasing attention both globally and in Europe. Recently for example Rossi et al., (2023)[1] conducted a comprehensive analysis of Europe's drought risks in their European Drought Risk Atlas. The atlas and the related European drought impact database (European Commission, 2023) combine conceptual and quantitative methods to advance impact-based assessments and aid in the development of effective drought management.

[1] Published after the pre-examination of this thesis.

2.4 Drought indicators and indices

Drought indicators and indices constitute an essential component of operative drought management, drought management planning, and early warning systems. They can be used to analyze drought characteristics, such as drought severity and duration, as well as to assess drought frequency.

Indicators refer to specific variables (e.g., precipitation, runoff, groundwater and soil moisture) that depict drought situations. *Indices*, on the other hand, are numerical calculations that represent the severity of drought, based on climatic or hydrometeorological data, including the aforementioned indicators. They are designed to quantify the nature of drought over a certain duration. Note, however, that indices can also be considered as indicators (WMO and GWP, 2016).

There is a plethora of drought indicators and indices to choose from, which is telling about the complex nature of the phenomenon (Mishra and Singh, 2010; Ward et al., 2020; WMO and GWP, 2016). To accurately detect and portray a drought for all affected sectors is difficult. Generally, all drought types have their own drought indicators or indices. For example, agricultural drought usually relies on soil moisture–based indices. Compound indices are also common, whereby several indices are combined – for example, the European Drought Observatory's Combined Drought Index (Cammalleri et al., 2021).

The drought indices used in the appended articles are so called standardized indices: the Standardized Precipitation Index (SPI), Standardized Precipitation and Evapotranspiration Index (SPEI), Soil Moisture Anomaly (SMA), Standardized Runoff Index (SRI), and Standardized Streamflow Index (SSI) (McKee et al., 1993; Modarres, 2007; Sepulcre-Canto et al., 2012; Shukla and Wood, 2008; Vicente-Serrano et al., 2010). Standardized indices were used because they are common and intuitive to interpret in an operative setting and easy to compare against each other. Similar indices are also planned for Finland's national drought early warning system (Ahopelto and Veijalainen, 2020). The indices give monthly negative values for droughts from -1 (mild drought) to -3 and over (extreme drought), while positive values indicate wetter months than average. One example index is presented in Figure 4 for 18 months.

The Run theory can be used to analyze drought events in detail (Yevjevich, 1967). In the Run Theory, continuous drought events are identified as runs and characterized by using concepts of duration, intensity, and severity (See Figure 4). Analyzing drought events with the Run Theory, instead of only analyzing monthly index values, provides more insight to drought as a phenomenon.

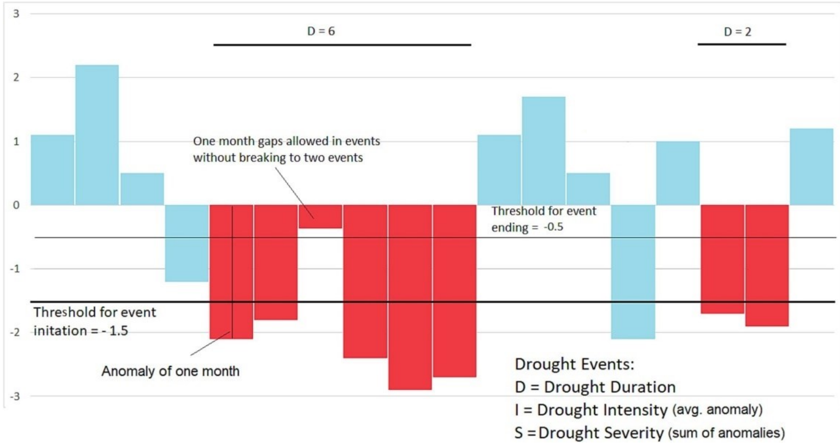

Figure 4. Explanations of how the drought events and their duration, intensity and severity are calculated with the Run Theory.

Another index used in the appended articles is the Water Depletion Index (WDI) developed by Brauman et al. (2016), which is used to analyze water scarcity, as well as seasonal and dry-year water stress. This index compares consumptive water use against available water resources.

2.5 Water security

Drought can also negatively affect national water security. Water security has many definitions (Cook and Bakker, 2012; Octavianti and Staddon, 2021; Zeitoun et al., 2016), but the UN-Water's (2013, page 10) comprehensive definition was used for this dissertation:

"*The capacity of a population to safeguard sustainable access to adequate quantities of and acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability*".

In this dissertation, water governance is seen to consist of actors or organizations and institutional frameworks, which facilitate and regulate their interactions towards desired outcomes (OECD, 2015; Pahl-Wostl, 2017) and water security is seen as the aim of water governance. As per its above definition, water security can be seen to entail two parallel objectives: first, enabling sustainable use and management of water for human and ecosystem's well-being, livelihoods and development; and second, protecting societies, economies and ecosystems from water-related hazards at all levels and scales, including droughts (Sadoff et al., 2020). Hence, nations need to address droughts to improve their water security. Droughts also affect other securities, such as food security via the highly water-dependent agriculture sector, and energy security via hydropower and cooling water.

Water security sets the aim for water policy and water resources management (including drought management). Water security endorses sustainability and adaptiveness of water resource management, while also emphasizing the importance of integrated approaches across sectors and scales. It also focuses on increasing economic welfare, enhancing social equity, long-term sustainability and reducing water related risks (Hoekstra et al., 2018). A high level of water security requires functional institutions and infrastructure supported with proper information (Sadoff et al., 2020).

In Finland, water security is at high level, but problems have been noted (Marttunen et al., 2019). Water security is often linked with water governance, and especially in a way that water security promotes good water governance and good water resources management (Cook and Bakker, 2012).

The impacts of drought extend beyond the immediate consequences on local communities and ecosystems. In fact, they have far-reaching effects that can significantly impact a nation's water security. Recognizing the urgency and importance of addressing droughts is therefore crucial for improving overall water security.

3. Research Design

3.1 Research context

The five appended articles provide a complementary view on the key themes of the dissertation. Together, they help to answer the overall aim (RQ3: How can drought management be improved in Finland?) and to discuss the theme more broadly. The linkages are, however, not straight forward, and this chapter describes how the papers originated and how they are interlinked.

Papers I and II were designed together as a pair and support each other. They both use the same "reference drought", which is the worst drought experienced in the last century in Finland (the drought of 1939–42). **Paper I** focused on water use and **Paper II** on climate change and drought impacts. The research was done as a part of three-year research project called 'From Failand to Winland' (hereafter referred to as 'Winland'), funded by the Strategic Research Council of Finland. This project investigated water, food, and energy security in Finland and their interconnections. Drought fitted the project's theme perfectly, as droughts in Finland had not been adequately studied previously. **Papers I and II** were instrumental for the design of **Paper III**, and the case area was chosen based on the results of **Paper I**. **Paper III** supported the drafting of the first ever DMP in Finland, which was carried out as a part of the LOSSI-project (Southwest Finland prepares for an increasing drought in a changing climate) (Ahopelto and Veijalainen, 2020). Continued implementation of the DMP is planned for 2023 and 2024.

A reoccurring theme in the appended articles (excluding **Paper V**) is *Water Security*, which was a central theme in the Winland project and offers the articles a broader perspective. Hence, **Paper IV** and a related article by Marttunen et al. (2019) were conducted to understand and improve the water security of Finland. Though most of the appended articles did not use workshops or stakeholder collaboration as methods (except **Paper IV**), there were several workshops related to the Winland project, some focusing on water security and drought, including the first ever drought-oriented preparedness exercise, which provided background and context to the appended articles. In addition to the Winland project, several other projects and tasks in the Finnish Environment Institute (SYKE) and the Ministry of Agriculture and Forestry (where the author has worked during this research process) gave additional in-depth information and tacit knowledge of the Finnish policy context.

The invitation to collaborate as a national representative and to conduct the Finnish survey for **Paper V** came from the lead-author of **Paper V** after the lead-author found **Papers I** and **II** online. The resultant pan-European study broadens the drought analysis and discussion from Finnish, basin-level **(Paper III)** and national-scale studies **(Papers I, II & IV),** to continental, EU-scale **(Paper V)**.

3.2 Methods

The appended research articles utilize multiple methodologies for their respective analyses. Each paper applies at least two different methods, encompassing both qualitative and quantitative approaches. Drought, being a multifaceted issue, ranges from the quantitative aspects of meteorology and hydrology to the qualitative factors associated with society and governance. Table 1 displays the primary methods applied in each paper, while more detailed descriptions are available within the appended articles.

Index analysis plays a pivotal role in this dissertation (**Papers I, III and V**). Indices serve as a means of converting vast and intricate data into a comprehensive and usable format for operational and decision-making purposes. These indices are also used in climate scenario evaluations.

In **Paper III**, data generation was used to complement insufficient data series, thereby creating an extensive data series for drought indices. This was also done for the climate scenario assessment.

For a deeper understanding of societal and governance issues associated with water security, **Paper IV** utilized semi-structured interviews and document analysis. **Paper V** used a survey to map the perceptions of the 2018 and 2019 drought in 28 European states.

Table 1. Summary of methods used in the appended articles.

	Paper I	Paper II	Paper III	Paper IV	Paper V
Quantitative methods					
Index analysis	X		X		X
Climate scenario analysis		X	X		
Hydrological modeling	X	X	X		
Data generation			X		
Qualitative methods					
Document analysis				X	
Survey					X
Interviews				X	

3.3 Data

Various datasets and other data sources were used in the appended research articles. The data source used depended on the unit of analysis and stretch from national to sub-basin level. All qualitative data was produced for the articles, except the documents in the document analysis. For quantitative analyses, the Finnish Environment Institute's hydrological model called Watershed Simulation and Forecasting System (WSFS) (Vehviläinen and Huttunen, 2001) was used to produce detailed data for **Papers I–III**. In addition, climate scenarios and global hydrological models were used from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) (Gosling et al., 2017). Water use data was collected from several national databases and for comparison from the global models. The data sources are summarised in Table 2 and in more detail in the appended research articles.

Table 2. Main data sources used in the appended articles.

Main data sources	Paper I	Paper II	Paper III	Paper IV	Paper V
Study area and related scale	Finland / National	Finland / National	Sirppujoki / Basin	Finland / National	Europe / Continental
Level of analysis	Sub-basin	Sub-basin	Basin	National	National/ Continental
National water consumption data	Veeti and Vahti databases 2015 and VEMALA for irrigation				
ISIMIP data (water use and availability)	PCR-GLOBWB, H08, and WaterGAP2 for 1971–2010				
Observation data		P, T, RH, wind speed for 1981–2010 W, Q for 1939–1942	P, T (1981–2020)		
Climate scenario data		28 climate scenarios for RCP2.6, 4.5 and 8.5 for 2040-2069	EC-E-K & Had-S models for RCP 4.5 and 8.5 for 2040-2069		
Hydrological modeling data with WSFS	Q and W for severe drought of 1939–42	Q and W for severe drought of 1939–42	Q, R, PET and SM for 1981–2010 and 2040-2069		
Interview data				Own interviews, metadata stored in Aalto data repository	
Index data					European Drought Observatory
Key documents				Legislative and governance documents	
Survey data					Country surveys

4. Results

This chapter presents the key results from the appended research articles in relation to the RQ1 “What kind of data and methods are needed to analyze drought risks in Finland?” and RQ2 “How is Finland affected by drought and how will climate change affect drought risk?”. The present results are highlights of the appended articles, and further details can be found in the articles themselves. Results related to the RQ3: “How can drought management be improved in Finland?”, are presented in Chapter 4.3 and discussed further in Chapter 5.

4.1 Drought risk analysis for Finland

The results suggest that to quantify the drought risk properly, several datasets, indices, and methods must be used. This is due to the complexity of the drought phenomenon. The appended articles give a few examples with a limited assortment of possible data sources and methodologies that can be used in drought management, and some common elements can be drawn from them. Good quality data and long datasets are essential for functional drought indices, but often they can be unavailable as in **Papers I–III**. Modeling and data generation can help to obtain longer datasets, but uncertainties grow in the process, as found in **Paper III**. A crucial step before obtaining detailed local datasets is to identify vulnerable areas with national analysis, (i.e., where to focus further efforts), as was done in **Papers I and II.**

Possibly vulnerable areas to drought were identified by utilizing national statistics and detailed hydrological modeling (**Papers I & II**) and comparing water consumption from the year 2015 on a sub-basin level against water resources during a severe drought (as in 1939–1942), with the Water Depletion Index. The most severe drought of the past century in Finland, 1939–1942, was modelled in **Paper II** with the hydrological model WSFS**,** since proper observations were not available. An actual drought event was seen as a more realistic comparison point for stakeholders to accept, than an artificially simulated drought. Water consumption data was collected from several data sources. The return water and irrigation data had a high level of uncertainty, since there was no data available for them. A short analysis of national drought impacts for Finland from a severe drought was analyzed in **Paper II,** which concluded that a severe drought, as the drought of 1939–1942, would have a significant impact on society. This was the first of such an analysis conducted specifically for Finland.

Paper I highlighted the Sirppujoki basin as a potentially vulnerable basin, which was further analyzed in **Paper III**. The different types of droughts were tested with 20 drought indices to understand how they perform and vary against each other. As expected, drought onset, duration and severity varied, depending on the index used. Thus, several indices should always be used to get a comprehensive understanding of a drought hazard. However, in an operative setting, too many indices can be disorienting. With a correlation analysis, the number of necessary indices can be lowered (**Paper III**).

Two of the most recent severe droughts in Finland (2002–2003 and 2018–2019) were analyzed in depth in the Sirppujoki basin, using several drought indices (see **Paper III**, Figure 5). These two drought events were very different in nature – the former being worst in winter, and the latter worst in summer. In Finland, droughts are sporadic and the timeseries are often too short for proper analysis (only two severe droughts occurred during 1990–2020). Thus, 990 years of weather data were generated for **Paper III**. The data generation was done by taking a short observation timeseries (30 years) in the Sirppujoki basin, which was complemented with 990 years of generated precipitation and temperature data. This generated weather data, which were then used as inputs to the WSFS hydrological model to simulate 990 years of evapotranspiration, discharge, soil moisture and surface runoff data in a static climate. These data were used to gain a better understanding of the drought characteristics, index behavior and frequencies from hundreds of simulated drought events in the basin, as opposed to using only the few drought events that actually occurred in the observed timeseries. However, using data generation and models increases uncertainties (**Paper III**); while data generation accompanied with hydrological models seemed a promising and novel way to acquire additional data for the drought analysis, the related increasing uncertainties need to be communicated to end-users and decision-makers.

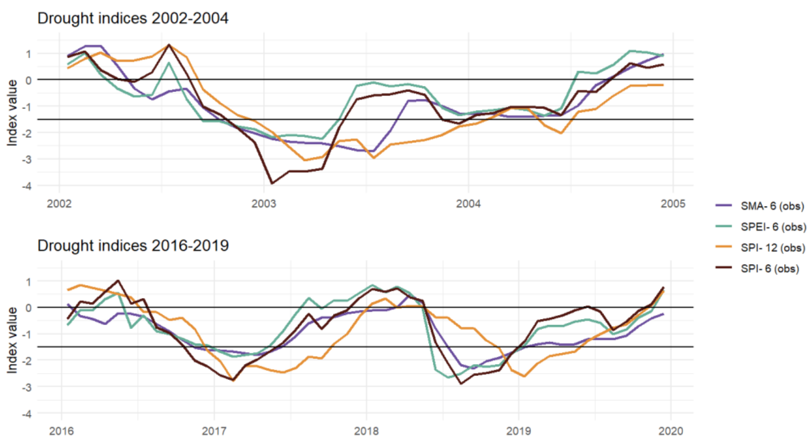

Figure 5. Droughts of 2002–2003 and 2018–2019 with some selected indices. The lower bolded line presents the drought initiation threshold (-1.5).

4.2 Agriculture affected most by drought in Finland

This chapter presents the key results to the RQ2: How is Finland affected by drought and how will climate change affect the drought risk? The results from the appended articles are synthesized into two parts: “Vulnerable areas and sectors” and “How climate change affects drought risk”

The results highlight potentially vulnerable areas in Finland. The findings show that the south and southwest regions of Finland would have problems with water availability during a severe drought (**Paper I**, Figure 6). Furthermore, a long-lasting severe drought caused the discharges to decrease at most by 80% compared to the average annual minimum discharges (**Paper II**). This type of long-lasting severe drought would affect all water-related activities, including agriculture, industries, water supply, hydropower, recreation, and navigation. For example, the reference drought was estimated to decrease hydropower generation by approximately 42% in Finland (**Paper II**). Drought impacts would not be limited to these sectors and areas; however, many water-intensive industries seem to be located in low-risk areas next to large water bodies (**Paper I**).

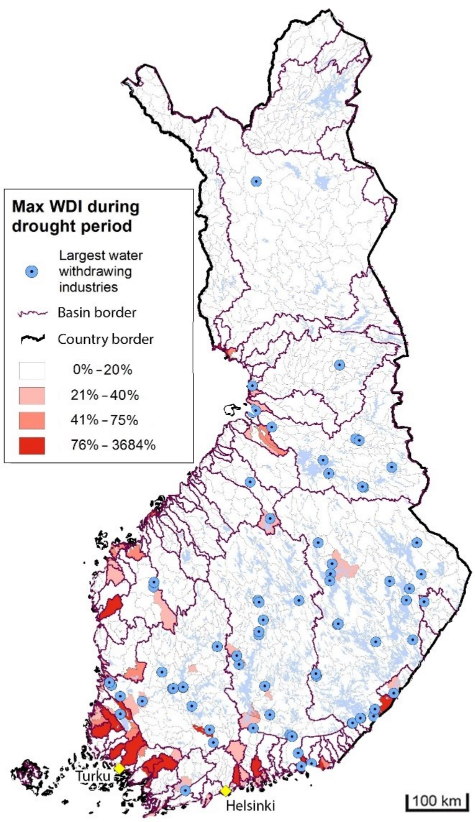

Figure 6. Maximum monthly WDI values during the reference drought period and locations for largest water-withdrawing industries.

To understand the magnitude of drought risk, better knowledge of drought hazard (i.e., the frequency and severity of drought events) under a changing climate is needed. Globally, climate change is estimated to increase drought hazards. However, drought hazard has not been extensively analyzed in detail in Finland. For Finland and the Sirppujoki basin, the results show an increase in drought hazard for 2040–2069 due to changing climate (**Papers II & III**). The results also indicate a decrease in minimum monthly river discharges for most rivers and lakes in southern and central Finland during the reference drought for all calculated climate scenarios. The results also show that climate change increases drought hazard in south and southwest Finland (**Paper II**), which are already vulnerable to drought (**Paper I**). These increases in drought hazard are largely due to the predicted longer growing season, earlier and smaller spring runoff, increased evapotranspiration (especially during late spring) and projected precipitation increase occurring more during winter season than during summer. However, there is uncertainty within the scenarios in terms of how much the increase in annual precipitation will occur during the winter period; if the increase of annual precipitation happens more in summertime, the drought hazard will not grow.

For the Sirppujoki basin, the analysis used four climate scenarios for 2040–2069 (**Paper III**, Figure 7). Despite the projected increase in annual precipitation in Finland, the number of drought events increases within all scenarios using the most studied indices with three-month accumulation. Solely precipitation-based (SPI) indices were found to behave differently to indices with evapotranspiration included (e.g., SPEI) (Figure 7), highlighting the importance of evapotranspiration.

The findings show that future drought events and severe drought events increase significantly according to SPEI and SMA indices (**Paper III**). This indicates that the frequency of drought events would increase especially with evapotranspiration-dependent indices and during the growing season, which would especially affect the agricultural sector. More climate scenarios and analysis of several basins or the whole nation would be needed to gain a better understanding of future drought hazard.

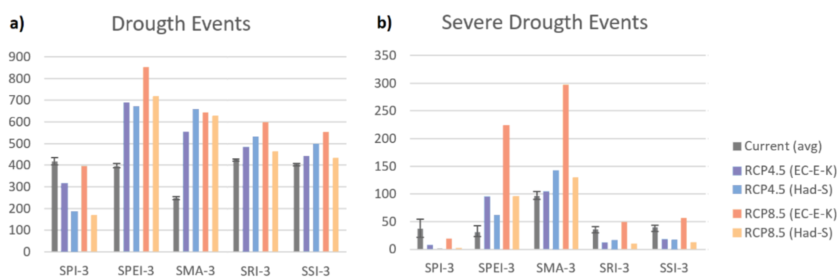

Figure 7. Number of generated (a) drought events and (b) severe drought events (severity<-12) with all scenarios and three-month accumulation. The current climate represents an average value of the two reference periods (1990–2019) and the data generated from observations. The error bar presents both model simulations in the reference period (EC-E-K and Had-S). The climate scenarios represent the period 2040–2069.

In answer to RQ2, the results suggest that the south and southwest of Finland would be most affected by drought and have potential problems with water availability during severe droughts. All water-related activities, including agriculture and industry, would be affected. Additionally, climate change is expected to increase the frequency and severity of drought events, at least in the Sirppujoki basin. The impact is particularly severe with evapotranspiration-dependent indices during the growing season, which would have a clear impact on the agricultural sector. The findings challenge the often-used climate change paradigm, that wet regions will become wetter and dry regions will become drier, which was originally presented by Held and Soden (2006). The paradigm has been recently questioned as too simplistic at local level (e.g., Polson and Hegerl, 2017; Xiong et al., 2022).

4.3 Understanding drought risk to improve drought management

This chapter presents key findings related to RQ3: "*How can drought management be improved in Finland?*". This chapter presents selected findings from the appended articles, while suggestions and discussion of how to improve drought management are presented in Chapter 5.

Analyzing past and future droughts is important, but a process is needed to establish how a nation or region systematically mitigates drought risks. In countries where drought is a common problem (e.g., Spain), such processes already exist. In countries like Finland, where drought risk is smaller, there is no process in place. The perception of the 2018–2019 drought and the current status of drought management in Europe, including Finland (Ahopelto, 2022), was surveyed in **Paper V**. Such a survey was the first of its kind in Finland, as well as Europe. In many countries, DMPs were missing, and drought management was reactive rather than proactive. The actual state of drought management was not seen to be good in most countries (**Paper V**, Figure 8). The findings concluded that drought management is not in a good status in Europe and is therefore in need of improvement. A drought directive from the EU could improve drought management in Europe significantly (**Paper V**).

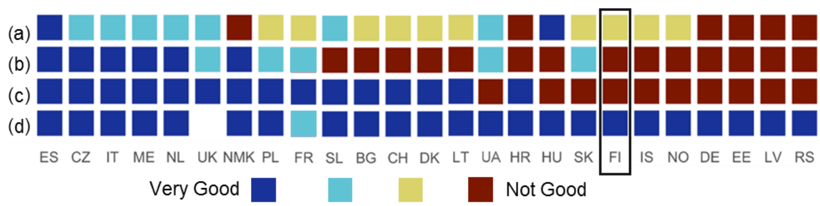

Figure 8. National representatives' joint opinion on (a) the actual state of drought management in their country, (b) the existence of a country-wide drought management plan, (c) the existence of national recommendations for actions to minimise drought risk, and (d) the benefit of an EU drought directive for their country, ordered by score (very good = 3; not good = 0). Finland is highlighted.

Good water governance, a high level of water security, and preparedness can all decrease the vulnerability and exposure components of the IPCC risk framework. Water governance, water security and resilience are all in relatively good condition in Finland, although challenges exist (**Paper IV**). Finland's National Climate Change Adaptation Plan 2030 presents a target (no. 13) that "*Drought risk management will have developed from the 2022 situation by 2030*", including operational early-warning systems, DMPs to risk areas and a permanent process to manage drought risks (Finnish Government, 2023). However, this process will not exist in a vacuum and will be built upon existing water governance systems of Finland.

Stakeholder involvement with adequate public resourcing is pivotal to successful water governance and high-level water security (**Paper IV**). This must be kept in mind also when drafting the drought management policies in Finland and elsewhere. Even though non-public stakeholders must have central roles in governance institutions such as drought management plans, the results suggest the need for a well-resourced public administrator to achieve this (**Paper IV**). This is also important for the implementation of the pilot DMP for the Sirppujoki basin.

5. Discussion

This chapter focuses on the overarching aim of the dissertation: *to understand drought risks in Finland and provide recommendations on how to improve drought management*. The discussion builds upon the results and background presented in previous chapters, and is structured in three parts: first, a methodological discussion (Chapter 5.1), and then a discussion about the possible implications via a practical and managerial perspective (Chapter 5.2), followed by a governance and water security perspective (Chapter 5.3).

5.1 Methodologies for drought management

Operational drought management often requires data intensive analysis and practical implementation of mitigation measures. This dissertation emphasizes the complex nature of droughts and the importance of holistic knowledge, as has been noted also by earlier studies (e.g., Hagenlocher et al., 2019; Van Loon et al., 2016). To highlight the aforementioned aspects, three methodological aspects are presented: uncertainties (of models, scenarios and indices), weather data generation, and future methods.

Firstly, it is crucial for researchers to effectively communicate the uncertainties embedded in models, data simulations, and climate scenarios (Sayers et al., 2017). While decision-makers ultimately hold the responsibility for their decisions, they may not be aware of all potential uncertainties. A duty therefore lies with the researcher to present this information in an easily digestible manner. A delicate balance must be struck in providing the right amount of information about uncertainties; too much information on uncertainty may lead to inaction, while too little may result in unnecessary risks or wasted resources.

In **Paper III**, significant differences in results were observed between the two climate models used. In contrast, **Paper II** employed seven scenarios to support decision-making, demonstrating the benefits of using multiple models and scenarios. To better inform decision making and operational drought management, it is recommended to use a variety of drought indices, scenarios, and models. This finding has been shared by many (e.g. GWP and WMO, 2016; Hao and AghaKouchak, 2013; Rajsekhar et al., 2015).

Secondly, data generation, which is not a novel method in hydrology but accompanied with hydrological modeling and climate change analysis, it can provide interesting and new research possibilities in drought research, where this method has not yet been fully utilized. The insufficiency of time-series data needed for making robust estimates for drought events is a well-known problem. This has been addressed recently from stochastic hydrology and climate change perspectives – for example, by Nazemi and Wheater (2015) – and the consideration of droughts by Borgomeo et al. (2015) and Herman et al. (2016). Brunner et al. (2021) listed stochastic data generation as an option to increase sample size in hydrology. Multiple studies (e.g. Chen and Zhang, 2021; Ilich, 2014) have, however, highlighted obstacles associated with this approach, indicating the need for more research to determine if this method is truly useful.

Generating weather data and modeling hydrological parameters from the generated data can offer solutions in data-scarce regions (**Paper III**). Hundreds of years' worth of generated data can help to understand uncertainties, but stacking data generation with modeling and climate chance scenarios increases uncertainties.

Lastly, there are many new methods and technologies in development that will progress drought management in near future. For example, global hydrological models are getting more accurate and better support local analyses (**Paper I**). Remotely sensed data offers a valuable solution to data-scarce regions, enhancing and supplementing observations with its broad coverage and accessibility. Weather forecasting and remote sensing technologies are also taking huge leaps and becoming cheaper and better (Alahacoon and Edirisinghe, 2022; Dorigo et al., 2017). Furthermore, many new Artificial Intelligence methods are under research, such as machine learning and neural networks, which may help in building better early warning systems and producing better drought indices (Kikon and Deka, 2022). These methods often require lots of data, and weather generators accompanied with hydrological modeling can help to create more data. At the same time, there is a danger of hiding the uncertainty in combined indices, though many myths, such as 'black box calculations', are often unwarranted (Maier et al., 2023). Nevertheless, these methods are likely to provide major improvements and possibilities for drought management in near future.

5.2 Understanding drought and drought risk

This chapter discusses three aspects from a practical drought management perspective: drought risk assessment, drought indices, and climate change implications. The overarching message is that it is impossible to manage drought without first understanding it.

Firstly, drought risk assessment related findings of the dissertation shed light on how large the current drought risk in Finland is and more specifically at the Sirppujoki river basin, and how drought risk might change due to climate change (**Papers I–III**). Assessments such as these have not been conducted in Finland previously and provide valuable information about the drought risk in Finland now and in the near future. However, evaluating the potential risk of drought is challenging due to its multifaceted nature. Also, each drought event varies and has distinct features. The impacts are often also indirect and can have a long chain of events, with surprising impacts. Thus, systematic ways to mitigate drought risks are vital. The frameworks presented in this dissertation – the

IDM, IPCC risk framework, and water security – can together provide a systematic and structured approach to study drought and drought risk. Such an approach is currently largely missing in drought management, as stated by Hagenlocher et al. (2019). Research, guidance, and knowledge building is necessary to facilitate the use of these frameworks.

In Finland, a drought impact database is needed, whereby past and future drought impact data could be stored and analyzed. Impact databases such as the Drought Impact Reporter in United States (Wilhite et al., 2007) could convince decision makers of the need for drought management and help with drought risk assessment.

Secondly, drought indices, which are used for example in drought early warning systems and DMPs, are not usually straightforward to put into operative use. Due to the creeping nature of drought, it can be difficult to determine when to commence measures for impact mitigation. Further, one index cannot satisfy the many differing needs for drought management (e.g., Zang et al., 2020). Ideally, every sector and basin would need localized and tailored indices. The most suitable indices should be chosen with local stakeholders in parallel with the drought management planning process (Tsakiris, 2017), and the indices chosen for operative use should strike a balance between complexity and simplicity. Local officials and stakeholders require support for understanding and fully utilizing drought indices and all they can offer in local drought management. In addition to DMPs and early warning systems, drought indices are useful when doing climate change analyses, as **Paper III** shows. By analyzing the characteristics of drought events, a better understanding of climate change scenarios can be gained and visualized better than by only analyzing, for example, changes in precipitation. However, solely precipitation-based (e.g., SPI) indices were found to behave poorly in climate change analyses, compared to indices that included evapotranspiration (e.g., SPEI). This finding was also noted by Vicente-Serrano et al. (2010).

Lastly, estimating how climate change increases the likelihood of severe drought in Finland is complex because the processes that lead to prolonged periods of low precipitation are complex themselves, and are not adequately captured by existing climate models (Ault, 2020; Mikkonen et al., 2015). Some studies have had mixed results regarding how climate change will affect droughts in Finland. Some reported decreasing drought hazards (Spinoni et al., 2017; Stagge et al., 2017), while others reported no significant change (Roudier et al., 2016), and some even reported increases (Grillakis, 2019; Ruosteenoja et al., 2018). The results depend mostly on the methods used, scope, and scale of the study. Spinoni et al. (2020) simulated the global change in meteorological drought frequency (events per decade) from the recent past to 2100. Less than two thirds of the simulations agreed on the change to be experienced throughout most of Finland. In **papers II and III** a limited set of climate scenarios with a more simplistic delta change method was used. In future studies, the full potential of climate model simulations should be utilised.

All the above depict the difficulty of making good estimations about future droughts. The novel results presented in this thesis are amongst the most detailed and localized analysis on drought hazard available for Finland, and the results predict an increase in drought hazard in the coming decades in at least south and southwestern Finland (**Papers II & III**). However, these results also have uncertainties.

From a water security perspective, a society should be prepared for the 'worst case scenario'. However, recent research has stated that Representative Concentration Pathway (RCP) 8.5 is highly unlikely due to recent climate pledges (Hausfather and Peters, 2020). Hence, end-users should mainly focus on the RCP4.5 scenario, as it is more plausible. In **Paper III**, the 2040-2069 period was analysed; however, end-users could benefit from more recent periods, offering more immediate and actionable data that can be integrated into near-term planning strategies (without overlooking the importance of longer-term forecasts).

The longer growing season and warmer summer could mean larger agricultural output in Finland, but this growth may be constrained by an increasing drought risk if no drought management measures are taken (Peltonen-Sainio et al., 2021). Other sectors will also suffer from increasing drought risk, though to a lesser extent than the agricultural sector. With effective drought management – including early warning systems, DMPs with effective mitigation measures, and drought indices – it is possible to counter the increasing drought risk in Finland, and even reduce it.

5.3 Management implications of drought

The methods and risk analyses presented in this dissertation are mainly quantitative. Though numbers are important tools, they are meaningless without a societal and environmental context – i.e., humans and nature. How drought management is implemented within existing governance systems is crucial for determining their level of success. The dissertation therefore emphasizes the need for both local and national level actions. This is discussed further below, with four main points in drought related governance and water security: DMPs, stakeholder involvement, water security, and the role of the EU.

First, DMPs are key institutions to manage drought risks in a systematic and intersectoral manner. The EU does not require member states to draft DMPs, but does suggest them (European Commission, 2012). Even though water governance and water security are at a high level in Finland (**Paper IV**), the same cannot be said about drought management. DMPs can be local or regional, but too large a planning area may lead to too abstract plans. Determining the appropriate scale of planning and action is therefore imperative for successful DMPs.

Finland's first DMP process was started for the Sirppujoki basin in 2019 through the LOSSI-project (Ahopelto and Veijalainen, 2020). In the LOSSI-project, stakeholders were not actively involved in drafting the DMP. However, local stakeholders are the key to successful implementation of plans in the future.

Local stakeholders are therefore planning to continue with implementation in 2023. In addition to Sirppujoki, there are no DMPs nor national drought strategies in place (**Papers III & V**), but national drought management guidelines are being drafted, and the Finnish government has set a target to improve drought management by 2030 (Finnish Government, 2023). The lack of drought management in Finland is not surprising, since drought risks are not as great as in many other countries and the image of Finland as the land of "endless" water resources does not promote a drought management agenda.

Drought management plans can be quite laborious to draft and implement, so they should not be required in areas where drought risks are small. There are also other ways to mitigate drought risks – for example, by adding drought-related emergency measures to sectoral safety protocols and adding drought risk management aspects to existing strategies or plans (e.g., climate adaptation plans). This technique can provide more cost-effective ways for drought risk mitigation. Effective drought management might often necessitate the integration of drought risk mitigation into existing frameworks when independent implementation is not feasible. However, sectoral approaches without a holistic, cross-sectoral and basin-wide view can lead to sub-optimal intra-sectoral solutions. The decision of the best way to mitigate drought risk is context specific and depends on the needs and capacity of local stakeholders.

Secondly, stakeholder involvement in drought management should not be executed only in a top-down format – the implementation of DMPs requires a functional process. Crucial for the successful implementation of DMPs is the inclusion of the right organizations and stakeholders, as has been noted by Tsakiris (2017). The will to mitigate drought risks needs to come from local stakeholders who see drought as a problem. Hence, drought management plans should only be drafted in places where local stakeholders want them (i.e., bottom-up, demand-driven, local DMPs). Effective national and regional drought strategies should not only disseminate information and increase awareness among local stakeholders, but also establish a support system and organizational framework that includes public administrators to assist communities if they choose to initiate a DMP process. Even though a more detailed DMP should be voluntary, some level of drought risk assessment could be mandatory, and national risk analyses could aid in this task. To sum up, both bottom-up and top-down formats are needed for drought management planning.

Thirdly, water security can support drought management in two ways: (1) water security can act as a conveyor bringing water into other sectors and actors' processes and policies (Varis et al., 2014), since water security is cross-sectoral by design and linkages to other securities are easy to detect (Marttunen et al., 2019); and (2) when drafting drought management plans or national drought policies, water security may provide clarity and be a cost-efficient tool to use (Taka et al., 2021). When working with cross-sectoral, collaborative governance processes with many stakeholders, proper coordination is essential. To guarantee equal and functional stakeholder participation, a properly funded public administrator is needed **(Paper IV)**.

Lastly, drought management is not mandated by the EU (Hervás-Gámez and Delgado-Ramos, 2019), though some member states do stand out with drought risks properly governed, such as Spain (Estrela and Vargas, 2012). There is a large difference in how well drought risks are managed and perceived between different member states in Europe, as the novel survey showed in **Paper V**. This heterogeneity within EU is easy to understand, since there is no binding directive, and hydrogeographic characteristics and drought risks vary greatly amongst the member states. Furthermore, climate change will alter drought risks differently in different regions of Europe; in the north, more annual precipitation is generally predicted, while in the south, the already water-stressed situation is estimated to worsen (Cammalleri et al., 2020).

An EU drought directive or regulation requiring member states to draft drought management plans and national drought policies would undoubtedly mitigate drought risks across Europe. However, such a strong policy might be inefficient and bureaucratic. In countries with good drought management systems in place, it may not improve the situation much, and in countries with lower drought risk like Finland, more flexible systems than EU directives and regulations would probably be more cost-effective. Other "softer" means of improving drought management across Europe should be explored more before binding directive or regulations are considered.

6. Conclusions

This dissertation provides insights into drought risk assessment, identifying vulnerable areas and ways to manage drought in Finland. Despite Finland's relatively low drought risk, recent drought events have underscored the need for proactive measures in sectors such as agriculture and water supply. The dissertation explores selected methodologies to assess drought risk and provides information about the potential impact of climate change to drought frequency and severity.

The dissertation applied a novel combination of various data and tools to understand and assess drought hazard and risk in Finland through five scientific articles. Methodologically, the weather data generation is a novel method in this context. The drought index analyses extended and improved the existing knowledge of drought hazards in Finland. The pan-European survey of drought perceptions was the first of its kind, and a new application of OECD water governance framework was used.

The dissertation examined what kind of data and methods are needed to analyze drought risks in Finland (RQ1). The results confirm that several datasets, indices, and methods need to be used to comprehensively assess drought risk. Good quality observations and long datasets are essential, but often unavailable. Based on the results, alternative data sources such as modeling and data generation can help, but uncertainties increase in the process, which need to be communicated to end-users.

The findings depict how Finland is affected by drought and how climate change will affect the drought risk (RQ2). The results portray south and southwestern parts of Finland as the most vulnerable areas to drought. These areas would benefit the most from the suggested drought mitigation measures. The results also indicate that climate change is likely to increase drought risks across most of Finland. However, more scenarios and models would be beneficial to better understand related uncertainties. Despite of such uncertainties, climate change adaptation measures are a necessity, particularly for sectors that are most impacted, such as agriculture. The findings indicate that the often used wet-getting-wetter and dry getting-dryer -paradigm related to climate change impacts is too simplistic.

Drought is a complex phenomenon and as such, systematic ways to address it are needed. Water security is a holistic concept with a clear aim, which can help water governance and drought management practices to be more efficient and structured. Water security is by design also linked to other securities such as food and energy security, which are also essential dimensions in drought management. Water security can therefore offer a valuable perspective and framework for drought management efforts. Other frameworks, such as the IPCC climate risk framework and the Integrated Drought Management framework, are also useful, as they support a more coordinated and holistic approach to drought management.

Several steps need to be taken to improve drought management in Finland (RQ3) and to mitigate drought risks effectively. As the most important steps, this dissertation recommends the establishment of voluntary local DMPs and a national drought strategy, supported by drought early warning systems and a drought impact database. Such measures may help Finland lower its drought risk and strengthen its resilience against future drought events, safeguard its water resources, and ensure the long-term sustainability of its various sectors affected by drought.

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