Drought and Surface Water in Alberta: Policy Reviews

by

Fatma Celen

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in
Forest Biology and Management

Department of Renewable Resources
University of Alberta

Abstract

Drought has an adverse effect on ecosystems, communities, and economies globally, making it difficult to manage water resources. It is vital to comprehend the dynamics of drought and surface water extent in Alberta, Canada, where water resources are essential for maintaining ecosystem functions and various industries. The frequency and severity of drought occurrences are predicted to rise as climate change continues to alter weather patterns, highlighting the critical need to comprehend and successfully manage risks associated with drought.

In my thesis, I focus on the dynamics of drought and surface water in Alberta from 2020 to 2022, with particular attention to how drought affects surface water availability. The Vegetation Health Index (VHI), derived from Advanced Very High Resolution Radiometer satellite data, is used to examine patterns of drought, while the Visible Infrared Imaging Radiometer Suite (VIIRS) flood index, derived from Suomi-NPP/VIIRS imagery, is used to analyze patterns of surface water extent. The data suggests that there were mostly no notable drought conditions in 2020. In contrast, there was a severe drought, particularly extreme droughts in Redcliff, Seba Beach, and Alberta Beach in 2021. Southern Alberta was the region most affected by drought in this particular year. This was demonstrated by the reduced VHI value, which suggested significant stress on the vegetation health. Subsequently, conditions improved in 2022, with only Bondiss and Alberta Beach experiencing severe droughts, while some areas had mild or moderate drought. Therefore, the vegetation health showed signs of recovery based on the VHI results.

Analysis of surface water extent reveals that surface water extent generally showed a relatively constant trend over the research period despite some noticeable variations within the province. Compared to its northern areas, the surface water extent in southern Alberta was

comparatively less. Also, surface water availability decreased in western Alberta while increasing in southern Alberta.

Lastly, regression analysis is used to identify the relationship between VHI and surface water extent. This relationship can provide policymakers with a policy tool. They can anticipate regions that might see reduced surface water levels by monitoring the values of VHI through the analysis. This can be important for proactive drought management and water resource management.

Preface

This thesis contains original work done by Fatma Celen and has been written according to the guidelines for a thesis format of the Faculty of Graduate & Postdoctoral Studies at the University of Alberta. The concept and idea of this work originated from Fatma Celen, and her co-supervisors Drs. Bruno Wichmann and Nadir Erbilgin of the University of Alberta. The whole thesis is composed of a single chapter.

This dissertation is dedicated to my beloved family

Acknowledgement

Firstly, I would like to express my deepest gratitude to my supervisors, Drs. Nadir Erbilgin and Bruno Wichmann, for their pivotal role in my academic journey. Dr. Erbilgin, thank you for the opportunity to work in your lab, your unwavering support, and your willingness to make time for me even during your busiest moments. Your guidance was a constant presence, ensuring I never felt alone during my adventure in Canada. Dr. Wichmann, your encouragement, insightful guidance, and dedication to my thesis were invaluable. You always made sure I left your office feeling motivated. The data you provided significantly contributed to the success of my research. I am truly grateful to both of you for your unique contributions.

The author wishes to express sincere thanks to Erbilgin's lab members, especially Guncha Ishangulyyeva, Leah Crandall, and Ateeq Shah, for their invaluable support throughout my journey. Moreover, I am deeply thankful to my friends, Nursah Yakut and Tuba Yildirim, whose support has been a source of strength throughout my journey.

I express my profound gratitude to all my family members, my mom, my dad, my brother and my fiancé for their unconditional love, amiable attitude, moral support, always believing in me and praying for my success. Specifically, my mom, your support has been my rock. Your endless love and sacrifices have been the foundation of my achievements. This achievement is as much yours as it is mine, and I will always be indebted for your presence and guidance.

Lastly, I would like to express my deepest appreciation to the Ministry of National Education of the Republic of Turkey for providing me with the scholarship. Their support has been crucial in enabling me to pursue my degree, and I am extremely thankful for the chances they have given me.

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Abbreviation	Definition
AVHRR	Advanced Very High-Resolution Radiometer
BT	Brightness Temperature
ENSO	El Nino Southern Oscillation
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
TCI	Temperature Condition Index
VCI	Vegetation Condition Index
VHI	Vegetation Health Index
VIIRS	Visible Infrared Imaging Radiometer Suite

1. Introduction

Climate change has become the most pressing environmental concern we face today (Locke & Mackey, 2009). The world is becoming increasingly concerned about it, which is primarily the result of human activity. Natural variability or human action has been attributed to the earth's climate change throughout history (du Plessis, 2019). It can result in a range of possible consequences for the environment, society, and economy (Gahlawat & Lakra, 2020). In particular, the economy, the ecology, and human health are all seriously threatened by drought (Ha et al., 2022). While droughts naturally happen, climate change has usually accelerated hydrological processes to cause them to occur more frequently and intensely, with numerous adverse effects (Mukherjee et al., 2018). It is possibly the least predictable of all atmospheric risks, emerging most slowly and lasting the longest among extreme phenomena (Mishra & Singh, 2010).

Drought poses a significant challenge to the agricultural heartlands of the Canadian Prairies, the three prairie provinces of Alberta, Saskatchewan, and Manitoba. The prairie economy is now facing a growing vulnerability exacerbated by the escalating severity of drought events (Bonsal & Regier, 2007). The agricultural sector has significant influence on the prairie economy. But the Canadian Prairies also rely on other sectors that are affected by drought, such as mining, oil, and gas, and energy production. This situation underscores the urgent need to explore the regional vulnerabilities specific to drought in Alberta.

This thesis provides a comprehensive investigation aimed at unravelling the complex dynamics of drought patterns within Alberta. By studying drought dynamics, my goal is to equip stakeholders with insights that can inform decision-making and proactive approaches to mitigate the adverse effects of drought. In doing so, I strive to contribute to the resilience and sustainability of the agricultural sector in Alberta. As I investigate, we acknowledge the multifaceted nature of drought and its far-reaching implications. From agricultural productivity to water resource management and beyond, the ramifications of drought extend across various sectors, underscoring the urgency of our inquiry.

This study delves into the analysis of agricultural drought in Alberta utilizing the Vegetation Health Index (VHI), which is a satellite data, for the summer months of 2020, 2021, and 2022. Among these years, the drought of 2021 was the worst in Alberta more than 60 years (Logie, 2023). By analyzing the extreme drought occurrence of 2021 in conjunction with the years preceding and following it, the study attempts to clarify drought dynamics over a multi-year timeframe. By scrutinizing the VHI data, a comprehensive knowledge of the dynamics of drought during the research period was attained, allowing for the precise identification of temporal and spatial patterns of drought across the region.

The need for water has grown significantly due to population growth and the development of the different sectors including agriculture, and different industries that depend on water. In many regions of the world, water scarcity occurs almost every year. Several factors, including climate change have exacerbated the shortage of water. Planning and managing water resources requires taking droughts into consideration (Mishra & Singh, 2010).

This study assessed surface water extent in Alberta for the summer months of 2020, 2021, and 2022 with the help of the flood index, which is a satellite-derived data. Changes in the surface water over time are determined, and transitions of decreasing or increasing surface water extent were observed. Lastly, the focus shifts towards elucidating the relationships between drought and surface water extent through regression analysis. By comprehending this relationship policymakers can improve their ability to anticipate and deal with water scarcity-related situations understanding. They can proactively address potential difficulties before they arise by monitoring places with restricted water availability based on VHI findings. To lessen the effects of water shortage, they can adopt timely interventions and adaptable solutions thanks to this proactive strategy, which encourages the development of more successful water resource management techniques.

2. Background: Exploring Drought Policies and Water Resource Management in Alberta

2.1 Alberta Water System

According to the Water Act of 2000, the Crown owns all of the province's water as well as the right to divert and utilize it. This implies that using water requires the provincial government's approval (Lambert, 2024). The Water Act, a piece of legislation, encourages and supports water management and conservation in Alberta. By enacting this legislation, the Alberta government commits to preserve current water rights and water supplies for future generations. The Water Act includes several methods to control water consumption from surface and groundwater sources, such as licensing, registration requirements for traditional agricultural uses, and statutory rights for residential usage (Government of Alberta, 2024d).

The government has water conservation objectives, which are about preserving natural water bodies and their aquatic habitats. These goals cover the amount and quality of water that should stay in rivers to protect a natural body of water and its aquatic ecosystem. These flow targets, which are applicable to all new licenses and current licenses with a retrofit provision, are governed by the first-in-time, first-in-right priority water allocation system (Government of Alberta, 2024e).

There are tens of thousands of surface and groundwater licenses in Alberta. Almost everyone who takes or diverts water in any significant amount, including oil firms, golf courses, municipalities, and farms, requires a license to do so (Lambert, 2024). Nevertheless, droughts cause water shortages for licensed water users in addition to affecting municipal and industrial water supplies, lakes, rivers, and reservoirs. The Water Act regulates the distribution of water and the shortage of it (Agriculture and Forestry, 2016).

2.2 Drought and Water Policies

Alberta, a province with a variety of ecosystems, from plains to boreal forests, faces a daunting task of reducing the effects of drought on its water resources in the face of growing climate change. Water resource management has significant challenges when there is a drought. The increased occurrence of extreme weather events and the diversity of precipitation patterns make water supplies more susceptible to drought conditions.

Unlike other natural disasters with direct and quick effects, drought can have indirect effects that extend over extended periods and large regions, making it more challenging to prepare for or respond to effectively (Wheaton et al., 2008). As with other natural disturbances, planning and preparation can lessen the effects of droughts (Loucks & van Beek, 2017). Though it is difficult to define when a drought exists, it is often more difficult to determine what constitutes an appropriate response to the drought. Making decisions at several levels is necessary to decide how best to respond to a drought. Private companies and the local, provincial, and federal governments may each have some influence on the planning and decision-making process (Wright et al., 1986). Various plans, strategies, and policies have been developed to address the drought, primarily emphasizing water conservation and management.

The majority of the water in Alberta comes from rain and snowmelt. The government of Alberta uses a network of water and snowpack monitoring stations to keep a close eye on the province's snowpack, rainfall, river levels, and water use. Alberta government is collaborating closely with all the partners, water users, and communities to take decisive action in anticipation of the coming drought. This includes taking practical, collaborative actions to manage and conserve water now and in the future, as well as to be ready for any shortages (Government of Alberta, 2024g).

The government of Alberta implements various strategies to properly manage water resources, guarantee sustainable utilization, and overcome the obstacles caused by the shortage of water. Some of these are as follows:

Alberta's Agriculture Drought and Excess Moisture Risk Management Plan

Agriculture Drought Risk Management Plan was published by the Government of Alberta in 2001. The Drought Action Plan advocates for a coordinated, scientifically grounded strategy for mitigating the consequences of Alberta's drought. It was updated in 2010 to cover drought response, monitoring, and reporting as the primary strategies. The management plan recognizes Alberta's recurrent drought event as a phenomenon. Since this time, science has advanced, and the knowledge of climate change evolving agricultural practices have led to its reissue (Government of Alberta, 2010a).

The Agriculture Drought and Excess Moisture Risk Management Plan, as it is revised, continues to offer a framework for a proactive, coordinated strategy to lessen the immediate and long-term impacts of excess moisture and drought on ranchers and farmers in Alberta. In addition to helping the agriculture sector to become better prepared and less susceptible to moisture extremes, it will direct government agencies in assisting producers to minimize the effects before, during, and after an adverse occurrence (Agriculture and Forestry, 2016).

Water for Life

The Alberta Government developed a Water for Life policy in 2003, which focused on issues related to water quantity, quality, and conservation. The policy examines how these factors have affected the province's water needs and looks at practical strategies to guarantee water supply for future generations. This policy introduces three primary objectives: secure and safe drinking water, healthy aquatic habitats, and reliable, high-quality water sources for a sustainable economy (Government of Alberta, 2003). In 2008, the government renewed the strategy; with this renewed strategy, the Alberta government is reaffirming its commitment to the Water for Life approach for the careful administration of the province's water quantity and quality for the benefit of Albertans both now and in the future, in addition to building on the excellent work already done (Government of Alberta, 2008). The two main focuses of the updated strategy were accelerating the actions and protecting the water supplies (Government of Alberta, 2009).

Three categories of partnership are identified in the Water for Life strategy. Each of them concentrates on involvement on a distinct geographic scale:

- Alberta Water Council is the level at which the province,
- Watershed Planning and Advisory Councils are the watershed scale in Alberta,
- Watershed Stewardship Groups are at the local level (Government of Alberta, 2024f).

While the government of Alberta is still in charge of managing water and watershed management and putting the Water for Life strategy into action, it also takes part as a partner in the Watershed Planning and Advisory Council and the Alberta Water Council (Government of Alberta, 2024f).

Watershed Resiliency and Restoration Program

The goal of the Watershed Resiliency and Restoration Program is to use natural watershed mitigation techniques to lessen the frequency, severity, length, and effects of floods and droughts (Government of Alberta, 2022). Severe flooding occurred in different areas in southern Alberta in 2013. In response to this disaster, the Alberta government launched many financial initiatives to support various recovery efforts. The province proceeded with initiatives to increase community resistance to these disasters in 2014. With restoration, conservation, education, stewardship, research, and data, Alberta Environment and Parks' Watershed Resiliency and Restoration Program seeks to enhance natural watershed functions to increase long-term resilience to droughts and floods (Government of Alberta, 2017).

Alberta Community Resilience Program

The Alberta Community Resilience Program, launched in the wake of the devastating 2013 floods, provides communities with the tools they need to respond to the current challenges by protecting essential infrastructure and promoting adaptability to more extreme weather occurrences. As a result, the province's overall disaster liability and vulnerability will decrease (Government of Alberta, 2019). The Alberta Community Resilience Program is a multi-year grant program that promotes integrated planning, healthy, functioning watersheds, and the building of long-term resilience to flood and drought disasters. The plan offers funding for initiatives that preserve essential facilities from drought and flooding (Government of Alberta, 2015)

Building Resiliency to Multi-Year Drought Project

The Alberta Water Council board approved it in March 2018. As part of the project, resources, and information on multi-year drought management in Alberta were compiled, making easier to deliver information obtained from small urban and rural municipalities to support the communities before, during, and after a drought. This project also supports Watershed Planning and Advisory Councils to effectively prepare, mitigate, respond to, and recover from multi-year droughts by including communities and municipalities (Alberta Water Council, 2021).

There are four modules in the Building Resiliency to Multi-Year Drought Guide. A summary of the multi-year drought in Alberta, definitions, roles and responsibilities, and management goals, approaches, resources, and tools are all covered in detail in each session (Alberta Water Council, 2020).

Improving Drought Resilience in Alberta Through Simulation

Drought is a natural occurrence that can have highly detrimental effects. To minimize the effects and respond appropriately, managing a drought necessitates extensive monitoring, decision-making, and communication before, during, and after the drought. However, these are frequently challenging to prepare fully in advance of a drought. Simulation exercises are a useful tool to assess management structure and communication techniques, as they offer an opportunity to go through a scenario that closely resembles an actual event (Alberta Water Council, 2024).

2.3 Policy Summary

The main findings from the policy analysis are provided in this section, with a thorough identification and categorization of all the plans, strategies, and policies related to drought preparedness and water management that were part of the policy analysis process. These policies included actions to guarantee sustainable management of water resources, encourage water conservation and efficient use, lessen the impact of drought, and strengthen community resilience to floods and droughts. They were categorized based on their publication year, objectives, and primary focus areas (**Table 1**).

Table 1. Classification of plans, policies and strategies related to water and drought in Alberta

Publication Year	**Plans, Policies, Strategies**	**Objectives**	**Focus areas**
2001	Alberta's Agriculture Drought and Excess Moisture Risk Management Plan (The Agriculture Drought and Excess Moisture Risk Management Plan)	Mitigating the impacts of drought and excessive moisture on ranchers and farmers in Alberta in the short and long term, Preparation, observation, documentation, and response to severe weather occurrences, Interacting with the agricultural sector.	Drought and Excess Moisture Effects Mitigation
2003	Water for Life	Safe and secure source of drinking water, Healthy aquatic environments, Reliable, high-quality water sources to support a sustainable economy.	Water Conservation/ Reliable Water Supplies

2014	Watershed Resiliency and Restoration Program	Reducing the occurrence, intensity, duration, and consequences of floods and droughts	Flood and Drought Effects Mitigation
2015	Alberta Community Resilience Program	Encouraging long-term resilience planning in Alberta so communities can be empowered to reduce risks and protect vital infrastructure from drought and flooding to promote public safety.	Resilience Planning
2018	Building Resiliency to Multi-Year Drought Project	Providing thorough information and guidance on water management roles and actions for municipalities facing climate change and drought, while emphasizing the significance of multi-year drought management in Alberta.	Drought Effects Mitigation
2020	Improving Drought Resilience in Alberta Through Simulation	Gathering, incorporating, and distributing detailed data, modeling outcomes, and suggestions for drought control to all relevant stakeholders in Alberta and other jurisdictions.	Resilience Planning

A review of drought management and water conservation measures indicates that governments have taken multiple approaches to minimize the effects of drought and water shortages. Implementing detailed management strategies to direct actions during drought events and water shortage is essential. These plans generally involve concerted efforts by communities, government agencies, and stakeholders to monitor drought conditions, evaluate water availability, and put adaptive measures in place to protect water resources. Financial assistance methods are necessary to assist in drought recovery efforts and encourage resilience in affected areas. Additionally, ensuring the sustainability and resilience of water systems during periods of drought requires policies that tackle the management of water quantity and quality. Drought simulation exercises can be useful for enhancing capabilities for drought event reaction and preparedness.

3. Measuring Drought in Alberta

Drought is one of the most devastating disasters in human history, with numerous severe consequences, despite the advancements in science and technology (Zhang et al., 2019). It has a complex evolving character with various degrees of intensity, frequency, spatial extent, and outcomes, and it can occur in almost all climatic zones (Ha et al., 2022). It is also a significant natural hazard that annually affects millions of people and large regions (Hesham et al., 2013; Wilhite, 2000).

Drought is among the most complicated and least understood natural phenomena since it has several contributing elements and underlying causes at various temporal and spatial scales (Kiem et al., 2016). The effects of drought are predicted to worsen with climate change (Miralles et al., 2019; Teuling, 2018) , rapid population increase, rising water consumption, and restricted water supplies (Fontaine & Steinemann, 2009). Alberta has seen the biggest net gain in interprovincial migration recently (Government of Alberta, 2024b), which has increased the demand for already scarce water resources and worsened the issues faced by drought.

The Canadian Prairies are prone to droughts; in the last 200 years, there have been over 40 significant droughts (Environment Canada, 2004). Prairie droughts typically do not result in catastrophic injury or death. Still, they have had terrible effects on the socioeconomic and environmental circumstances in the provinces as well as Canada's grain sector (Khandekar, 2004).

Despite the various negative impacts of droughts, the term "drought" does not have a universal definition (Hao et al., 2015) and also the definition of "drought" varies depending on the context and the location. In this study, drought will be considered a prolonged period (months or years) in which precipitation is below average and causes a shortage of water (Cunha et al., 2019).

Drought is often categorized into four types: Meteorological, agricultural, hydrological, and social-economic (Dracup et al., 1980). Any drought typically begins with a lack of precipitation (meteorological drought). If it persists for a longer time, it can also cause streamflow issues (hydrological drought) and soil moisture depletion, which is referred to as agricultural drought (Van Loon, 2015). A socio-economic drought happens when there is a weather-related shortage in water supply, which causes demand for an economic good (water) exceeds supply (Mishra & Singh, 2010). Lastly, ecological drought is a recently created term that incorporates the ecological, climatic, hydrological, economic, and cultural aspects of drought. It is described as an episodic shortage of water that pushes ecosystems over their thresholds of susceptibility, affects ecosystem services, and sets off feedback loops in human and natural system (Crausbay et al., 2017).

Various operational and research drought monitoring models have been created in recent years. However, due to the intricate processes involved in the beginning and development of droughts, drought warning and prediction systems remain the least developed among other natural disasters (UNEP, 2012). Droughts can occur over short or long periods (a few weeks to decades) and cover different areas (a few kilometers to entire regions). Their effects typically take time to manifest, are frequently indirect, and might continue long after the drought ends. Thus, drought risk often goes unnoticed and remains a "hidden" hazard (Pendergrass et al., 2020; UNDRR, 2019). It does not have a single, "straightforward" form. Depending on variables, including the impacted area, length, severity, and society's capacity to adjust to water scarcity, each drought presents differently. Therefore, while the overall characteristics of a drought often resemble each other, the specific characteristics differ from one drought to the next and change during a single drought (Bonsal et al., 2011; Evans et al., 2011)

Drought indices are widely used for drought evaluation, primarily to determine drought characteristics, i.e. their length, intensity, and areal extent (Hesham et al., 2013). Although over a hundred drought indices have been created thus far, no single drought measure can adequately capture the complex and multifaceted characteristics of drought (Sandholt et al., 2002), and their suitability also varies depending on the conditions and the area. For instance, the Palmer Index was created especially for dry, sub humid and semiarid regions; it does not account for the surface water contributions made by snowmelt, but the important thing is that snowmelt is common in Alberta (Shen et al., 2003).

Over the past few decades, many drought indices have been used remote sensing data (Hao et al., 2015), offering valuable insights into droughts' temporal and spatial distribution (Du et al., 2013). Satellite data is a straightforward, rapid, and affordable tool to observe drought on a regional scale (Domenikiotis et al., 2004). A widely used drought index developed from remote sensing is the Vegetable Health Index or VHI. The effectiveness of satellite-based vegetation health indices (VHI) over other drought indices makes them a popular tool for monitoring drought and evaluating vegetation growth, particularly in areas with limited water resources (Jiang et al., 2021).

The VHI combines the two other drought indices, the Temperature Condition Index (TCI) and the Vegetation Condition Index (VCI) (Hesham et al., 2013; Wang et al., 2014). A study evaluating the vegetation health index, vegetation condition index, and temperature condition index separately shows that these indices can be utilized to predict the drought four to eight weeks ahead of time. Given that TCI and VHI have a significantly positive correlation, it may be able to determine when the drought began based on TCI's decline (Jiang et al., 2021). The VHI's capacity to identify droughts early can be seen as an additional benefit.

My objective is to examine patterns of drought severity spatially and temporally, focusing on yearly comparisons to identify notable variations. Understanding the drought pattern has become crucial for managing water resources and developing policies related to drought in Alberta.

3.1 Study Area

Alberta, one of the most extensive and varied provinces in Canada, serves as the study area for this research. Stretching over 1220 km from north to south, its area of roughly 662950 km^2 shares borders with the Northwest Territories at 60°N and Montana at 49°N. The western boundary stretches northward around 120°W, with British Columbia to the west, after following the top of the Rocky Mountains along the Continental Divide to roughly 54°N. Saskatchewan's eastern boundary is located at 110°W (Environment Canada, 2020).

The Canadian Prairies, including Alberta, have a semi-arid climate, partly due to the region's location in the rain shadow of the Canadian Rockies. The windward side of the Rocky Mountains has orographic precipitation due to the mountains blocking the moist, westerly winds from the Pacific Ocean. Nonetheless, Alberta, situated on the leeward side of the Canadian Rocky Mountains, remains relatively moist, with an average yearly precipitation of 600 mm or more (Mwale et al., 2009).

Overall, the Canadian prairies are known for their highly variable precipitation both geographically and temporally, a characteristic known as non-stationarity, which can occasionally result in endemic droughts (Mwale et al., 2009; Nkemdirim & Weber, 1999). The precipitation in northern Alberta varies from approximately 400 mm in the northeast to over 500 mm in the northwest. In contrast, in southern Alberta, it varies from less than 350 mm in the southeast to approximately 450 mm (Mwale et al., 2009). The Rocky Mountains are influenced by changes in the Pacific Ocean's Sea surface temperature, which in turn generate precipitation variability. These variations are frequently caused by large-scale climate anomalies such as El Nino Southern Oscillation (ENSO) (Nkemdirim & Weber, 1999).

3.2 Data

Remote sensing data have recently been utilized to create drought indices (Gouveia et al., 2017; Kogan, 1997). Remotely sensed satellite data offers substantial benefits and is essential for monitoring drought, specifically its temporal and spatial dynamics (Quiring & Ganesh, 2010).

Several satellite drought monitoring indices are created using data from the Advanced Very High-Resolution Radiometer (AVHRR) of the NOAA (National Oceanic and Atmospheric Administration) polar-orbiting satellite series, MODIS (Moderate Resolution Imaging Spectroradiometer), and other satellites. These indices, which often use radiometric measurements of the state and dynamics of the vegetation, take advantage of the distinct spectral signatures of the canopy elements, especially in the red and near-infrared (NIR) regions of the spectrum (Huete et al., 2002). This study uses AVHRR satellite data to identify and monitor agricultural droughts in Alberta.

3.3 Vegetation Health Index

The VHI, one of the remotely sensed drought indices, is essential for determining agricultural drought because it considers thermal and vegetation conditions (Bhuiyan et al., 2006; Kogan, 1995a). VCI evaluates the vegetation state based on the Normalized Difference Vegetation Index (NDVI) (Bento et al., 2018). The basis for TCI is the AVHRR thermal band translated to brightness temperature (BT), and TCI is used to quantify the stress on vegetation brought on by excessive wetness and heat (Singh et al., 2003).

The NDVI obtained from NOAA/AVHRR has been widely used in crop yield evaluation and forecasting, and vegetation monitoring (Kogan, 1995a, 1995b). The contribution of geographical resources to the amount of vegetation is correlated with the fluctuation of NDVI values. This contribution varies greatly depending on a region's geography, vegetation, soil, and climate. High NDVI values may be found in tropical rainforest regions due to the abundance of tropical forest flora, but low NDVI values are typical in desert regions. The effects of the weather are not the cause of these differences (Domenikiotis et al., 2004). Weather and environment make up the NDVI. The combined area of the weather and ecosystem components is smaller in vegetated regions, so it is challenging to identify weather-related NDVI variations. Therefore, when using NDVI for weather influence on vegetation studies, the weather and ecosystem components must be kept apart. Estimating the effect of weather on vegetation has been done using the VCI (Kogan, 1995a), which is provided by the equation:

$$\mathrm{VCI} = 100\,\frac{\mathrm{NDVI} - \mathrm{NDVI_{min}}}{\mathrm{NDVI_{max}} - \mathrm{NDVI_{min}}}$$

where NDVI, NDVImax, and NDVImin represent the multi-year maximum NDVI, multi-year minimum NDVI, and smoothed weekly NDVI for each grid cell. The VCI ranges from zero for severely unfavourable circumstances to 100 for ideal circumstances (Kogan, 1997).

As the drought gets worse, the land surface will experience thermal stress. Therefore, a thermal stress indicator based on remote sensing, the TCI, is suggested to identify temperature-related drought phenomena (Kogan, 1995a).

The VCI and the TCI algorithms are similar. Likewise, years with favourable conditions tend to produce the greatest vegetation, whereas years with exceptionally unfavourable weather, which is mostly dry and hot, produce the least amount of vegetation. Therefore, extreme weather events (drought and no drought conditions) are contained in the absolute maximum and lowest BT (brightness temperature), estimated over several years. The maximum and minimum values produced can be used as standards to measure a region's environmental potential (Kogan, 1995a, 1997). The following equation represents:

$$\mathrm{TCI} = 100\ \frac{\mathrm{BT_{max}} - \mathrm{BT}}{\mathrm{BT_{max}} - \mathrm{BT_{min}}}$$

where BT, BTmax, and BTmin represent the weekly radiant temperature that has been smoothed and the multi-year maximum and minimum for each pixel in a specific location. Like the VCI, TCI values range from 0, which indicates highly unfavourable conditions, to 100, which indicates optimal circumstances; greater TCI values indicate healthy vegetation (Kogan, 2001).

The VCI and TCI are frequently estimated using the NDVI and BT, respectively. Usually, it is unknown what the ideal weights for TCI and VCI should be, so VHI is calculated by giving both components the exact weight of 0.5 (Hesham et al., 2013; Wang et al., 2014):

$$\mathrm{VHI} = 0.5\ (\mathrm{VCI} + \mathrm{TCI})$$

VHI has been widely used for early drought warning, crop yield and production monitoring, irrigated regions and excessive wetness evaluation, and vegetation cover and temperature anomalies (Karnieli et al., 2010; Seiler et al., 1998). According to (Kogan, 2001), the vegetation state of VHI is divided into five classes: severe, extreme, moderate, mild, and no drought (**Table 2**).

Table 2. The classification of drought based on the VHI (Kogan, 2001)

VHI Values	**Drought Classes**
<10	Extreme drought
<20	Severe drought
<30	Moderate drought
<40	Mild drought
>40	No drought

3.4 Spatial Analysis

This study uses publicly available satellite data from the National Oceanic and Atmospheric Administration (NOAA). Specifically, the data are part of the VIIRS program with observations characterized by Advanced Very High Resolution Radiometer (AVHRR) of polar-orbiting satellites. The format of the raw data is at the 4-kilometer geographical resolution.

Quantum Geographic Information System (QGIS) software was used for processing and analyzing the raw data and aggregate the information to Alberta census subdivisions. The VHI data and the Alberta census subdivision shapefiles were used to obtain the weekly average VHI values for each subdivision. The study concentrated on the summer months of June through August, which are crucial for vegetation development and drought monitoring. Three years of consecutive temporal and geographical aggregation were conducted to identify annual and spatial trends in drought conditions and vegetation health. This approach produced spatial maps with the summertime average VHI values for every subdivision and every year examined (2020-2022).

4. Identifying Surface Water Extent in Alberta

Surface water is defined as water that is present on the earth's surface. This includes any water that gathers on the ground or in a river, lake, or wetland. Rain and snowfall provide an annual "renewed" supply of this water, which is also naturally lost through evapotranspiration (plant moisture loss) and subsurface recharging into the groundwater (Government of Alberta, 2010b).

Surface water resources provide most of the water used by Alberta's industry and people. In addition to supporting business, agriculture, and leisure pursuits, this essential resource gives us access to clean drinking water. The aquatic ecosystem, our economy, and human health depend on a clean, plentiful supply of surface water (Government of Alberta, 2010b). The semi-arid Canadian Prairies are highly dependent on surface water supplies (Gan, 1998). Surface water resources, which are primarily supplied by snowpacks in the Rocky Mountains, provide for around 97% of Alberta's water allocations. Although it only has 5% of the province's population, the Oldman River basin in southern Alberta produces roughly 25% of all water allocations in the province (Dixon et al., 2014).

Although surface water is the subject of this study, groundwater plays a crucial role in the hydrological cycle that must be acknowledged. Particularly in dry spells, groundwater is an essential reserve that helps restore surface water resources including lakes, rivers, and wetlands. In times of low precipitation, it serves as a buffer, preserving surface water levels and ecological balance.

The geographical diversity of Alberta contributes to the fluctuation in water availability. Northern Alberta is characterized by abundant natural lakes and expansive rivers, whereas southern Alberta possesses fewer and smaller waterways. These disparities underscore the complexity of water management within the province, exacerbated further by environmental phenomena such as droughts, which can swiftly deplete water reserves and disrupt the delicate balance of water ecosystems. The northern region of the province provides 80% of the water supply, whereas the southern half of the province supplies 80% of the water demand (Government of Alberta, 2010b).

Alberta’s water resources face pressures from human activities such as urbanization, industrialization, and agricultural expansion (Ahopelto et al., 2019; Kummu et al., 2016). Water supplies may also be stressed by growing sectors like as mining and oil and gas extraction, which require water for industrial processes and wastewater production. For example, fracking is known for using a lot of water. It uses a modest amount of water compared to regional water demand, yet it can nevertheless put stress on already water-stressed areas and degrade aquifers (Hitaj et al., 2020). The fracking process can require billions of gallons of water, placing significant pressure on local water supplies and ecosystems (Freyman, 2014). In Alberta, a province with a thriving oil and gas industry, fracking is a major factor in extracting resources from underground reservoirs. This important function increases the demand for the area's water supplies.

Drought, a natural phenomenon, poses a significant challenge to water availability, reducing accessible water over extended periods, often months or even years (Ahopelto et al., 2019). Severe droughts that destroy water reserves can result in shortages, declining water quality, and even supply disruptions (Ding et al., 2011).

The ramifications of water scarcity and drought extend far beyond environmental concerns, impacting communities’ access to vital water resources for domestic, agricultural, industrial, and infrastructural needs. During droughts, communities may face stringent water use restrictions, soaring water prices, and even the depletion of essential water sources like wells, posing profound challenges to livelihoods and economic stability. Nevertheless, water shortage is expected to worsen due to population growth and rising living standards (Chen & Li, 2016; Lehner et al., 2006; Rosegrant et al., 2009).

Canadian farmers and rural residents need to have access to enough high-quality water for a range of purposes. Water is necessary for agriculture to function in different aspects such as industrial uses in the agricultural sector; cleaning and waste management; crop productivity and health; livestock production; agricultural chemicals and fertilization; industrial uses for food and non-food agricultural products; drinking water and quality of life (Corkal & Adkins, 2008). Agriculture, a cornerstone of Alberta's economy, can significantly impact water availability.

Monitoring surface water dynamics is essential for managing water resources, agriculture, predicting droughts, and climate change. It is now feasible to assess surface water dynamics spatially and temporally with the help of remote sensing satellite data (Dastour et al., 2022).

This study examines the surface water extent pattern in Alberta from 2020 to 2022 using VIIRS (Visible Infrared Imaging Radiometer Suite) data. My objective is to understand surface water coverage through satellite-based data.

4.1 Methods

In this study, I used data collected from satellites. Analyzing water extent patterns utilizing VIIRS imagery primarily relies on datasets derived from the Suomi-NPP/VIIRS instrument. Specifically, data from imager bands 1 (600~680 nm), 2 (850~880 nm), 3 (1580~1640 nm) and 5 (1050~1240 nm) are utilized, each offering a resolution of 375 x 375 meters pixels. These spectral channels, spanning the visible, near-infrared, and short-wave infrared ranges, provide crucial physical information essential for surface water identification.

The decision-tree technique integrates reflectance values from VIIRS imager channels with a suite of spectral indices. These indices are crafted based on established research methodologies, as documented in studies by (Li & Sun, 2021). The resulting information is the share of the pixel that is covered by water. The water index I use to examine surface water in Alberta is in percentage terms, i.e. can take values from 0 (no water in the pixel) to 100 (pixel is completely covered by water).

Harnessing the wealth of information provided by VIIRS data, I generate temporal and spatial insights into water extent across Alberta's subdivisions.

4.2 Spatial Analysis

The publicly available data were collected from VIIRS NOAA & GMU and consist of satellite-based information from Suomi-NPP/VIIRS imagery. The raw data has a resolution of 375 m and represents the surface water. As with vegetation analysis, Quantum Geographic Information System (QGIS) software was used to process and analyze spatial data and to produce annual maps. Again, the geocoded raw data is aggregated into spatial units corresponding to Alberta's subdivisions to enable regional analysis. The water data jointly with the Alberta census subdivisions shapefile allows us to obtain daily average surface water availability values for each subdivision. These units serve as localized zones for assessing water extent, offering a fine-grained perspective for understanding surface water dynamics at a local scale.

The study concentrated on the summer months of June through August, which, as discussed before, is a key period for vegetation and drought monitoring. The sampling period is again 2020-2022, which allows for identifying temporal and geographical trends in surface water availability.

This information is summarized in various maps that showed the dispersion of average summertime surface water extent.

5. Regression Analysis

This work tests the hypothesis that drought conditions influence surface water extent in Alberta during 2020-2022. A regression analysis was carried out to investigate the relationship between the vegetation health index (VHI), which is a widely used index for detecting, monitoring and evaluating the drought impact on vegetation health, and the availability of surface water resources. Because we are interested in understanding water fluctuations, the VHI is the independent variable and surface water availability is the dependent variable.

The following linear regression model was used to evaluate the association between VHI and surface water availability:

$$W_i = \beta_0 + \beta_1 VHI_i + \varepsilon_i$$

where W_i represents water availability reflecting the water extent in the census subdivision i (from 0-100), the VHI_i is the vegetation health index of census subdivision i representing the drought measure (from 0-100), β_0 and β_1 are coefficients for the intercept and slope, respectively, and ε is the error term. The regression uses observation weights based on the area of each census subdivision. To explore the period with the most variation, only data from 2021 was used. While we discuss statistically significant results from the analysis of the 2021 data, the analysis of the three years, or that of 2020 and 2022 individually, do not show statistically significant relationships between surface water and drought.

6. Results

6.1 Droughts

Droughts and water deficit impact ecosystems, economics, and livelihoods, posing serious difficulties by declining water availability, reducing agricultural productivities, negatively affecting different industries such as agriculture, oil and gas, tourism, energy sector. This thesis delves into the patterns of agricultural drought, changes in surface water extent, and the relationship between drought and surface water availability. The frequency and intensity of drought occurrences are expected to increase in Alberta because of the dry years and El Nino, which has exacerbated vulnerabilities and highlighted the urgent need for efficient mitigation and adaptation measures.

The VHI data for the summers of 2020, 2021, and 2022 in Alberta indicates different drought severity trends, with significant variations across the province over the years. **Figure 1** shows the VHI for Alberta's CSDs for the years of 2020-2022. The results are based on the VHI index for the summer of each year.

In 2020, my investigation found that Alberta experienced mostly no agricultural drought, with a few locations showing some stress on the health of the vegetation. Extreme and severe drought conditions were not recorded in 2020. Red Cliff was the only census subdivision (CSD) dealing with a moderate drought. Except for Red Cliff, four CSDs reported mild drought conditions and the remaining areas did not experience any drought conditions. These four census subdivisions are: Medicine Hat, Banff, Rainbow Lake, and Fox Creek.

Drought conditions mostly were not seen in northern Alberta in 2021, but in western Alberta in moderate and mild cases and some locations in southern Alberta in severe cases. I found that Redcliff, Seba Beach, and Alberta Beach CSDs experienced the extreme drought conditions.

Alberta Beach is notable among these places for having experienced the worst drought. Twenty CSDs have severe droughts with VHI between 10-20. These are the following: Medicine Hat, Barnwell, Duchess, Champion, Vulcan, Calgary, Didsbury, Innisfail, Sylvan Lake, Sunbreaker Cove, Rocky Mountain House, Mannville, Ma-Me-O Beach, Thorsby, Stony Plain, Bondiss, Banff, Valleyview, Wembley, Grande Prairie. Some of the CSDs experiencing moderate drought are: Edmonton, Cypress County, Newell County, Brooks, Acadia No.34, Special Area No.3, Special Area No.4, Vulcan County, Wheatland County, Red Deer County, Lacombe County, Brazeau County Parkland County, also some CSDs having mild drought include Warner County No. 5, Cardston County, Pincher Creek No. 9, Willow Creek No. 26, Provost No. 52, Stettler County No. 6, Ponoka County, Clearwater County, Minburn County No. 27.

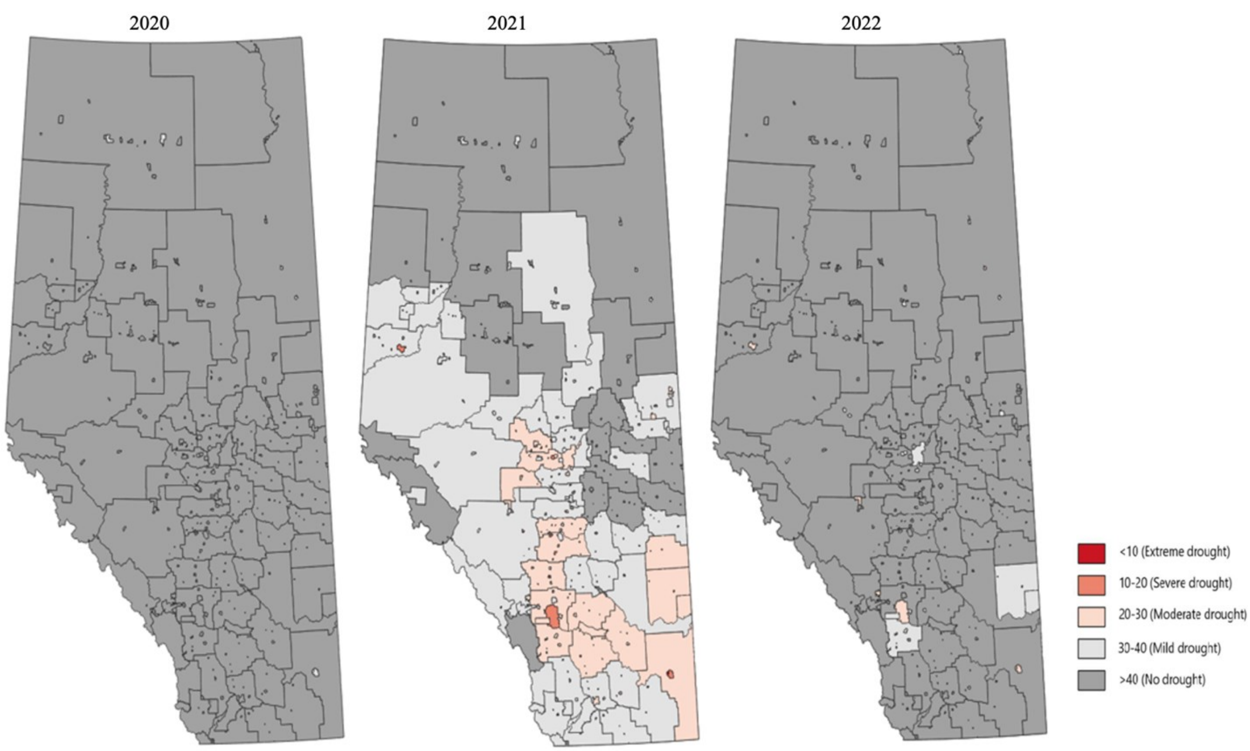

Figure 1. Temporal and spatial analysis of drought occurrences over the period

In 2022, Alberta had ideal agricultural conditions with no drought stress except for a few places. The vegetation looks healthier than in previous years, indicating better agricultural possibilities. Bondiss and Alberta Beach had severe drought conditions, with no census subdivisions of extreme drought in 2022. Additionally, I found that some CSDs had moderate drought. These are: Medicine Hat, Redcliff, Champion, Calgary, Sunbreaker Cove, Rocky Mountain House, Banff, Grande Prairie.

Regional differences are emphasized by the spatial distribution of drought intensity. Comparing these three-year periods of data highlights the considerable differences in the severity of the drought and how it affects the health of vegetation in Alberta. While there was mostly no drought in 2020 and 2022, there was more drought in 2021, particularly in southern Alberta.

By comprehending the spatial and temporal dynamics of drought severity, individuals and organizations may better predict and adapt to changing conditions. Effective water management may need an understanding of the dynamics of drought. Droughts can impact water availability (see section 6.3 Regression Estimates).

6.2 Surface Water Extent

The surface water extent data for Alberta's 2020, 2021, and 2022 summers indicate variations across the province. **Figure 2** shows the temporal and spatial data of surface water extents for Alberta’s CSDs in these years. The figure presents quantile classifications by dividing the data into equal-sized groups, with quantiles based on the aggregated data from all years. With this approach, we examine variability across time and space. Equal-sized groups ensure consistency and comparability in the analysis, making creating visualizations that maximize variance representation easier.

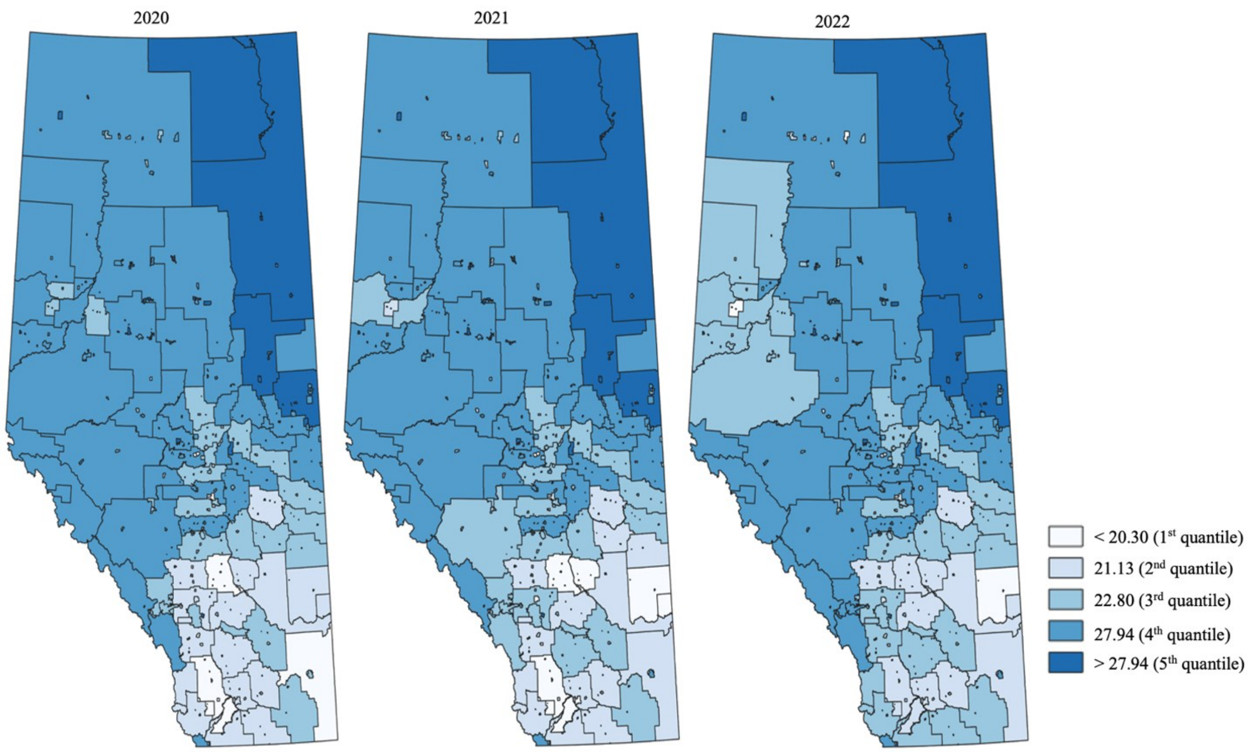

Figure 2. Temporal and spatial analysis of surface water extent over the period

A key outcome of the research is the development of a classification map elucidating the spatial distribution of surface water coverage. In this representation, lighter areas indicate relatively lower water levels, while darker regions signify higher water availability. The findings reveal a generally stable trend in surface water extent over the study period, although there are notable differences across different regions of the province.

In 2020, 22% of the CSDs fell into the first quantile, representing the lowest level of surface water extent. They include Redcliff, Barnwell, Champion, Stony Plain, Duchess, and Vulcan. 18% of the CSDs, for example, Thorsby, and Valleyview were in the second quantile. The third quantile included 20% of the CSDs, indicating moderate levels of surface water extent, such as Medicine Hat, Banff, Rocky Mountain House, Innisfail, Calgary, and Mannville. 20% of the CSDs were classified into the fourth quantile. Didsbury, Sylvan Lake, Wembley and Grande Prairie were some

CSDs that fell into this quantile. Lastly, 20% of the CSDs were in the fifth quantile, reflecting the highest levels of surface water extent, such as Alberta Beach, Sunbreaker Cove, Ma-Me-O Beach, Seba Beach, and Bondiss. This classification highlights the significant variations in surface water extent across different CSDs.

In 2021, the pattern of surface water extent changed as follow: 23% of the CSDs fell into the first quantile such as Redcliff, Barnwell, Champion, Stony Plain, and Duchess. The second quantile saw 17% of the CSDs. Some are Thorsby, Rocky Mountain House, Mannville, and Didsbury. The third, fourth, and fifth quantiles remained consistent at 20% of the CSDs. In the third quantile, notable CSDs such as Valleyview, Innisfail, and Calgary were represented. Medicine Hat, Banff, Sylvan Lake, Wembley and Grande Prairie were included in the fourth quantile. Finally, the fifth quantile consisted of Vulcan, Alberta Beach, Sunbreaker Cove, Ma-Me-O Beach, Seba Beach, and Bondiss,

In 2022, the first quantile saw a decrease in the surface water extent compared to previous years, with only 15% of the CSDs felling into this category. Barnwell, Champion, Duchess, and Vulcan were some of these CSDs. The second quantile, including such as Stony Plain, Thorsby, Alberta Beach, Redcliff, Didsbury, Calgary, and Mannville experienced an increase, comprising 26% of the CSDs. The third quantile included 21% of the CSDs and included Rocky Mountain House, Innisfail, and Grande Prairie. The distribution of the fourth and fifth quantiles, each at 19% of the CSDs, was recorded. Medicine Hat, Banff, Sylvan Lake, and Wembley were some CSDs felling into the fourth quantile. Sunberaker Cove, Ma-Me-O Beach, Seba Beach, Bondiss, and Valleyview were in the fifth quantile.

In all years, the two top quantiles were predominantly composed of subdivisions in Northern Alberta, whereas the lower quantiles were more common in Southern Alberta. From

2020 to 2022, Western Alberta moved down to a lower quantile in the distribution of surface water extent, while southern Alberta moved up to higher quantiles. Census subdivisions in the Northeast consistently rank in the top quantile.

6.3 Regression Estimates

The regression analysis of the 2021 VHI and surface water availability data revealed statistically significant relationship between the two variables. Surface water extent and the VHI are positively correlated, as illustrated by the indication that a linear regression analysis coefficient is greater than zero ($\beta_1>0$). I found a 0.24 percentage point decrease in water extent for every percentage point decrease in the VHI (**Table 3**). This suggests the following relationships: as drought conditions get worse, vegetative health declines and leads to a decline in surface water.

Table 3. Regression analysis of vegetation health index (VHI) on surface water extent

Water	**Coefficient**	**Std. Err.**	**t- value**	**P-value**	**95 % Conf. Interval**	
VHI	0.241705	0.016832	14.36	0.000	0.208610	0.2748011
Constant	14.78128	0.684737	21.59	0.000	13.43501	16.12755

The results can inform water management and policy development. The estimates in **Table *3*** indicate to the government the magnitude of the impact of droughts on water supply and as such may play a crucial role in shaping the policy decisions concerning water distribution, drought control, and conservation of the environment. Through targeted measures and early warning system development, policymakers may mitigate the detrimental impacts of drought periods by prioritizing initiatives and implementing these findings.

In summary, this thesis advances our knowledge of drought dynamics and the availability of surface water in Alberta. By describing the interactions between drought and surface water extent, this study provides important information for stakeholders, researchers, and policymakers responsible for managing water resources in drought-prone regions.

7. Conclusion

7.1 Discussion

Understanding the trends and dynamics of vegetation health index and surface water extent is important for making informed decisions on various factors, including incorporating regional vulnerabilities to drought and water deficit into existing policies or formulating new policies accordingly. The data on these variables are displayed in the tables below, providing information on their trends and variability throughout the given time frame.

Table 4. Vegetation health index (VHI) trends over three years

VHI	2020	2021	2022
N	389	389	389
Mean	63.706	36.080	50.470
Median	64.119	36.119	49.652
STDEV	12.641	11.625	12.612
Min	25.835	1.401	17.562
Max	97.243	86.452	87.525

There is a decline in the mean and median from 2020 to 2021, followed by an increase in 2022. This indicates a fluctuating pattern in drought over the three years under study. Based on the standard deviation, it indicates that the variability in VHI is relatively consistent across the three years, with slight fluctuations. The wide range between the minimum and maximum values suggests that drought varies from year to year, indicating that the state of vegetation health is not stable (**Table 4**).

Table 5 specifically highlighted census subdivisions with severe or extreme drought conditions in any year of the research period which was developed to provide a focused analysis of drought patterns across census subdivisions for 2020, 2021, and 2022. Researchers and decision-makers can use this knowledge to enhance the effectiveness of drought management and resilience-building approaches by allocating resources and interventions to regions susceptible to severe or extreme drought conditions.

Given that Redcliff has had a drought for the past three years, **Table *5*** may suggest that this area is prone to continuous drought. Vulcan, Didsbury, Manville, Wembley did not experience drought in 2020, extreme drought in 2021 and no drought again in 2022; this shows a variable sensitivity to drought events over time. However, this does not imply there was no issue in 2022 for these CSDs. The fact that there was no severe drought in the years that followed does not lessen the importance of the severe drought that occurred in 2021. CSDs may not suffer a severe drought in later years, but the consequences of the severe drought might still be felt. Consequently, even though specific observations could differ from year to year, this knowledge can help examine the general pattern of drought consequences and formulating plans to strengthen community resilience in the face of climate variability.

Table 5. Drought patterns with severe or extreme drought

Dissemination Geography Unique Identifier (DGUID)	Census Subdivision (CSD)	2020	2021	2022
4813012	Alberta Beach	No drought	Extreme	Severe
4815035	Banff	Mild	Severe	Moderate
4802023	Barnwell	No drought	Severe	Mild
4813053	Bondiss	No drought	Severe	Severe
4806016	Calgary	No drought	Severe	Moderate
4805004	Champion	No drought	Severe	Moderate
4806032	Didsbury	No drought	Severe	No drought
4802036	Duchess	No drought	Severe	Mild
4819012	Grande Prairie	No drought	Severe	Moderate
4808008	Innisfail	No drought	Severe	Mild
4811008	Ma-Me-O Beach	No drought	Severe	Mild
4810034	Mannville	No drought	Severe	No drought
4801006	Medicine Hat	Mild	Severe	Moderate
4801018	Redcliff	Moderate	Extreme	Moderate
4809015	Rocky Mountain House	No drought	Severe	Moderate
4811038	Seba Beach	No drought	Extreme	Moderate
4811048	Stony Plain	No drought	Severe	Mild
4808027	Sunbreaker Cove	No drought	Severe	Moderate
4808012	Sylvan Lake	No drought	Severe	Mild
4811021	Thorsby	No drought	Severe	Mild
4818018	Valleyview	No drought	Severe	Mild
4805006	Vulcan	No drought	Severe	No drought
4819011	Wembley	No drought	Severe	No drought

Error! Reference source not found. shows very slight variations in the mean and median s urface water extents over the three years. The average values of surface water extents exhibit overall stability despite minor fluctuations that typically stay within a small range. The standard deviation values vary over time but always remain within a close range, indicating gradual rather than significant shifts in the variability of surface water extents. However, there are variations in the minimum and maximum values throughout the years, showing variations in the availability of surface water each year.

Table 6. Surface water extent trends over three years

Water	2020	2021	2022
N	423	423	423
Mean	27.382	27.802	27.186
Median	22.012	21.912	21.887
STDEV	13.833	15.064	14.219
Min	18.734	19.120	19.210
Max	86.525	99.666	82.468

The variations observed in surface water patterns can be attributed to a multitude of factors, including regional characteristics, climatic variability, and human activities. While most of Alberta's population and water demands are in the southern half of the province, the majority of the province's water is found in its northern half. Furthermore, the water consumption for agricultural and animal use is greater in the Southern Alberta, relative to Northern Alberta. Finally, Southern Alberta typically receives less precipitation than Northern Alberta. All these factors can contribute to the drought conditions in the Southern Alberta.

Water issues become evident that proactive water management strategies, informed by interdisciplinary research and community engagement, are imperative to ensure the sustainable utilization of water resources in Alberta and beyond. This necessitates the adoption of innovative technologies for water conservation, the implementation of policies promoting water efficiency, and the establishment of collaborative governance frameworks that integrate the needs of diverse stakeholders while safeguarding the integrity of ecosystems. Only through concerted efforts can the government, non-governmental organizations, and Albertans address the challenges of water deficit and ensure the resilience and well-being of present and future generations.

It has been argued in the literature that the VHI can warn decision-makers early, assisting them in putting preventive measures in place before drought occurrences (Jiang et al., 2021). In addition to using the VHI, my research offers new insights about droughts in Alberta. The regression analysis investigation of the relationship between the VHI and surface water extent shows that variations in drought conditions can be indicative of changes in surface water availability. The slope (0.24) represents the rate of change in surface water availability for a given change in the VHI (**Table 3**). For every percentage point decrease in the VHI, there is a corresponding decrease of 0.24 percentage points in water extent. By quantifying this relationship, we can predict the extent of the correlation between drought conditions and surface water. This relationship can help policymakers with early detection of water shortage. Early action may be taken to manage water resources in the areas where water shortage is detected. This finding will help policymakers identify patterns of declining water availability in targeted regions, enabling them to detect drought early and recognize the impacts of drought on water. Policymakers can more efficiently direct their attention and resources toward regions facing reduced water supply by comprehending the relationship between VHI declines and water shortage.

7.2 Recent Policy Developments

As discussed above, the Water Act of Alberta is a prior allocation act that grants competing water users precedence based on first in time. The Act does not prioritize uses according to their intended use (e.g. municipal uses over irrigation uses). Large volumes and senior permits on some of the most significant streams and rivers in southern Alberta, such as the Bow, Oldman, St. Mary, Belly, and Waterton, are held by only a few of Alberta's irrigation districts. While there is usually enough water to accommodate all licensed users (even though not enough to guarantee the health of aquatic ecosystems in all places through adequate instream flows), in drought years, the shortage of water implies that the actual water availability is below the maximum water consumption volume granted by their water licenses. Even during droughts, the Water Act permits senior license holders to freely allocate their water allowances and discontinue the water availability of other license holders. However, in recent years, senior license holders have supported to "share the shortage," a system in which each participating licensee accepts a corresponding reduction in their allocations, rather than asserting their entire legal entitlement (Bankes, 2024).

The "Drought Command Team" was formed by the Minister of Environment and Protected Areas, who gathered the major water license holders to negotiate water sharing agreements. In addition, the Alberta government created a new Water Advisory Committee to provide recommendations on handling an upcoming drought and hired consultants, WaterSMART Solutions, to lead the talks about water sharing and participate in modeling exercises (Bankes, 2024).

The Alberta government and owners of water licenses have been working together to create voluntary water-sharing agreements. Ensuring everyone has access to water is the goal of water-sharing agreements (RMA, 2024). Water levels are monitored bi-weekly and, based on this information, the agreements are activated when and where necessary.

The agreements have been signed by municipalities, irrigation districts, and industrial participants regarding four sub-basins: the Red Deer River, the Bow River, the Oldman River mainstem, and the upper tributaries of the Oldman River (King, 2024). The sub-basins are a component of the broader South Saskatchewan River Basin, which supplies water to Red Deer, Calgary, Lethbridge, Medicine Hat, and other major cities in Alberta. The river basin spans the boundary between Saskatchewan and Alberta (Dryden & Turner, 2024). If drought circumstances continue, 38 of the largest and oldest water license holders in these basins have voluntarily committed to reducing their water usage. Recognizing that water used for human consumption is the most important use, municipalities have committed to reducing their usage by 5 to 10% (RMA, 2024). These municipalities are Calgary City, Lethbridge City, Medicine Hat City, Lethbridge County, Red Deer City, County of Red Deer, Drumheller town, Town of Stettler, Warner County (Dryden & Turner, 2024).

These agreements have been designed to be proactive, risk-aware, and flexible enough to be modified quickly when situations change (Government of Alberta, 2024c). Every two weeks, the agreements' actual water amounts will be revised by the most recent water supply prediction. Advanced and extremely sophisticated drought modeling was carried out by WaterSMART Solutions, which produced a range of hypothetical river flow scenarios and conditions. To ensure that water use doesn't exceed supply, the precise amount of water used for the next two weeks will be modified as necessary based on this information and the state of the environment (Government of Alberta, 2024c).

A report released on May 2024 by the Government of Alberta states that water levels in certain reservoirs located in southern Alberta are significantly lower than average for this season. Based on the bi-weekly observation, the agreements for the Oldman South Saskatchewan River basin and its southern tributaries have been activated. No activation of the agreements had occurred for the Red Deer River basin or the Bow River basin (Wichers, 2024).

Alberta also has a 2024 Drought Response plan. This strategy will assist in directing the province through all drought circumstances. This strategy addresses everything from water-sharing agreements and conservation plans to announcing an emergency and giving water the highest priority for the health and safety of people. This initiative aims to provide communities, businesses, farmers, ranchers, and Albertans with the necessary support (Government of Alberta, 2024a).

The plan has a five-stage drought response strategy. The plan's goals are to: protect Albertans' health and safety from the effects of the drought; reduce the effects of the drought on the province's communities, economy, and environment; implement a proactive, risk-based approach to quickly assess, prepare for, and respond to the effects of a drought. Additionally, the plan aims to ensure that responses to drought conditions are flexible and adjusted in real-time as information changes, empowering all Albertans to take appropriate action, conserve water, and cooperate (Gibson, 2024).

Currently, Alberta is in Stage 4 of the drought response plan. The government is currently collaborating with large water users to make use of all available regulatory and non-regulatory measures. There are a few examples of plans for responding to water shortages, quick approvals for temporary water diversion from new sources, and water-sharing agreements (Government of Alberta, 2024a).

7.3 Limitations and Future Research

There are numerous other methods and indices for evaluating drought conditions, even if the focus of this thesis is on using the Vegetation Health Index (VHI) as a measure of drought. Although the VHI is a useful tool for evaluating drought circumstances, it is important to understand that evaluating drought conditions can be complicated and may require taking into account several different indices. It would be helpful to investigate how the VHI can be integrated with other drought indices to provide a more comprehensive picture of drought conditions. Some studies highlight the significance of combining several indexes (Alahacoon et al., 2021; Han et al., 2020; Nam et al., 2015).

While surface water extents are the focus of this theory, it's crucial to recognize that drought affects a broader range of hydrological phenomena than only surface water. Groundwater, for example, was not the focus of my investigation. Although surface water extent offers important information on water availability, groundwater analysis in my study is a crucial part of managing water resources. A study conducted in the western United States shows that interactions between surface water and groundwater have a significant impact on water management in the semi-arid region (Helmus et al., 2009). Another study shows that groundwater acts as a natural buffer against climate change, including drought because it reacts to weather conditions far more slowly than surface water (Macdonald et al., 2012). The complexity of managing water resources is highlighted by the interdependence of surface water and groundwater during drought conditions (Thatch et al., 2020). Therefore, it may be crucial to comprehend this relationship for water management. Also, it is still uncertain if variations in groundwater levels are responsible for the observed patterns of drought, which were especially noticeable during the severe drought of 2021. The lack of groundwater data is a drawback of this research, as it could potentially impact the comprehension of water availability and drought events in the studied region by influencing groundwater dynamics.

One of the significant limitations of my thesis is the temporal scope, which only covers the period from 2020 to 2022. Although there was a severe drought in 2021, the differences in surface water extent were not observed. This may indicate a possible lag effect, whereby the impacts of drought on water resources can appear later. The three-year duration of this study may not be sufficient to adequately capture these lagged effects.

The combination of satellite and ground data can greatly enhance future research on drought monitoring. The limits of in situ monitoring are mitigated by satellite data, which provides a wide range of relevant metrics at high spatial and temporal resolution (Rassl et al., 2022). The study demonstrates the significant potential for integrated analysis of satellite and ground-measured data in drought monitoring (Jain et al., 2010). While satellite data by itself may provide insightful information, combining it with other data sources and ground-based observations can greatly improve drought monitoring.

Future studies could examine variables that influence surface water extent variations, such as changes in land cover, precipitation patterns and human activities. Some studies have focused on what affects surface water and consequently emphasized human activities and climate variability. If these causes are studied in addition to my research, the reason for the variability of surface water situations in census subdivisions could be identified in Alberta.

This study looks at how Alberta's water supplies are impacted by drought through VHI. My goal is to quantify the correlation between surface water availability and droughts. It's also critical to recognize that surface water may also influence the VHI. Variations in surface water levels and groundwater availability, for example, can have a significant effect on vegetation health, which is reflected in VHI values. This bidirectional link underscores the interdependence of drought and water, emphasizing the need for taking into account both viewpoints for a thorough examination. Comprehending the impact of water availability on drought could enhance the precision of drought monitoring and offer important insights into the adaptability of ecosystems.

7.4 Final Remarks

The Vegetation Health Index (VHI) could be used to integrate the government's current practice of regularly evaluating and reporting on soil moisture conditions as part of Alberta's Agriculture Drought and Excess Moisture Risk Management Plan, which could greatly increase the effectiveness of this policy. The VHI offers important insights into patterns of agricultural drought, which are indicative of deficiencies in soil moisture. By combining VHI data with currently conducted soil moisture monitoring efforts, policymakers can better understand drought conditions and their effects on agricultural productivity.

My research demonstrates the correlation between VHI and surface water extent. By incorporating this information into current risk management practices in Alberta's Agriculture Drought and Excess Moisture Risk Management Plan, policymakers will be better equipped to predict and handle issues related to water shortages. They can keep a close eye on areas with less water available and act proactively to address the possible problems before they become more serious.

In light of this, including VHI data in current monitoring methods for soil moisture not only offers insights into patterns of agricultural drought but also makes it easier to implement early intervention techniques to address issues with water availability. Reactive approaches and emergency reactions are expensive and usually only offer temporary solutions (Agriculture and Forestry, 2016). In contrast, taking proactive steps based on the knowledge gained from VHI data enables more efficient long-term planning and resource allocation, which reduces the need for expensive emergency actions and provides long-term solutions to problems with drought and water shortages.

References

Agriculture and Forestry. 2016. Agriculture drought risk management plan. https://open.alberta.ca/dataset/19be574e-8a12-41f3-9880-403f93747655/resource/9c4ba961-016c-42f2-ac51-f49d41de8b01/download/2016-albertas-agriculture-drought-excess-moisture-risk-management-plan-2016-06-16.pdf

Ahopelto, L., Veijalainen, N., Guillaume, J., Keskinen, M., Marttunen, M., & Olli, V. 2019. Can there be water scarcity with abundance of water? Analyzing water stress during a severe drought in Finland. *Sustainability*, *11*, 1548. https://doi.org/10.3390/su11061548

Alahacoon, N., Edirisinghe, M., & Ranagalage, M. 2021. Satellite-based meteorological and agricultural drought monitoring for agricultural sustainability in Sri Lanka. *Sustainability*, *13*(6), Article 6. https://doi.org/10.3390/su13063427

Alberta Water Council. 2020. Building resiliency to multi-year drought in Alberta: -Tools for small urban and rural municipalities. https://policycommons.net/artifacts/1886590/building-resiliency-to-multi-year-drought-in-alberta/2635905/

Alberta Water Council. 2021. Building resiliency to multi-year Drought. Alberta Water Council. https://www.awchome.ca/projects/building-resiliency-multi-year-drought-6/

Alberta Water Council. 2024. Drought simulation. Alberta Water Council. https://www.awchome.ca/projects/improving-drought-resilience-alberta-through-simulation-24/

Bankes, N. 2024. Alberta’s water sharing “agreements.” *ABlawg*. https://ablawg.ca/2024/05/01/albertas-water-sharing-agreements/

Bento, V., Trigo, I., Gouveia, C., & Dacamara, C. 2018. Contribution of land surface temperature (TCI) to vegetation health index: A comparative study using clear sky and all-weather climate data records. *Remote Sensing*, *10*, 1324. https://doi.org/10.3390/rs10091324

Bhuiyan, C., Singh, R. P., & Kogan, F. N. 2006. Monitoring drought dynamics in the Aravalli region (India) using different indices based on ground and remote sensing data. *International Journal of Applied Earth Observation and Geoinformation*, *8*(4), 289–302. https://doi.org/10.1016/j.jag.2006.03.002

Bonsal, B. R., Wheaton, E. E., Meinert, A., & Siemens, E. 2011. Characterizing the surface features of the 1999–2005 Canadian prairie drought in relation to previous severe twentieth century events. *Atmosphere-Ocean*, *49*(4), 320–338. https://doi.org/10.1080/07055900.2011.594024

Bonsal, B., & Regier, M. 2007. Historical comparison of the 2001/2002 drought in the Canadian Prairies. *Climate Research*, *33*(3), 229–242.

Chen, F., & Li, J. 2016. Quantifying drought and water scarcity: A case study in the Luanhe river basin. *Natural Hazards*, *81*(3), 1913–1927. https://doi.org/10.1007/s11069-016-2162-y

Corkal, D. R., & Adkins, P. E. 2008. Canadian agriculture and water. 13th IWRA World Water Congress, Montpellier.

Crausbay, S. D., Ramirez, A. R., Carter, S. L., Cross, M. S., Hall, K. R., Bathke, D. J., Betancourt, J. L., Colt, S., Cravens, A. E., Dalton, M. S., Dunham, J. B., Hay, L. E., Hayes, M. J., McEvoy, J., McNutt, C. A., Moritz, M. A., Nislow, K. H., Raheem, N., & Sanford, T. 2017. Defining ecological drought for the twenty-first century. *Bulletin of the American Meteorological Society*, *98*(12), 2543–2550. https://doi.org/10.1175/BAMS-D-16-0292.1

Cunha, A. P. M. A., Zeri, M., Deusdará Leal, K., Costa, L., Cuartas, L. A., Marengo, J. A., Tomasella, J., Vieira, R. M., Barbosa, A. A., Cunningham, C., Cal Garcia, J. V., Broedel, E., Alvalá, R., & Ribeiro-Neto, G. 2019. Extreme drought events over Brazil from 2011 to 2019. *Atmosphere*, *10*(11), Article 11. https://doi.org/10.3390/atmos10110642

Dastour, H., Ghaderpour, E., & Hassan, Q. K. 2022. A combined approach for monitoring monthly surface water/ice dynamics of Lesser Slave Lake Via earth observation data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *15*, 6402–6417. https://doi.org/10.1109/JSTARS.2022.3196611

Ding, Y., Hayes, M. J., & Widhalm, M. 2011. Measuring economic impacts of drought: A review and discussion. *Disaster Prevention and Management: An International Journal*, *20*(4), 434–446. https://doi.org/10.1108/09653561111161752

Dixon, D., Boon, S., & Silins, U. 2014. Watershed-scale controls on snow accumulation in a small montane watershed, southwestern Alberta, Canada. *Hydrological Processes*, *28*(3), 1294–1306. https://doi.org/10.1002/hyp.9667

Domenikiotis, C., Spiliotopoulos, M., Tsiros, E., & Dalezios, N. 2004. Early cotton yield assessment by the use of the NOAA/AVHRR derived Vegetation Condition Index (VCI) in Greece. *International Journal of Remote Sensing*, *25*, 2807–2819. https://doi.org/10.1080/01431160310001632729

Dracup, J. A., Lee, K. S., & Paulson Jr., E. G. 1980. On the definition of droughts. *Water Resources Research*, *16*(2), 297–302. https://doi.org/10.1029/WR016i002p00297

Dryden, J., & Turner, C. 2024. Alberta announces what it says are the largest water-sharing agreements in its history. *CBC News*. https://www.cbc.ca/news/canada/calgary/alberta-rebecca-schulz-water-irrigation-evan-davies-1.7178619

Du, L., Tian, Q., Yu, T., Meng, Q., Jancso, T., Udvardy, P., & Huang, Y. 2013. A comprehensive drought monitoring method integrating MODIS and TRMM data. *International Journal of Applied Earth Observation and Geoinformation*, *23*, 245–253. https://doi.org/10.1016/j.jag.2012.09.010

du Plessis, A. 2019. Climate Change: current drivers, observations and impacts on the globe's natural and human systems. *Water as an Inescapable Risk: Current Global Water Availability, Quality and Risks with a Specific Focus on South Africa* (pp. 27–53). Springer International Publishing. https://doi.org/10.1007/978-3-030-03186-2_3

Environment Canada. 2020. Ecoclimatic regions of Canada. https://cfs.nrcan.gc.ca/publications/download-pdf/23092

Environment Canada. 2004. Threats to water availability in Canada. National Water Research Institute, Burlington, Ontario. *NWRI Scientific Assessment Report Series No. 3 and ACSD Science Assessment Series No. 1. 128 p.*

Evans, E., Stewart, R. E., Henson, W., & Saunders, K. 2011. On precipitation and virga over three locations during the 1999–2004 Canadian prairie drought. *Atmosphere-Ocean*, *49*(4), 366–379. https://doi.org/10.1080/07055900.2011.608343

Fontaine, M. M., & Steinemann, A. C. 2009. Assessing vulnerability to natural hazards: impact-based method and application to drought in Washington State. *Natural Hazards Review*, *10*(1), 11–18. https://doi.org/10.1061/(ASCE)1527-6988(2009)10:1(11)

Freyman, M. 2014. Hydraulic fracturing and water stress: water demand by the numbers. 49–50.

Gahlawat, I. N., & Lakra, P. 2020. Global climate change and its effects. *Integrated Journal of Social Sciences*, *7*(1), Article 1.

Gan, T. Y. 1998. Hydroclimatic trends and possible climatic warming in the Canadian Prairies. *Water Resources Research*, *34*(11), 3009–3015. https://doi.org/10.1029/98WR01265

Gibson, C. 2024. Alberta releases drought response plan, including steps it would take to declare emergency | *Globalnews.ca*. Global News. https://globalnews.ca/news/10464968/alberta-government-drought-response-plan/

Gouveia, C. M., Trigo, R. M., Beguería, S., & Vicente-Serrano, S. M. 2017. Drought impacts on vegetation activity in the Mediterranean region: An assessment using remote sensing data and multi-scale drought indicators. *Global and Planetary Change*, *151*, 15–27. https://doi.org/10.1016/j.gloplacha.2016.06.011

Government of Alberta. 2003. Water for Life: Alberta's Strategy for Sustainability. https://open.alberta.ca/dataset/77189444-7456-47f7-944c-085272b1a79c/resource/17c41dc3-1692-4cf9-b931-2892c57a62b1/download/2003-water-life-albertas-strategy-sustainability-november-2003.pdf

Government of Alberta. 2008. Water for Life strategy | *Alberta.ca*. https://www.alberta.ca/water-for-life-strategy

Government of Alberta. 2009. Water for Life: Action Plan. https://open.alberta.ca/dataset/2a91e8c6-ea9a-44c4-a76d-cd35a9a296f7/resource/49531a5a-e16c-4250-a9a4-0028fa500854/download/2009-waterforlife-actionplan-nov2009.pdf

Government of Alberta. 2010a. Agriculture drought risk management plan. https://open.alberta.ca/dataset/8b030bf3-0dca-4e8d-80e2-316f82c263ff/resource/6fcf7f47-a070-4f50-a065-19bc175ce092/download/2010-agriculture-drought-risk-management-plan-alberta-adrmp-final.pdf

Government of Alberta. 2010b. Facts about water in Alberta. https://open.alberta.ca/dataset/1832cd36-bbeb-4997-ae81-67d3eedfcfe5/resource/18a9d64b-bad8-413a-8c63-77a548ec9d88/download/4888138-2010-facts-about-water-in-alberta-2010-12.pdf

Government of Alberta. 2015. Alberta Community resilience program: Program overview—*Open Government*. https://open.alberta.ca/publications/alberta-community-resilience-program-program-overview

Government of Alberta. 2017. Watershed resiliency and restoration program. https://open.alberta.ca/dataset/09550b4b-5cff-4429-b652-b8c69d598a27/resource/ba9d58c2-1880-4a90-a3f2-6661f01b14ee/download/wrrp-guide-feb03-2017.pdf

Government of Alberta. 2019. Albertans investing in resilient infrastructure. https://open.alberta.ca/dataset/c255dabe-47d1-447d-825a-c6f6d63d266c/resource/700b37c5-038f-44a2-8fed-da7fd8a01e7a/download/acrp-progress-report-2019-08.pdf

Government of Alberta. 2022. Watershed resiliency and restoration program: Improving Alberta's natural watershed resiliency to flood and drought—*Open Government*. https://open.alberta.ca/publications/9781460141311

Government of Alberta. 2024a. Alberta releases drought response plan. https://www.alberta.ca/news.aspx

Government of Alberta. 2024b. Current provincial population estimates | *Alberta.ca*. https://www.alberta.ca/population-statistics

Government of Alberta. 2024c. Major water-sharing agreements ready for Alberta. https://www.alberta.ca/news.aspx

Government of Alberta. 2024d. Water allocations and transfers | *Alberta.ca*. https://www.alberta.ca/water-allocations-and-transfers

Government of Alberta. 2024e. Water conservation objectives | *Alberta.ca*. https://www.alberta.ca/water-conservation-objectives

Government of Alberta. 2024f. Watershed management – Partnerships | *Alberta.ca*. https://www.alberta.ca/watershed-management-overview

Government of Alberta. 2024g. Drought – What government is doing | *Alberta.ca*. https://www.alberta.ca/drought-what-government-is-doing

Ha, T. V., Huth, J., Bachofer, F., & Kuenzer, C. 2022. A review of earth observation-based drought studies in Southeast Asia. *Remote Sensing*, *14*(15), Article 15. https://doi.org/10.3390/rs14153763

Han, S., Li, Z., Huang, C., Zhou, Y., Zong, S., Hao, T., Niu, H., & Yao, Y. 2020. Monitoring droughts in the Greater Changbai Mountains using multiple remote sensing-based drought indices. *Remote Sensing*, *12*, 530. https://doi.org/10.3390/rs12030530

Hao, C., Zhang, J., & Yao, F. 2015. Combination of multi-sensor remote sensing data for drought monitoring over Southwest China. *International Journal of Applied Earth Observation and Geoinformation*, *35*, 270–283. https://doi.org/10.1016/j.jag.2014.09.011

Helmus, A. M., Fernald, A. G., VanLeeuwen, D. M., Abbott, L. B., Ulery, A., & Baker, T. T. 2009. Surface Water seepage effects on shallow ground-water quality along the Rio Grande in Northern New Mexico1. *JAWRA Journal of the American Water Resources Association*, *45*(2), 407–418. https://doi.org/10.1111/j.1752-1688.2008.00293.x

Hesham, Y., Khalil, A., & Hassanein, M. 2013. Drought Monitoring over Egypt by using MODIS Land Surface Temperature and Normalized Difference Vegetation Index. *Nature and Science*.

Hitaj, C., Boslett, A. J., & Weber, J. G. 2020. Fracking, farming, and water. *Energy Policy*, *146*, 111799. https://doi.org/10.1016/j.enpol.2020.111799

Huete, A., Didan, K., Miura, T., Rodriguez, E. P., Gao, X., & Ferreira, L. G. 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, *83*(1), 195–213. https://doi.org/10.1016/S0034-4257(02)00096-2

Jain, S. K., Keshri, R., Goswami, A., & Sarkar, A. 2010. Application of meteorological and vegetation indices for evaluation of drought impact: A case study for Rajasthan, India. *Natural Hazards*, *54*(3), 643–656. https://doi.org/10.1007/s11069-009-9493-x

Jiang, R., Liang, J., Zhao, Y., Wang, H., Xie, J., Lu, X., & Li, F. 2021. Assessment of vegetation growth and drought conditions using satellite-based vegetation health indices in Jing-Jin-Ji region of China. *Scientific Reports*, *11*, 13775. https://doi.org/10.1038/s41598-021-93328-z

Karnieli, A., Agam, N., Pinker, R. T., Anderson, M., Imhoff, M. L., Gutman, G. G., Panov, N., & Goldberg, A. 2010. Use of NDVI and land surface temperature for drought assessment: merits and limitations. *Journal of Climate*, *23*(3), 618–633. https://doi.org/10.1175/2009JCLI2900.1

Khandekar, M. L. 2004. Canadian prairie drought: A climatological assessment. Environmental Policy Branch, Alberta Environment.

Kiem, A. S., Johnson, F., Westra, S., van Dijk, A., Evans, J. P., O'Donnell, A., Rouillard, A., Barr, C., Tyler, J., Thyer, M., Jakob, D., Woldemeskel, F., Sivakumar, B., & Mehrotra, R. 2016.

Natural hazards in Australia: Droughts. *Climatic Change*, *139*(1), 37–54. https://doi.org/10.1007/s10584-016-1798-7

King, J. 2024. Concerns raised over Alberta's water-sharing agreement | *Globalnews.ca*. Global News. https://globalnews.ca/news/10439808/alberta-water-sharing-agreement-concerns/

Kogan, F. N. 1995a. Application of vegetation index and brightness temperature for drought detection. *Advances in Space Research*, *15*(11), 91–100. https://doi.org/10.1016/0273-1177(95)00079-T

Kogan, F. N. 1995b. Droughts of the late 1980s in the United States as derived from NOAA polar-orbiting satellite data. *Bulletin of the American Meteorological Society*, *76*(5), 655–668. https://doi.org/10.1175/1520-0477(1995)076<0655:DOTLIT>2.0.CO;2

Kogan, F. N. 1997. Global drought watch from space. *Bulletin of the American Meteorological Society*, *78*(4), 621–636. https://doi.org/10.1175/1520-0477(1997)078<0621:GDWFS>2.0.CO;2

Kogan, F. N. 2001. Operational space technology for global vegetation assessment. *Bulletin of the American Meteorological Society*, *82*(9), 1949–1964. https://doi.org/10.1175/1520-0477(2001)082<1949:OSTFGV>2.3.CO;2

Kummu, M., Guillaume, J. H. A., de Moel, H., Eisner, S., Flörke, M., Porkka, M., Siebert, S., Veldkamp, T. I. E., & Ward, P. J. 2016. The world's road to water scarcity: Shortage and stress in the 20th century and pathways towards sustainability. *Scientific Reports*, *6*(1), 38495. https://doi.org/10.1038/srep38495

Lambert, T. 2024. Priority? Licence transfers? Here's how Alberta's water system works. *CBC News*. https://www.cbc.ca/news/canada/edmonton/priority-licence-transfers-here-s-how-alberta-s-water-system-works-drought-1.7115044

Lehner, B., Doell, P., Alcamo, J., Henrichs, T., & Kaspar, F. 2006. Estimating the impact of global change on flood and drought risks in Europe: A continental, integrated analysis. *Climatic Change*, *75*, 273–299. https://doi.org/10.1007/s10584-006-6338-4

Li, S., & Sun, D. 2021. JPSS VIIRS flood mapping (VFM) algorithm theoretical basis document. SMAP. https://smap.jpl.nasa.gov/documents

Locke, H., & Mackey, B. 2009. The Nature of climate change. *International Journal of Wilderness*, *15*, 2.

Logie, G. 2023. Mapping drought from space—part 1. *Sparkgeo*. https://sparkgeo.com/blog/mapping-drought-from-space-part-1/

Loucks, D. P., & van Beek, E. 2017. Water resource systems planning and management: An introduction to methods, models, and applications. Springer Nature. https://doi.org/10.1007/978-3-319-44234-1

Macdonald, A., Bonsor, H., Ó Dochartaigh, B., & Taylor, R. 2012. Quantitative maps of groundwater resources in Africa. *Environmental Research Letters*, *7*, 024009. https://doi.org/10.1088/1748-9326/7/2/024009

Miralles, D. G., Gentine, P., Seneviratne, S. I., & Teuling, A. J. 2019. Land–atmospheric feedbacks during droughts and heatwaves: State of the science and current challenges. *Annals of the New York Academy of Sciences*, *1436*(1), 19–35. https://doi.org/10.1111/nyas.13912

Mishra, A. K., & Singh, V. P. 2010. A review of drought concepts. *Journal of Hydrology*, *391*(1), 202–216. https://doi.org/10.1016/j.jhydrol.2010.07.012

Mukherjee, S., Mishra, A., & Trenberth, K. E. 2018. Climate Change and drought: A perspective on drought indices. *Current Climate Change Reports*, *4*(2), 145–163. https://doi.org/10.1007/s40641-018-0098-x

Mwale, D., Gan, T. Y., Devito, K., Mendoza, C., Silins, U., & Petrone, R. 2009. Precipitation variability and its relationship to hydrologic variability in Alberta. *Hydrological Processes*, *23*(21), 3040–3056. https://doi.org/10.1002/hyp.7415

Nam, W.-H., Hayes, M., Svoboda, M., Tadesse, T., & Wilhite, D. 2015. Drought hazard assessment in the context of climate change for South Korea. *Agricultural Water Management*, *160*, 106–117. https://doi.org/10.1016/j.agwat.2015.06.029

Nkemdirim, L., & Weber, L. 1999. Comparison between the droughts of the 1930s and the 1980s in the Southern Prairies of Canada. *Journal of Climate*, *12*(8), 2434–2450. https://doi.org/10.1175/1520-0442(1999)012<2434:CBTDOT>2.0.CO;2

Pendergrass, A. G., Meehl, G. A., Pulwarty, R., Hobbins, M., Hoell, A., AghaKouchak, A., Bonfils, C. J. W., Gallant, A. J. E., Hoerling, M., Hoffmann, D., Kaatz, L., Lehner, F., Llewellyn, D., Mote, P., Neale, R. B., Overpeck, J. T., Sheffield, A., Stahl, K., Svoboda, M., Woodhouse, C. A. 2020. Flash droughts present a new challenge for subseasonal-to-seasonal prediction. *Nature Climate Change*, *10*(3), Article 3. https://doi.org/10.1038/s41558-020-0709-0

Quiring, S. M., & Ganesh, S. 2010. Evaluating the utility of the Vegetation Condition Index (VCI) for monitoring meteorological drought in Texas. *Agricultural and Forest Meteorology*, *150*(3), 330–339. https://doi.org/10.1016/j.agrformet.2009.11.015

Rassl, A., Michel, D., Hirschi, M., Duguay-Tetzlaff, A., & Seneviratne, S. I. 2022. Climatological drought monitoring in Switzerland using EUMETSAT SAF satellite data. *Remote Sensing*, *14*(23), Article 23. https://doi.org/10.3390/rs14235961

RMA. 2024. Major water-sharing agreements ready for Alberta—RMA. Rural Municipalities of Alberta. https://rmalberta.com/news/major-water-sharing-agreements-ready-for-alberta/

Rosegrant, M. W., Ringler, C., & Zhu, T. 2009. Water for agriculture: Maintaining food security under growing scarcity. *Annual Review of Environment and Resources*, *34*(1), 205–222. https://doi.org/10.1146/annurev.environ.030308.090351

Sandholt, I., Rasmussen, K., & Andersen, J. 2002. A simple interpretation of the surface temperature/vegetation index space for assessment of surface moisture status. *Remote Sensing of Environment*, *79*(2), 213–224. https://doi.org/10.1016/S0034-4257(01)00274-7

Seiler, R. A., Kogan, F., & Sullivan, J. 1998. AVHRR-based vegetation and temperature condition indices for drought detection in Argentina. *Advances in Space Research*, *21*(3), 481–484. https://doi.org/10.1016/S0273-1177(97)00884-3

Shen, S., Howard, A., Yin, H., Khurshed, F., & Akbar, M. 2003. Statistical analysis of drought indices and Alberta drought monitoring. https://shen.sdsu.edu/pdf/shen_howarddrought_2003.pdf

Singh, R., Roy, S., & Kogan, F. 2003. Vegetation and temperature condition indices from NOAA AVHRR data for drought monitoring over India. *International Journal of Remote Sensing*, *24*, 4393–4402. https://doi.org/10.1080/0143116031000084323

Teuling, A. J. 2018. A hot future for European droughts. *Nature Climate Change*, *8*(5), Article 5. https://doi.org/10.1038/s41558-018-0154-5

Thatch, L. M., Gilbert, J. M., & Maxwell, R. M. 2020. Integrated hydrologic modeling to untangle the impacts of water management during drought. *Groundwater*, *58*(3), 377–391. https://doi.org/10.1111/gwat.12995

UNDRR. 2019. Chapter 6: Special section on drought | *GAR*. United Nations Office for Disaster Risk Reduction. https://gar.undrr.org/chapters/chapter-6-special-section-drought.html#

UNEP. 2012. Early warning systems a state of the art analysis and future directions. *Environmental Development*, *4*, 136–171. https://doi.org/10.1016/j.envdev.2012.09.004

Van Loon, A. F. 2015. Hydrological drought explained. *WIREs Water*, *2*(4), 359–392. https://doi.org/10.1002/wat2.1085

Wang, H., Lin, H., & Liu, D. 2014. Remotely sensed drought index and its responses to meteorological drought in Southwest China. *Remote Sensing Letters*, *5*(5), 413–422. https://doi.org/10.1080/2150704X.2014.912768

Wheaton, E., Kulshreshtha, S., Wittrock, V., & Koshida, G. 2008. Dry times: Hard lessons from the Canadian drought of 2001 and 2002. *Canadian Geographies / Géographies Canadiennes*, *52*(2), 241–262. https://doi.org/10.1111/j.1541-0064.2008.00211.x

Wichers, G. 2024. Southern Alberta reservoirs low for time of year. *Alberta Farmer Express*. https://www.albertafarmexpress.ca/news/southern-alberta-reservoirs-low-for-time-of-year/

Wilhite, D. 2000. Drought as a natural hazard: Concepts and definitions. *Drought, a Global Assessment*, *1*.

Wright, J. R., Houck, M. H., Diamond, J. T., & Randall, D. 1986. Drought contingency planning. *Civil Engineering Systems*, *3*(4), 210–221. https://doi.org/10.1080/02630258608970446

Zhang, D., Li, Z., Tian, Q., & Feng, Y. 2019. Drought Assessment in a semi-arid river basin in China and its sensitivity to different evapotranspiration models. *Water*, *11*(5), Article 5. https://doi.org/10.3390/w11051061