Bridging the Water Adaptation Gap Objective 2 Risk Report: Hydroclimatic and water security risks in Southern Saskatchewan

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Executive Summary

This report partially fulfills objective two of our Bridging the Water Adaptation Gap Project. Its purpose is to review our previous work, as well as literature, surrounding climate change risk in relation to water security in our study area of Saskatchewan. Our report is organized into five chapters. In Chapter 1, Hurlbert and Diaz provide a definition and explanation of climate change risk as well as water security. This chapter is an important precursor and foundational unification of the interdisciplinary science that follows in subsequent chapters. In Chapter 2, Wheaton et al. review hydro-climatic variability in the prairie provinces with a focus on drought, excessive moisture, and the increasing variability. Chapter 3 by Finlay and Hillis provides an important addition to our team. This chapter reviews the research and literature surrounding water quality in our southern prairie landscape with specific sections dedicated to algal growth, cyanobacteria, mercury in fish, plastic pollution, and invasive species. These risks are situated within observations concerning prairie lake food webs, but also include agricultural pond water quality and the very important work on Indigenous views of water quality and climate change. Chapter 4 by Zapata and Beltran establishes a foundation for thinking about risks to primary economic sectors in relation to water in our prairie province. Focusing on agriculture and water allocation, it unifies our thinking of the economic value of water and raises questions for our project's consideration in its upcoming work. Finally, Kishchuk's Chapter 5 on land use and water related climate risk highlights the importance of agricultural drainage, land use change, and wetland restoration.

Table A on the following page summarizes the main impacts of water security risks on four sectors (livelihoods, primary economic activities, ecosystems, and infrastructure) in Southern Saskatchewan. Appendix A expands on Table A and provides references. Further relevant information is found in Appendices B-I. This report provides our background knowledge of risk enabling us to move forward exploring the dimensions of these risks with our partners and potential partners in our regional water (problem) sheds.

Table A: Impacts of water security risks on four sectors (livelihoods, primary economic activities, ecosystems, and infrastructure) in Southern Saskatchewan. See Appendix A for an expanded table with references.

Risk categories	**Livelihoods**	**Primary economic activities**	**Ecosystems**	**Infrastructure**
Risk related to water scarcity	*Droughts tend to cause more damage, last longer and cover larger areas than other weather extremes, which makes impacts worse and adaptation more challenging. *Crop insurance dependency and coverage are expected to grow as climate change progresses. *Decreased fish populations.	*Droughts impact many economic sectors, including agriculture, water supplies, energy production, industry, mining, forestry, recreation, human health, and society. * Impacts on agriculture are particularly important due to its prominence in Saskatchewan's economy.	*Environmental impacts from major drought include reduced water quality, wetland loss, soil erosion and degradation, and ecological habitat destruction. * Future warming projects a decrease in summer streamflow and an increase in winter streamflow.	*Water is needed for other critical infrastructure (e.g., education, health).
Risks related to excessive moisture	*Loss and damage of household assets (mainly rural) due to heavy rains and floods. * Floods make up most of the Federal Disaster Financial Assistance Arrangements (DFAA) payments in the Prairies Provinces. *Projected extreme precipitation are expected to increase the potential for future urban flooding.	*Loss & damage in productive agriculture, mining and hydroelectricity, crop/livestock production, farm infrastructure, local government and infrastructure upgrades and net farm income.	* Higher runoff into aquatic ecosystems could potentially load more nutrients and contaminants into these systems, raising nutrient concentrations, increasing pH, and elevating the salinity of the systems.	*Loss & damage to water infrastructure, including wastewater treatment plants, and roads.
Risks related to climatic variability	* Rapid changes between extreme weather affect many aspects of people's livelihoods, including plants, animals, energy systems, transportation, etc. * Human health risks from changing diseases.	*Changing diseases affect agricultural production of crops and livestock.	* Rapid changes from drought to flood (and vice versa) can damage ecosystems and increase risk of pollution. *Changes in climate systems (such as the El Niño–Southern Oscillation) can affect lake dynamics.	* Cascading infrastructure risks from extreme conditions affect various types of infrastructure.
Risks related to water quality	*High levels of cyanotoxins. *Poor source water quality affects drinking water quality, particularly in remote and Indigenous communities and non-Indigenous communities in Saskatchewan. *Late-season cyanobacterial blooms.	*Cyanobacterial blooms have led to drinking water advisories and negative impacts on tourism. *Decreased property values for lakeside properties. *Cyanobacterial toxins have killed cattle in all the prairie provinces. *Sulfate concentrations in agricultural ponds are also	*Negative impacts of cyanobacterial blooms include increased turbidity, oxygen depletion, and cyanotoxins which can cause "liver, digestive and neurological diseases when ingested. *Nutrients and warm temperatures can combine to have synergistic effects on cyanobacterial growth in shallow water bodies.	*Water treatment plants. *Wastewater treatment plants also often require expensive upgrades to meet governmental regulations and improve the removal of nutrients such as P and N that negatively impact downstream water quality.

Risk categories	**Livelihoods**	**Primary economic activities**	**Ecosystems**	**Infrastructure**
		a concern.	*Late-season cyanobacterial blooms freeze into the fall's ice and release blue-coloured pigments in the winter. *Metal pollution of water. *Plastic pollution (microplastics and microfibers).	
Risks related to warming air temperatures	*Effects of increased temperature on urban areas prone to heat. *Summer fish kills which negatively affected the low oxygen caused by high temperatures and/or decomposition of algal blooms. *Warmer water temperatures contributed to increased concentrations of the toxin microcystin that are harmful to public health.	*Warmer water temperatures are reducing oxygen concentrations in lakes, which may reduce fish habitat. *Reduction of fish habitat noted above could negatively affect Saskatchewan's recreational fishing tourism industry.	*Warmer surface waters will lead to changes in lake thermal stratification. *Changes in nutrient availability. *Lower oxygen is detrimental for fish and invertebrates, alters nutrient availability, and increases metals' toxicity. *Cyanobacteria often reach maximum growth rates at warmer water temperatures.	*Shorter periods of ice cover: ice roads are open for a shorter period of time, which may reduce transportation in northern areas of the province.
Risks from invasive species	*Invasive species may negatively impact subsistence fishing	* Invasive species such as dreissenid mussels, smallmouth bass and Prussian carp may negatively impact native fish populations, which could impact the recreational fishing industry. *The Northern Pine Beetle has impacted forestry.	*Warmer water temperatures and changes in precipitation may favour the spread of invasive species from south to north. *Increasing frequency of extreme events may make ecosystems more vulnerable to the invasion of new species. *Zebra and quagga mussels can drastically change many aspects of a lake, including nutrient cycling, the underwater light climate, and food web interactions, which can negatively affect fish at the top of the food web.	*Invasive dreissenid (zebra and quagga) mussels can severely impede the function of a variety of infrastructure, including facilities with water intake pipes.
Risks from land use changes	* Draining wetlands reduces flood and drought protection and recreational opportunities.	* Draining wetlands reduces flood and drought protection, increasing economic risks. However, drainage also increases net economic accruals from crop production	* Agricultural drainage removes many benefits (or ecosystem services) provided by wetlands.	* Wetlands may be considered 'natural infrastructure' since they reduce the severity of floods.

Chapter 1: Bridging the Water Adaptation Gap: Introduction to Identifying Regional and Social-Ecological Systems Risks in Saskatchewan, Canada

Margot Hurlbert and Harry Diaz

The problem of climate change, and its impacts on water specifically, is daunting. As climate change impacts increase in intensity and duration, there is also an increase in the variability in the water cycle inducing extreme events, affecting water quality, and reducing the predictability of water availability. Thus, sustainable development and the enjoyment of human right to water are impacted (UN Water, 2022). Water is ubiquitous, and involved in all life, ecosystems and human livelihoods. Agriculture is the largest water user and a fundamental sector that provides food, economic output and employment. But other related industries including mining, oil and gas mining and production, and power production - all highly dependent on water. All these water dependent activities are affected by our changing climate; climate change adaptation is a critical need (UN Climate Change, 2021).

Ensuring water security now and into the future is an important goal for an adaptation strategy and necessary for achieving the sustainable development goals (SDGs). **Water security** is defined as that proactive adaptive capacity built through collaborative planning by diverse stakeholders and governance systems in order to safeguard the sustainable availability, access to, and safe use of adequate, reliable and resilient quantity and quality of water for health, livelihoods, ecosystems and productive economies. In this way, water security and climate change are both environmental and social problems (Scott et al., 2013). Adapting in preparation for future climate change to ensure water security will be fundamental for retaining our landscapes, ecosystems, and associated livelihoods, economic resources and infrastructure.

This document is a report of one of the initial research activities of the Bridging the Water Adaptation Gap Project (BWAGP), a project financed by the Social Sciences and Humanities Research Council of Canada (SSHRC). The BWAGP is a project that combines inter and transdisciplinary research. The project, which involves Argentina, Canada, Chile, and Uruguay, is oriented to develop a more efficient, coordinated, and sustainable adaptation strategy. Rather than pursuing an strategy of multiple adaptive strategies, where the narrow interests of individual and institutions define the different forms of adaptation, the project aims to develop a regional adaptive strategy that integrates scientific evidence and the value and interests of multiple stakeholders. This document presents and discusses research activities in the Province of Saskatchewan, Canada. It resulted from a meeting with our Saskatchewan partners in September, 2022 wherein the major climate change regional social-ecological system risks were identified. Our interdisciplinary team leveraged the information about the main hydroclimatic and water security risks identified by our partners and amassed this literature review to summarize academic and grey literature in our study area in Saskatchewan. In order to ensure relevance for diverse actors, these risks were explored in relation to four regional sectors of study, including ecosystems, primary economic activities, livelihoods and infrastructure. The study area includes the South Saskatchewan River Basin, the Carrot River Basin, the Quill Lakes River Basin, the Upper and Lower Qu'Appelle, and the Assiniboine River Basin (see Figure 1.1). These basins are all below the boreal forest tree line in Saskatchewan, Canada and represent waters flowing from the west to the east through Saskatchewan, a closed water basin, and a basin draining into Manitoba and arising in Saskatchewan.

Climate change impacts (including increasing frequency and intensity of drought and flood) are projected to worsen with droughts being two to four times more likely and precipitation events 1.5 to 2.7 times more likely (Arias et al., 2021). The ranges of likelihood are dependent on whether Greenhouse Gas emissions (GHGs) can be reduced. While we are on a path upwards of 3°C, with significant GHG reductions, redirecting our path to well below 2°C is still achievable (Arias et al., 2021). The World Economic Forum's top four risks over the next ten years are environmental in nature and include failure to mitigate and adapt to climate change, biodiversity loss, ecosystem collapse, and natural disasters from extreme weather (WEF, 2023). For Canada, the top identified climate change risks include physical infrastructure, northern communities, human health and wellness, ecosystems and fisheries (Council of Canadian Academies, 2019). For the prairies, incidents of droughts affecting agriculture and forests were identified as dominant negative climate change impacts (ibid).

Many people in Saskatchewan identify the impact of climate change as being 'less cold', a point that seems to agree with the accumulated evidence. The province is experiencing warming with the annual average number of days over 30°C having risen and anticipated to increase by 29.0 days from the 1976-2005 period to the 2051-2080 period (Prairie Climate Centre, 2019). Our average winter minimum temperature has increased to minus 16 degrees Celsius today from minus 22 degrees Celsius before 1965 (a 6 degree Celsius warming). Our average frost-free growing period has similarly increased to 140 days, up from 106 days in the mid-1960s (Cross, 2020; SRC, 2020). This warming has manifest in such things as the advent of West Nile virus and the unprecedented extent and severity of the pine beetle infestation (Kurz et al., 2008).

Droughts can be economically devastating. The 2001-2002 drought, which affected mainly the southwest area of Saskatchewan, produced an estimated reduction in GDP in Canada of 5.8 Billion (Wittrock and Wheaton 2017; Wheaton et al. 2010).

Figure 1.1: Saskatchewan study area for the Bridging the Water Adaptation Gap Project (BWAGP). The study area consists of six watersheds (the South Saskatchewan River, Carrot River, Quill Lakes, Upper and Lower Qu'Appelle River, and the Assiniboine River), which are starred and outlined in blue in this figure. Figure was adapted from Saskatchewan Association of Watersheds (n.d.).

Losses are probably greater in terms of cultural heritage, ecosystem services and the informal economy, impacts that are difficult to measure. Floods are equally devastating, resulting in crop loss, damage to houses, infrastructure and loss of lives. Recently heat domes and fires have been unprecedented in Saskatchewan summers and models suggest an increased risk of these events (Sauchyn et al., 2020). These losses become more serious in perspective, if we take into consideration that climate change involves an increasing frequency and intensity of floods, fires, and droughts, and their impact on livelihoods, health, ecosystems and species, business, and the economy.

The project is focused on the concept of risk. Risk is defined as a situation that involves exposure to danger (Oxford Learner's Dictionaries, 2023). In a more technical sense, it could be defined as the probable impact on objectives due to inadequate or incomplete knowledge or understanding because of a deficiency in information (uncertainty) (ISO, 2021). Thus, risk can be calculable as the probability of an event occurring that becomes an emergency, and potentially a disaster. But risk can also be socially constructed through experiences, emotions, attitudes and beliefs and mediated by culture and geography (Hurlbert, 2018). The combination of the former realist' perspective on objective calculable risk and its socially constructed character (which determines priority or anticipation and planning) are germane.

In relation to climate change risk is defined as "the potential for adverse consequences for human or ecological systems recognizing the diversity of values and objectives associated with such systems " (Hurlbert et al., 2019, p. 680). Climate change risks may change over time and space due to human decision-making and socio-economic changes. Risks can arise from responses that do not achieve their intended result or incur trade-offs or negative side effects with other societal objectives. Climate risks are dynamic and changing, a combination of multiple stressors that unfold together, compounding together with other risks and cascading through scales, times and sectors presenting the potential for surprise (Viner et al., 2020). Climate policies have inherent risks from uncertainty in implementation, effectiveness or outcomes of climate policy, climate-related investments, technology development or adoption and system transitions (Reisinger et al., 2020).

Risk is an abstract concept that could only be understood and researched in relation to an empirical situation. In these terms, the project has been focalized in the study of "risk situations" using a spatial approach to make sense of the heterogenous and complex drivers of climate risk as well as the different adaptation capabilities and priorities at the regional level (Mollinga, 2020).

In the context of climate change a risk situation is characterized by dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological systems to the hazards. This is depicted on the iconic propeller diagram used by the IPCC, which is illustrated in Figure 1.2. While vulnerability is a function of both exposure to climate hazards and social conditions that determine sensitivity (or the degree to which a system is affected by climate related stimuli). Vulnerability is not a description of a people or their communities but a result of systemic patterns of inequity that drive or cause differential exposure, sensitivity and levels of adaptive capacity (Hurlbert et al., 2020). Adaptation seeks to reduce risks by reducing exposure and vulnerability to climate hazards.

Risk situation could be very complex. While compound risks arise from the interaction of hazards, either a single extreme event or multiple coincident or sequential interacting events, cascading risks is an event or trend that triggers others such as a domino or contagion effect and can be associated with the vulnerability component of risk such as those which occurs with critical infrastructure (ibid.). Multiple interacting hazards, such as concurrent heat and drought are now key areas of study. To date the physical science has not taken into consideration the multiple interactions of ecological, social, and economic drivers of exposure and vulnerability. Responses to risk are also key drivers of risk that have not been holistically considered. As Simpson et al. (2021) indicate, climate risks are increasingly related to limited and ineffectual responses from people, producers, society and government. More work on interactions among multiple risks are required not just among 'determinants' of a risk. The interaction of multiple risks such as climate change and Covid-19 can overwhelm response.

In the same vein, globally interconnected climate change risks are only beginning to be understood and experienced. Multi food supply failures exacerbate urbanization, migration, and conflict as El Nino and La Nina events potentially create cascading risk through northern and southern hemispheres. In a synthesis of the latest peer-reviewed, state-of-the planet research, more than one third of scientists identified the underlined threat posed by the synergistic interplay and feedback loops between the top global risks that 'might cascade to create global systemic crisis." These include extreme heatwaves accelerating global warming by releasing large amounts of stored carbon, at the same time intensifying water crisis and/or food scarcity; loss of biodiversity weakens the capacity of natural and agriculture systems to cope with climate extremes increasing vulnerability to food crisis (Future Earth, 2020).

Risk can result from the impacts of climate change as well as human responses to climate change. "Risks results from dynamic interactions between climate related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards" (Hurlbert et al., 2019, p. 680). This report explores risks of climate impacts identified by our partners and existent literature to understand risk interaction as integrated, compounding and cascading systems of crisis in complex entangled, interconnected systems and problems, rather than as discrete events.

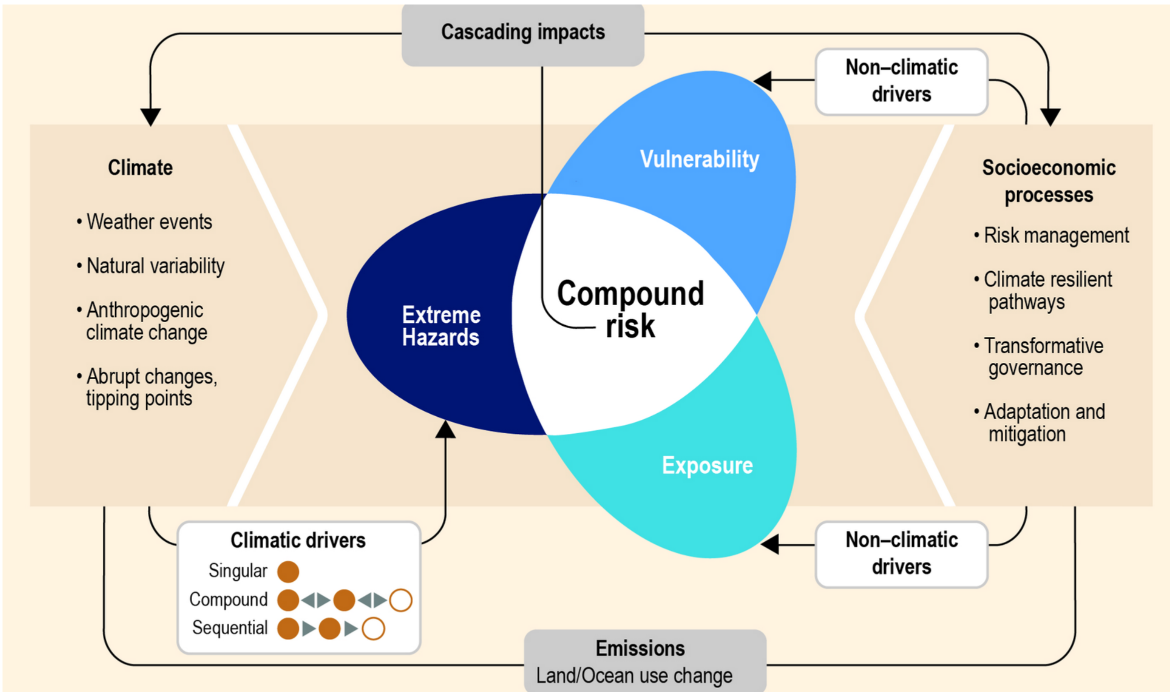

Figure 1.2: Risk Propeller Diagram **(IPCC, 2019)**.

The focus of this report is the hazards that have characterized Saskatchewan during the last 22 years. Based on an extensive bibliographical and archival research we have identified the main climate and non-climate related hazards that have impacted the province since 2020. The identification of these hazards and their dynamics will allow to contextualize the next research stages in the process, which involve assessments of the exposures and vulnerability of our regional sectors: livelihoods, economic systems, ecosystems, and infrastructure, as well as an assessment of climate governance.

Saskatchewan has been historically affected by significant climate related hazards. A land-climate-society interacting hazard in the province is that of land degradation and desertification. In this regard the arid and semi-arid regions such as that in south western Saskatchewan have been exposed to droughts of extreme severity, where rural people and ecosystems have been vulnerable to related risks, which might include drought, food insecurity, migration and loss of agricultural and wild biodiversity. Another hazard that has been important to Saskatchewan's landscape is the disruption of flow regimes in river systems such as the South Saskatchewan River. Exposed are the people that rely on this water resource and particularly vulnerable have been water intensive agriculture systems, and ecosystems and endangered species. Risks include loss of livelihoods and identity, indebtedness, and migration. The last example might be the hazard of depletion or exhaustion of groundwater where often semi-arid areas are exposed and farmers, people reliant on the system for drinking water, agricultural production may be especially vulnerable. Risks of water insecurity, food insecurity, conflict, may be prevalent (Hurlbert et al., 2019).

This report covers drought, excessive moisture, and hydro-climatic variability in Chapter 2, water quality and ecosystem health risks in Chapter 3, risks to primary economic sectors in Chapter 4, and land use and water-related climate risks in Chapter 5. Table A summarizes the impacts of water security risks on four sectors (livelihoods, primary economic activities, ecosystems, and infrastructure), which is detailed further in Appendix A. Later appendices include a table of climatic hazards relating to water in Saskatchewan since 2000 (Appendix B), a map (Appendix C) and timeline (Appendix D) of those hazards, notes on multi-year droughts in Saskatchewan (Appendix E), key reports from the Provincial Auditor of Saskatchewan regarding disaster compensation (Appendix F), a listing of Watershed Association Boards (Appendix G), maps from the Canadian Drought Monitor (Appendix H) and two tables showing how the likelihood of natural hazards changes with projected climate change (Appendix I).

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Chapter 2: The Canadian Prairies Agricultural Region is the Canadian Hotspot for the Risks of Drought, Excessive Moisture and Hydro-Climatic Variability

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2.1: Highlights

- The purpose of this report is to document recent findings regarding the nature of past and possible future drought and excessive moisture events. The roles of the strong hydro-climatic variability of the Canadian Prairies and projected climate change are considered.
- Drought can be defined in various ways, but the essence of the meaning is a prolonged period of abnormally dry weather resulting in insufficient water resources for the economy, environment and society. Drought is one of the worst hazards for the economy, environment and society.
- New findings about the characteristics of drought include the evaluation of its life stages, of sudden onset droughts, switches of wet and dry conditions, snow droughts and spatial evolutions.
- Hydro-climatic variability is especially strong in the Canadian Prairies and decadal variability tends to characterize droughts and excessive moisture events. Multi-decadal variability and decades-long drought are also confirmed by paleo-climatic research.
- Droughts are having more impacts now because of the compounding effects of other hazards including heat waves and intense precipitation, which are becoming more frequent.
- Climate change is a critical driver of the changing nature of hydro-climatic variability. Human-driven climate change is documented as worsening various characteristics of drought and excessive moisture now and into the future.

- Understanding changing characteristics of drought, such as life stages of drought and excessive moisture linkages, are important to improve the fit with planning and preparedness that help reduce impacts.
- Improved understanding of drought impacts to the economy, ecosystems, livelihoods and infrastructure, as well as interactions of risks is required. Enhanced understanding of the risks of drought and excessive moisture is required for improved adaptation. Reducing vulnerabilities to this hydro-climatic variability requires many vital components such as awareness, monitoring, research, outlooks, planning, management and preparedness.

2.2: Abstract

Recent findings are documented regarding the nature of past and possible future drought and excessive moisture events in the Canadian Prairies. The roles of the strong hydroclimatic variability and projected climate change are also considered. Drought and excess moisture are among the greatest natural hazards in the Canadian Prairies as they cause considerable risks to the economy, environment, and society. The temporal trends of drought and excessive moisture conditions appear to be dominated by multi-year to decadal variability occurring over a background of a steadily warming climate. Main drought and excessive moisture times are documented with emphasis on the 2000 to 2022 period. Multi-year drought and wet periods are especially damaging and are challenging for adaptation. Consecutive severe drought years for Saskatchewan, for example, occurred in 2001-2002, 2017-2018, and 2020-2022. Wetter years for Saskatchewan included 2000, 2005, 2010 to 2014, and 2019. A wide range of possibility exists regarding future expected drought and excessive moisture temporal-spatial patterns, as well as hydro-climatic variability. However, such extremes are expected to have several characteristics that are likely to increase risks in the future. These changes include increased persistence, little change or shorter beginning and ending of droughts. Substantial hydro-climatic variability will continue to occur with a greater frequency of extreme precipitation. Negative impacts can be avoided or reduced with effective adaptation, but some limits of adaptation will be reached.

Keywords: Drought, excessive moisture, Canadian prairie, review, climate change, hydro-climatic variability, risks, impacts, adaptation, vulnerability

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2.3: Introduction and Purpose

Drought and excess moisture are among the greatest natural hazards in the Canadian Prairies. Droughts are arguably the most significant hazards, often affecting more people and frequently resulting in more loss and damage than any other natural disaster (e.g., Bonsal et al., 2020). Droughts tend to last longer and cover larger areas than other extremes. This makes impacts worse and adaptation more challenging. Persistent, large-area droughts are among the costliest natural disasters, having major effects on most sectors. These include agriculture, water supplies, energy production, industry, forestry, recreation, human health and society. For an example of costs, during the 2001 and 2002 drought years over Canada, the country's Gross Domestic Product fell by an estimated $5.8 billion, while previously reliable water supplies such as streams, wetlands, dugouts, reservoirs, and groundwater were placed under stress and often failed (Wheaton et al., 2005, 2008). Furthermore, the environmental impacts from major drought episodes are varied but often include reduced water quality, wetland loss, soil erosion and degradation, and ecological habitat destruction (Bonsal, Wheaton, Chipanshi, et al., 2011).

In the recent natural hazard assessment of Saskatchewan plausible worst-case droughts were determined to have major to catastrophic negative effects (Wittrock et al., 2018). When a changing climate was considered, the aggregate risk factor of drought increased from high risk to an extreme risk category. Convective storms can deliver intense rainfalls and these were also considered to be in the high-risk category, and shifted towards the extreme level with climate change.

Excessive moisture conditions and associated flooding have also caused considerable damage, loss, and disruption on the Canadian Prairies. One measure of the severity of damages is the payments made under the Federal Disaster Financial Assistance Arrangements

(DFAA). Halliday (2018) noted that floods, especially in the Prairies Provinces make up most of the DFAA payments with the Prairies experiencing the largest payouts during 1970 to 2014. Saskatchewan received 20% of the national payouts and the largest per capita payment during 2005-2014. Payments from the Saskatchewan Provincial Disaster Assistance Program were especially high because of the excessive precipitation and flooding during 2010 to 2014 (Halliday, 2018).

The temporal trends of drought and excessive moisture appear to be dominated by multi-year to decadal hydro-climatic variability (Bonsal et al., 2004, 2019) occurring over the background of a steadily warming climate. Excessive moisture, sometimes with large area flooding, is a part of this variability and also causes considerable damage. Therefore, excessive moisture associated with heavy precipitation events and climatic variability is also considered here.

The purpose of this report is to review and to further analyze recent findings regarding the nature of drought and excessive moisture events (DEM), as set within the context of the strong hydro-climatic variability of the Canadian Prairies and with projected climate change. Indications of why we should care are provided, in terms of impacts. A huge challenge is that drought impacts are mostly invisible (e.g., soil moisture, plant stress) unlike most other extremes, and they require comparisons, monitoring and evaluation over time. Impacts of drought are often not well documented, and this adds to the challenge of understanding drought risks and reducing them.

On the Prairies, less research has been carried out on past and future excessive or extreme moisture conditions and flooding than on drought. One Canada-wide study examined changes to short-duration intense precipitation events using several RCM runs (Mailhot et al., 2012). They documented that over the southern Canadian Prairies, 20-year return periods of annual maximum daily precipitation increased by 12–18%. More recently, X. Zhang et al. (2019) reported that across the entire Canadian Prairies, the 10-year extreme, 24-hour precipitation amount is projected to increase by 5.1% (low emission scenario) and 18% (high emission scenario) by the end of the 21st century. The 50-year extreme amount is projected to increase by 6.5% and 21.3% respectively. On longer annual scales, overall future precipitation and water resource projections suggest that in Canada, the north will become wetter and the south drier, however, the boundary between wet and dry shows substantial inter-model variability (Maloney et al., 2014).

Droughts are complex phenomena with several definitions. Simply stated, drought is a prolonged period of abnormally dry weather that depletes water resources for human and environmental needs (AES Drought Study Group., 1986). However, each drought is different depending on factors such as area affected, duration, intensity, frequency, antecedent conditions, and the region's capability to adapt to water shortages. Droughts also differ from other disasters (e.g., excessive moisture, floods) since they have longer durations, larger areas, and lack easily identified onsets and terminations. They can also interact with other hazards, including heat, dust storms, and wildfire. For example, after or during a drought, rainfall can produce more damaging runoff. These interactions make it even more crucial to work to decrease the damages of droughts.

Drought types begin as lack of precipitation (meteorological types) and propagate through to agricultural, ecological, hydrological, and socio-economic types with those categories of impacts.
Impacts of drought can often be extreme and wide ranging as droughts can last for months, seasons, and years and cover large areas (Bonsal et al., 2020; Bonsal, Wheaton, Chipanshi, et al., 2011). The most common type of drought and impacts are those on agriculture, including decreased crop, grassland and hay yields and soil erosion. These effects can ripple through to effects on water and ecosystems, then on to communities, provinces, and to the nation. Another set of adverse impacts of drought is those on water quality. Droughts often result in reduced water supplies, water scarcity, and some dangerous water quality problems. Excessive moisture and flooding also can cause adverse water quality effects.

Furthermore, the recurrence of drought is practically certain since drought is a climatological characteristic of most environments (Maybank et al., 1995). Droughts occur on a variety of temporal and spatial scales with their impacts being dependent on the timing and sequencing of dry and warm periods. For example, a shortage of water at a critical time for crop growth may initiate agricultural drought, but hydropower generation would not be affected if reservoirs have adequate supplies. Climate anomalies that last from a month to years are the root of most droughts, however, human impacts on resources and climate, and the changing demand for water are also major contributing factors (McKay et al., 1989).

2.4: Data and Methods

The nature of drought is more complex than other extreme events. A comparison is made with excessive moisture events as they are often indicators of the nature of the start and end of droughts. Both drought and excessive moisture are usually measured by water balance indicators, such as the commonly used Palmer Drought Severity Index and the Standardized Precipitation Evapotranspiration Index. The switches between these two extremes are a main aspect of hydro-climatic variability.

The official source for monitoring and reporting drought in Canada is the Canadian Drought Monitor (AAFC 2022b).This monitor uses several precipitation and temperature indicators in five main drought categories. These are based on precipitation percentiles with their related statistical return periods. An analysis of past droughts was done using the Canadian Drought Monitor (AAFC 2022b) and other sources from 2000 to 2022. Main areas of drought of different categories and examples of agricultural impacts were documented.

Recent literature of the past few years is emphasized in this review, with relevance to the Canadian Prairie agricultural area. The entire Prairie Provinces agricultural area is used as the study region since droughts tend to migrate from one part to another so the broader picture is required. Also, adaptation limitations grow as the size of the areas affected grows. The review is guided by the question: What are the new findings about drought and excess moisture conditions that are relevant to the Canadian Prairies? More details of the methods are included in the respective sections, as needed.

2.5: Results

Hydro-climatic Variability of the Prairie Provinces

The Canadian Prairies region has a naturally variable climate in terms of temperature and precipitation. A global database of the climate moisture index (Vorosmarty, 2005) for the period 1950-2000 shows two large regions where the annual coefficient of variation is classified as high. These two regions with the highest inter-annual hydroclimatic variability are in the interiors of Eurasia and North America. The later region is comprised mostly of the Canadian Prairies. The Prairies receive an annual average of ~450 mm of precipitation, however, the year-to-year variability is high, ranging from an annual low of 300-350 to a high of 500-550 mm (McGinn, 2010). Within the year, precipitation distribution is seasonal with an average of 20-35% falling during June and July, and up to two-thirds occurring during the growing season months of May to August (Bonsal et al., 1999). These precipitation amounts and seasonality are the principal climate features of the Canadian Prairie region that effectively determine the vitality of its ecosystems and economic activities (McGinn, 2010).

The aforementioned inter and intra-annual variability in precipitation makes the region particularly susceptible to hydro-climatic extremes. This includes periodic droughts and excessive moisture events, with the former being more prominent in terms of frequency, duration, area of coverage, and impacts. The occurrence of extremely dry conditions or drought, as well as prolonged wet periods, often results in serious impacts to the region's natural environment, economy, and society.

Hydro-climatic extremes are caused by disruptions to an expected precipitation pattern and in the case of drought, can be intensified by unusually high temperatures. The major factor in the onset and perpetuation of drought generally involves anomalous circulation patterns in the mid troposphere. Over the Canadian Prairie ecozone, growing season (May to August) extended dry periods were associated with a persistent circulation pattern that includes a large-amplitude ridge centred over the area. The ridging creates 'blocking conditions' that displace cyclonic tracks and associated moisture advection (from the Pacific Ocean and Gulf of Mexico) away from the area (Chakaravarti, 1976; Dey, 1982; J. Liu et al., 2004). Conversely, excessive wet conditions are associated with a collapse of the ridge and thus a higher frequency of zonal flow over the Prairie region. The upper-level jet stream is often displaced southward in a west–east alignment along the Canada–United States border causing surface-level cyclones to be steered over the Prairies. The wet conditions are aided by the advection of moist air into the Prairies from the southern United States and the Gulf of Mexico (Dey, 1977; Shabbar et al., 2011).

Investigations of past climate change have shown that the Canadian Prairies have experienced significant warming (particularly, during winter and spring) and a slight increase to precipitation during the instrumental record. For example, between 1948-2016, annual mean temperature increased by about 1.9°C. Seasonally, winter mean temperatures have increased by 3.1°C, spring by 2.0°C, summer by 1.8°C, and autumn by 1.1°C. In terms of precipitation, mean annual amounts increased by about 7% with spring showing 13.6%, summer 8.4%, and autumn 5.8% increases. However, winter precipitation decreased by 5.9% (X. Zhang et al., 2019). In association with the warming, there was a significant decrease in the snow to rainfall ratio (Vincent et al., 2015). In terms of droughts and excessive moisture, substantial inter-annual and inter-decadal variability has occurred with decadal variations being more prominent, and no long-term trends being evident (e.g., Bonsal et al., 2017, 2019).

Evaluation of the inter-annual and decadal variability over the Oldman and Swift Current Creek Watersheds in Alberta and Saskatchewan show no discernible trends in the past ~100 years, approximately (Bonsal et al., 2017). However, evidence of increased inter-annual variability since the middle 1980s was found using the 30-year standard deviation of summer SPEI.

Continued warming and changes to the nature of precipitation are expected to significantly impact the frequency and magnitude of hydro-climatic extremes across the Canadian Prairies including the South Saskatchewan River Basin (SSRB). Projected annual temperature increases range from 1.5°C – 2.3°C for the period 2031 to 2050 and from 1.9°C to 6.5°C from 2081 to 2100 (based on low emissions (RCP 2.6) and high (RCP 8.5) emission scenarios). As with the historical period, the greatest changes are projected for the winter (X. Zhang et al., 2019). Annual precipitation is projected to increase in the range of 5.0% - 6.5% (2031-2050) and 5.9% - 15.3% (2081-2100). The majority of the precipitation increase is again during the cold season with smaller increases projected for summer. Future precipitation will be comprised of less snow and more rain (X. Zhang et al., 2019).

Despite the projected increases in precipitation, future warming is expected to likely result in a decline of over-winter snow accumulation and an increase in winter and spring and a decrease in summer water availability, such as summer streamflow and soil moisture. This is mainly attributable to the projected increase in evapotranspiration and reduction in snow-to-precipitation ratio (Forbes et al., 2011; Kienzle et al., 2012; Lapp et al., 2009; MacDonald et al., 2011; Shepherd et al., 2010; St. Jacques et al., 2013, 2018; Tanzeeba & Gan, 2012). Most studies also showed earlier spring snowmelt onset (e.g., Bonsal et al., 2019). The median values for several future scenarios reveal that by end of this century, natural river flow in the region may be reduced by 4% to 13% (Martz et al., 2007).

Paleoclimatic information further enriches the short instrumental records and underscores the amazing climatic variability of the Canadian Prairies. The instrumental record fails to capture the wider range of hydro-climatic variability and necessitates this further information. The paleoclimatic records show that the climatic regime shifts from predominantly interannual variation to extended wet and dry spells (Sauchyn, 2023; Sauchyn & Kerr, 2016).

In summary, projected climate change is expected to have several impacts on the hydroclimatology variability of the Canadian Prairies, including:

- Future droughts and soil moisture deficits are projected to be more frequent and intense across the southern Canadian Prairies during summer, and to be more prominent at the end of the century under a high emission scenario.
- The seasonal availability of freshwater will continue to change, with an increased risk of water supply shortages in summer.
- Warmer winters and earlier snowmelt will combine to produce higher winter streamflows, while smaller snowpacks and loss of glacier ice during this century will combine to produce lower summer streamflows, with shifts from more snowmelt-dominated toward rainfall-dominated regimes.
- Warmer summers will increase evaporation and contribute to reduced water availability despite more precipitation during the year.

The Changing Nature of Main Historical Droughts

Although many areas of Canada periodically experience drought, western regions in the rain shadow of the Rocky Mountains are more drought-prone due to their naturally high precipitation and climatic variability and distance from the ocean. During the past two centuries, several long-duration droughts have occurred in western Canada. In southern areas of Alberta, Saskatchewan, and Manitoba for example, severe droughts were observed in the 1890s, 1930s, late 1950s to early 1960s, 1980s, 1999-2005, 2015, and most recently in 2021 (Bonsal et al., 2020; Bonsal, Wheaton, Chipanshi, et al., 2011; Bonsal & Regier, 2007; Wheaton, 2000). Droughts can also be initiated and/or accentuated during the cold season when a lack of precipitation results in lower than normal spring runoff and soil moisture recharge and thus, reduced stream flow and reservoir replenishment.

Ten major severe past droughts in the agricultural area of the Canadian Prairies (1900-2014) were documented by Bonsal et al., (2020). That work established the main characteristics of these selected droughts including their life stages, that is, onset, growth, persistence, peak, retreat, and termination as well as characteristics of duration, severity and intensity. The median duration of these ten major droughts was found to be almost two years, at 19.5 months, with median growth of three months and a retreat time of five months. They also examined seasonality of droughts as the greatest impacts are often found during the growing season. Nine of the ten major droughts peaked in severity during the growing season.

An assessment of the Canadian Drought Monitor for the more recent series of droughts during 2000 to 2022 is listed in Table 2.1. Several characteristics are determined, including their main areas, severity indicators, and examples of impacts. The existence of moderate drought (D1 category) according to the Canadian Drought Monitor was used to define main drought areas and years in the prairie agricultural region (AAFC, 2022b). August is the target month used to represent each year, except for 2003 when September was used as August was not available. The reasons for using August include that it is: 1) the end of the agricultural year, 2) a good indicator of agricultural conditions, including crop and forage production and water supplies, and 3) follows the warmest month, on average. The comments section of Table 2.1 provides additional descriptors, especially indicating the prominent locations of drought.

The Canadian Drought Monitor uses five categories, where D1 is classed as moderate drought, D2 is severe drought, D3 is extreme drought, and D4 is exceptional drought. The monitor is developed from many sources including precipitation and temperature indicators, Normalized Difference Vegetation Index, Palmer Drought Index, precipitation percentiles, and the Standardized Precipitation Index. The precipitation percentiles of the categories generally relate to the following return periods: D1 1/5y, D2 1/10y, D3 1/20y, D4 1/50y (AAFC, 2022a).

Table 2.1: Main droughts during 2000 to 2022 in the Canadian Prairie agricultural region and their main characteristics. Drought years with extreme drought areas (D3) and worse are marked in bold as they are major droughts. The characteristics for the years 2000 to 2002 were not available for the Canadian Drought Monitor, so the source used was Bonsal, Wheaton, Meinert, et al., (2011) for August Palmer Drought Severity Index. Impact examples are from the CDM, except as noted. Abbreviations are used for the provinces and directions.

Drought Years (main)	Main areas with at least moderate drought (D1)	Main areas with worse than moderate drought (D2+)	Impact Examples	Comments
2000	Moderate drought only in S AB	None		Wet in S SK
2001	Much of AB and SK except for SE SK	Severe to extreme drought covers much of SK and AB	Severe and long-lasting impacts for many sectors (Wheaton et al., 2008).	Wet in far SE SK and parts of MB
2002	Central to N AB and N SK	Central to E AB and N central to W SK	Severe and long-lasting impacts for many sectors (Wheaton et al., 2008).	Contrast from drought to wet in SW SK and SE AB
2003	Mostly E and S central SK and much of MB	Smaller areas of D2 within the D1		
2004	Mostly central E AB and some in W central SK	None		

2006	South central MB and S SK	South and central MB		Sharp transition from abnormally dry to severe drought
2007	South AB and SW SK	D3 in S AB	Poor pasture production and some livestock water shortages	S AB and SW SK drought
2008	Central and NW AB, S SK	D2 in NW AB and S SK	Water and forage shortages, poor crop and forage production	Mainly split between N AB and S SK droughts
2009	Central and NW AB with spillover into W SK	D4 in central and east central AB	Crop and forage yields decreased Water hauling and new wells needed Fire bans instituted Many counties declared drought disaster areas More impacts and adaptations documented by Wittrock et al. (2010).	Mainly an AB and W SK drought
2010	NW and west central AB	D3 in NW AB	Poor soil moisture, stressed crops and grasslands More impacts and adaptations documented by Wittrock et al. (2010).	A W AB drought
2011	Central and SE MB	None	Heat and dryness stressed crops and grasslands	Only MB drought
2012	NW AB and SE MB	None	Lower than normal on-farm water supplies, low pasture and hay production in SE MB	Most agricultural areas are out of drought
2014	NW AB	Some D2 in NW AB	Peace River region had poor soil moisture and agricultural production, low water supplies	Mainly a Peace River drought
2015	Most of AB with spillover into W SK	Large portions of D2 in AB with D3 in central and S AB	Heat and soil moisture deficits desiccated crops and grasslands	Mainly an AB drought due to long-term deficits with some relief in August
2017	South to central AB and much of SK	D2 covers much of SK to some D4 in the south	Most crops and pastures affected in S AB and SK	Mainly a SK and S AB drought Rapid onset with severe intensification (Hadwen & Schaan, 2021).
2018	Central to S AB, much of SK and MB	D2 in central AB, central and S SK and central to S MB	Many moderate to severe impacts Surface water, hay and pasture shortages Crop conditions declined	Extensive drought coverage across the prairies

2020	SW AB, SW SK and central N to S corridor in SK	None	Dry conditions and heat resulted in some yield losses, reduced water supplies and fire risk	Much of SK, MB and S AB is abnormally dry
2021	All AB, SK and MB	D2 to D3 dominated the prairies D2 is extensive across the prairies with in all provinces with D4 in SK and especially MB	Crop yields dropped about 20-40%, quality dropped also Surface water supplies a concern Grasshopper problems	MB is hardest hit, but the entire region suffered with 99% of the agricultural region still in drought Rapid onset
2022	Central and SW SK	D2 areas increased in central and SW SK	Poor crop yields in SW SK, W MB, grasshopper and flea beetle outbreaks. Water quality and livestock feed concerns in south central SK	Regions still recovering from 2021 drought Mostly a SK drought, esp W SK Harvest delayed in eastern SK due to excess spring moisture 52% of agricultural region in D0 to D2

The methodology for the Canadian Drought Monitor was changed after 2006 (Tyler, AAFC p. comm). Therefore, the information would be less comparable for 2003 to 2005. However, that earlier period is fairly well documented in other work, including Bonsal, Wheaton, Meinert, et al. (2011) and Wheaton et al. (2008). They describe extreme to exceptional drought patterns especially in 2001-2002 using such methods as the Palmer Drought Severity Index. In 2001, extreme drought and worse focussed on central and southern Alberta and central and southwestern Saskatchewan. By 2002, the worse areas had shifted northward across central Alberta and Saskatchewan. The 2003 drought had a similar pattern, but was less severe. By 2004, the drought had again weakened and retreated farther into Alberta.

Recent droughts, their impacts and adaptation measures used, e.g. of 2015 and 2021, are less well documented than the earlier droughts during 1999-2005 (Bonsal et al., 2020; Bonsal, Wheaton, Meinert, et al., 2011; Stewart et al., 2011; Wheaton et al., 2008) and 2009-2010 (Wittrock et al., 2010). The drought of 2001-2002 covered massive areas across Canada and North America, brought record drought and impact conditions, and was set in a multi-year dry period. Western Saskatchewan was drier in 2001 than in any year of the 1930s dust bowl. That drought also appeared to cover more areas of Canada compared to the infamous droughts of 1931, 1961 and 1988 (Wheaton et al., 2008). That drought had a rapid onset (flash drought), extended farther northward than previous major droughts, and had a very long persistence stage (Bonsal et al., 2020).

The drought year of 2021 is an important example of an extreme and extensive drought. It was also exacerbated by the heat dome of 2021. Severe drought encompassed practically all of the agricultural prairies (Figure 2.1), with large areas of extreme to exceptional drought in Saskatchewan and Manitoba.

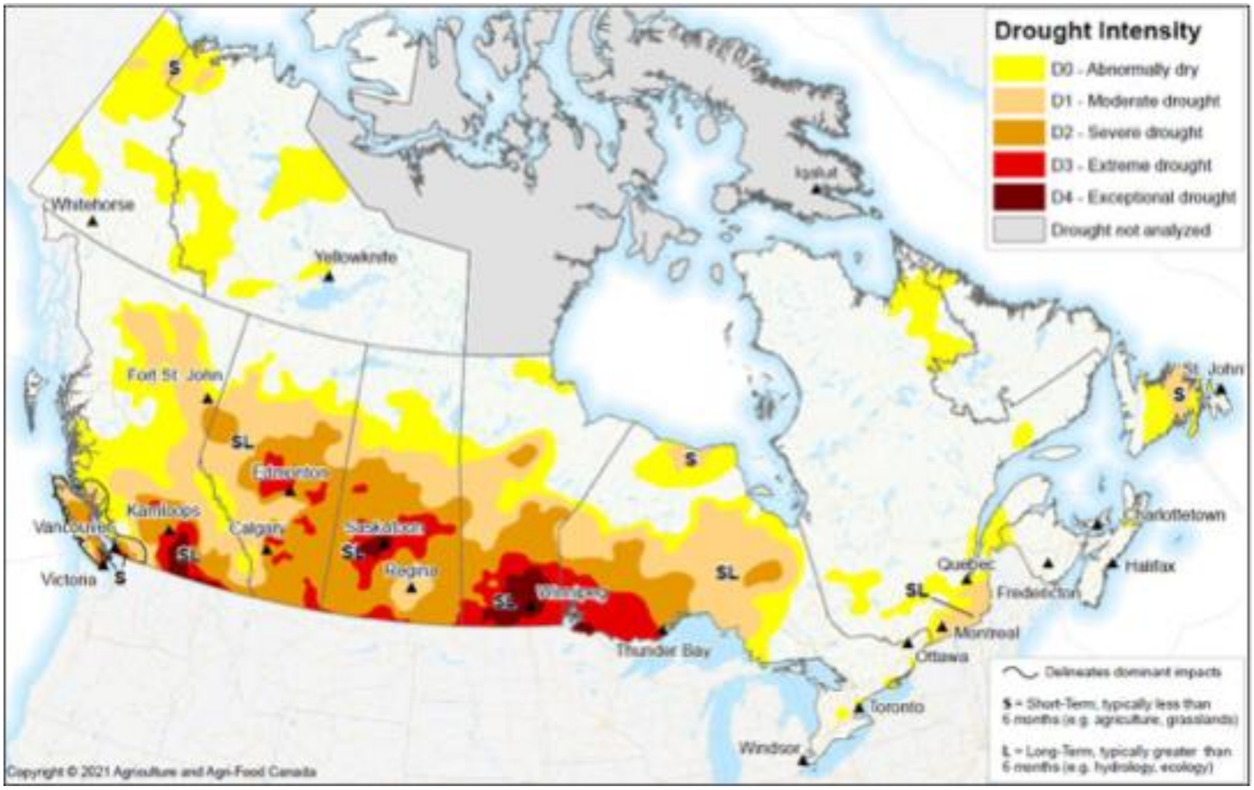

Figure 2.1: Canadian Drought Monitor map, August 2021 (AAFC, 2022b).

More about Impacts and Adaptations

Impacts of the 2001-2 drought were very serious including record low crop and forage production, multi-sector effects, failed water supplies, dust storms, large employment losses and huge costs, as mentioned earlier. Even with considerable work and advanced technology used to adapt to the drought, residual short- and longer-term impacts resisted adaptation and provided lessons for future adaptation improvements (Wheaton et al., 2008).

Assessments of adaptation options used for droughts are even more rare than that for impacts. Wittrock et al. (2010) used a media survey to supplement the information on impacts and to detail characteristics of adaptation measures, including main topics, timing, and geographic details for the drought of 2008-2010. The results of the media survey of adaptation measures found more emphasis was placed on the topic of crops as compared with the topics of livestock and water, possibly indicating a greater level of concern. Although the drought had become entrenched during the winter of 2008 to 2009, the number of media articles did not show an increase until May 2009. This may have indicated a lack of awareness of the importance of winter droughts.

Note that a few years from 2000 to 2022 are not included in Table 2.1. These years were relatively wet and had no areas in moderate drought (i.e.,2005, 2013, 2016, 2019) in the agricultural region. Alternatively, years with major droughts beyond the moderate drought category into the D3 drought and worse are 2007, 2009, 2010, 2015, and 2021. These major drought years appeared mainly in the western prairies. Increasing knowledge of these characteristics of drought is vital for improved and successful adaptation to their impacts. Information about these characteristics is also vital to compare with future possible droughts to bring awareness of improvements required to plan for and to deal with impacts.

Flash (Rapid Onset) Droughts

Not long ago, researchers wrote that the start and end of droughts were difficult to determine. This was because drought was considered only to be a “creeping” disaster. Now researchers have begun to use more indicators and to evaluate many characteristics of drought and the wet times between droughts. These include not only the start and end of droughts but also the other stages in droughts’ life cycles. Then, recently the concept of “flash” or sudden onset droughts arose, acknowledging that droughts are not just creeping disasters, but can emerge quickly and also end quickly.

The concept and definitions of “flash or sudden onset” droughts are still emerging. However, rapid onset droughts have already been documented for the Canadian Prairies. Bonsal et al. (2020) examined the characteristics of severe historical and projected droughts. They also found indications of more flash droughts in the future. They mentioned that flash droughts could be more problematic as the warning and preparation times are diminished. The drought stage work revealed two events that had very rapid onsets in that the growth stage was zero months (Bonsal et al., 2020). These were 1914-15 and 2001-3 droughts. We can also define the concept of flash retreat of droughts. At least two of these most severe droughts retreated rapidly.

The more recent rapid onset drought of 2017 was documented by Hadwen and Schaan (2021). They described the early snowmelt and dry spring leading to a very dry summer. They also describe many impacts and make recommendations. Jencso et al. (2019) document the lessons learned from the 2017 flash drought that extended across the U.S. Northern Plains and the Canadian Prairies.

Multi-year Droughts

Long or multi-year droughts and excessive moisture events tend to have much more severe impacts and threaten to exceed adaptation abilities. Three sets of consecutive severe droughts and worse (+D2) of two years in length have occurred during 2000 to 2022 (Table 2.1). Consecutive years with severe drought or worse in Saskatchewan are 2001-2002, 2017-2018, and 2020-22. The last set was separated by only one year (2019), so adaptation would have been even more difficult.

Chipanshi et al. (2006) assessed consecutive droughts in the Canadian Prairies during 1959 to 2000. Their map of the number of consecutive droughts shows that Saskatchewan has had a maximum multi-year drought lasting four years. This occurred in the southwest during the growing season. They found that three years was a common multi-year length during that period. Previous droughts in both the instrumental and paleo records demonstrate clearly that very long droughts of many consecutive years are possible.

The evolution of the different stages of severe multi-year droughts was examined by Bonsal, Wheaton, Meinert, et al. (2011). An example for the 1999 to 2001 drought in the agricultural region of the prairies is in Figure 2.2. The growth stage is fairly rapid, followed by an extensive persistence stage. The retreat stage was fairly long and the termination stage was intermittent. This demonstrates the complexity of droughts using the stage concept.

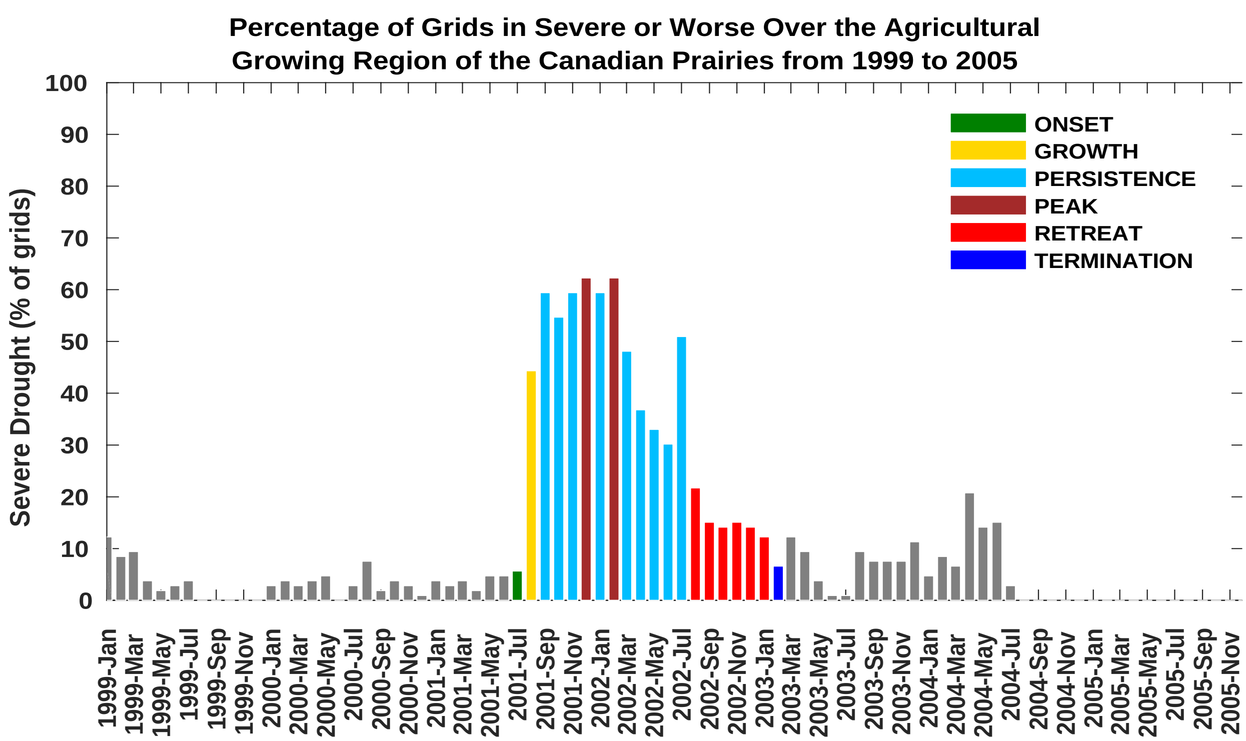

Figure 2.2: Evolution of Severe Drought (SPEI) by Percentage of Grid Area, 1999 to 2005, Canadian Agricultural Prairies (Z. Liu et al., 2019)

Patterns of Future Possible Droughts

In terms of hydro-climatic extremes, global and regional climate models (GCMs/RCMs) project future increases in summer continental interior drying and associated risk of droughts. The greater risk is ascribed to further increases in temperature and resultant evapotranspiration not being offset by precipitation increases (e.g., Trenberth, 2011). Investigations into future droughts across the southern Canadian Prairie provinces (from an ensemble of GCMs) indicated the prevalence of more frequent summer drought in the latter half of the 21st century with persistent dry, warm conditions expected after about 2040 (Bonsal et al., 2013). Results also revealed that multi-year droughts lasting 10 or more years are more likely than what has been historically observed. The fourth-generation Canadian RCM showed similar findings over the southern Canadian Prairies for the period 2041–2070 (PaiMazumder et al., 2013). Many studies also revealed considerable differences among individual climate model projections (e.g., Bonsal et al., 2017, 2020; Jeong et al., 2014; Masud et al., 2017; Tam et al., 2019).

Future annual and summer changes of a water balance model, the Standardized Precipitation Evapotranspiration Index (SPEI) overall western Canadian river basins were assessed with six GCMs for the periods 2041–2070 and 2071–2100 (relative to 1971–2000), using medium emission (RCP 4.5) and high emission (RCP 8.5) scenarios (Dibike et al., 2017). Southern watersheds showed a gradual increase in annual water deficit throughout the 21st century, while the opposite was true for northern basins. For summer, however, all river basins except those in the extreme north are expected to experience decreasing water availability. Canada-wide 21st-century drought projections were assessed on seasonal to annual scales based on the SPEI using bias-corrected temperature and precipitation projections from 29 GCMs participating in the Coupled Model Inter-comparison Project Phase Five (CMIP5) with three different forcing scenarios (RCP 2.6, RCP 4.5 and RCP 8.5). Over the Prairies, results showed increased drying in summer and particularly for annual scales (Tam et al., 2019). The drying was most pronounced at the end of this century under the higher emission scenarios. Using this same SPEI information, it was also pointed out that the tendency for drought is expected to accelerate mid-century.

Future possible droughts have several characteristics that are similar, but others that are different from past droughts in the Canadian Prairies. These differences include increased intensity, duration, frequency, and similar seasonality as summarized below (Wheaton et al., 2013 documenting many sources):

- Increased intensity of dryness driven by the increased evapotranspiration potential of higher temperatures and longer growing seasons
- Droughts of six to ten months become more common. The frequency of longer droughts increasing by about four events by the 2050s
- Long-duration droughts of five years and longer more than double by 2100
- Decade-long droughts increase in frequency to more than three by 2100

Bonsal et al. (2020) provided more recent and detailed descriptions of future possible droughts, including their life cycle stages, and they compared them with past major droughts. Although they found large uncertainty and under-estimations in future drought projections, several features were documented (Table 2.2). The modelled historical under-estimates the characteristics of historical droughts, so the change is also noted to deal with this bias. Even with the under-estimation, characteristics such as persistence, duration, and frequency increase into the far future. The change data indicate that growth and retreat stages show little future change, but many models project shorter durations of these shoulder stages. This means more flash droughts should be expected. Considering this expectation in drought warning and preparedness actions will act to reduce the negative impacts of drought, as possible, until certain thresholds are reached and gaps in capability emerge.

Table 2.2: Drought stage median lengths (months) for historical period, modelled historical, and modelled future periods. The change from modelled future periods compared with modelled historical is included. Future projections are for RCP 8.5 (high emission scenario). (Data from Bonsal et al., 2020).

Period	**Growth**	**Persistence**	**Retreat**	**Duration**	**Frequency** (Per decade)
Historical	3.0	10.5	5.0	19.5	0.9
Modelled Historical	1.0	9.0	3.0	14.0	0.4
Near Future 2021-60	1.0	12.0	2.0	18.0	1.3
Far Future 2061-2100	1.0	18.0	2.0	25.0	1.7
Change: Near future minus modelled historical	0	3.0	-1.0	4.0	0.9
Change: Far future minus modelled historical	0	9.0	1.0	11.0	1.3

A summary of projected changed features representative of the near future (2021-2060) with the high emission scenarios and include (Bonsal et al., 2020):

- The frequency of major droughts per decade increases from a median of 0.9 per decade in the past to 1.3 per decade.
- More flash (rapid onset) droughts were simulated in the future. This is a warning for adaptation as the warning and preparation time would be much diminished.
- Worst cases of the persistence stage show an average increase of about eight months from the past cases. Depending on the season of persistence, this would be more daunting for adaptation and could result in limitations for adaptation. Longer drought durations can result in greater losses as water supplies and other required resources are depleted and much more damage results.
- The retreat stage of major droughts was found to be slightly shorter in duration, possibly indicating more rapid termination of droughts. This could mean more rapid switches from dry to wet conditions. The linkage with extreme precipitation is possible and should be assessed.
- Droughts continue to peak during the growing season showing little change from the past

- Spatial pattern changes are evident in the agricultural region, with increased severity projected for northern to central Alberta, southeastern Saskatchewan and southwestern Manitoba. This increased severity indicates significant drought concerns and greater requirements for adaptation measures.

Such results are similar to those indicated for other regions of the world in terms of increasing drought concerns. Although these results summarized from Bonsal et al., (2020) are mainly median numbers, information for worst-case scenarios was indicated as those are needed for risk assessments.

Impact of Climate Change on Soil Moisture in Saskatchewan

Drought impacts are mediated through soil moisture. Therefore, soil water content (SWC) is an important hydrologic state variable to document and consider here, with a focus on Saskatchewan. SWC is related to actual and potential evapotranspiration, precipitation, water storage and infiltration, runoff, and overall water balance. In the sub-humid climate of southern Saskatchewan, precipitation in the growing season usually is exceeded by evapotranspiration, such that SWC limits vegetation growth and crop yield more than any other factor for most years. Plans to irrigate current and even more agricultural land require an assessment of SWC variability across spatial and temporal scales, including climate change considerations.

An example for the Qu'Appelle River Basin is provided for more detail. Zare et al. (2022a, 2022b) evaluated the reliability of the Soil and Water Assessment Tool (SWAT) to estimate SWC for the Qu'Appelle River Basin. They used high-resolution satellite data and field measurements to calibrate the SWAT model. Then they applied climate model data from 11 Regional Climate Models (RCMs). Figure 2.3 shows the results of SWAT-simulated SWC for an historical baseline (1975–2005), the near future (2021–2050) and the distant future (2051–2080). All 11 model experiments produce declining soil moisture. In some cases, however, most of the decrease occurs in the near future. A smaller decline in the distant future might be a function of increased precipitation as the climate warms. Differences in SWC among models and 30-year periods could also reflect natural climatic variability and the cycling of wetter and drier conditions from one decade to the next.

The spatial variability in SWC across the Qu'Appelle River Basin was determined for several climate model experiments with results for the historical baseline, near future and distant futures (Zare et al., 2022b) (Figure 2.4). These maps clearly illustrate declining soil moisture throughout the basin, but at different rates. Thus, a future with drier soils through the southern prairies is a much-simplified scenario; the impact of climate change on soil moisture is estimated to vary according to soil properties, topography and land cover as shown here for one of the prairie watersheds.

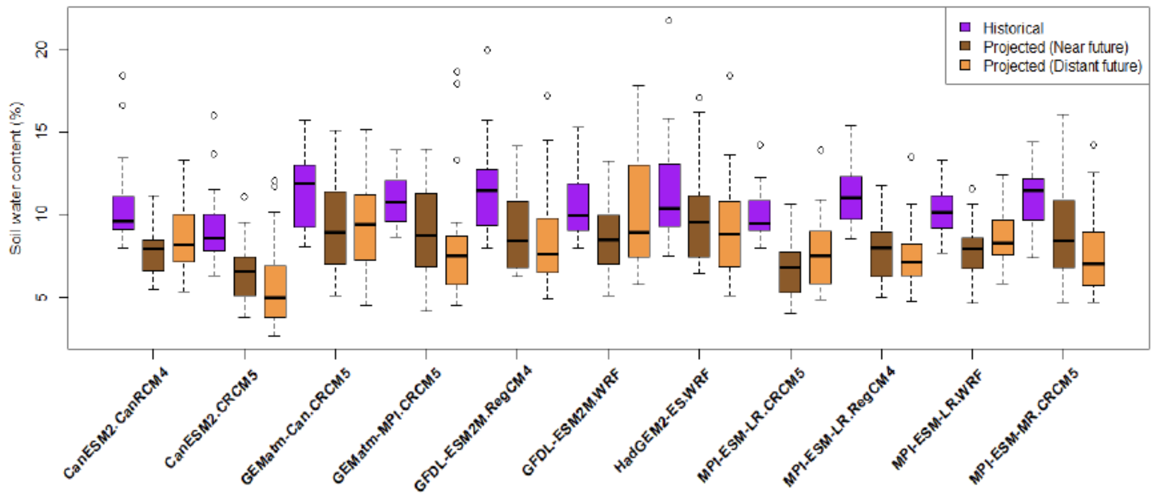

Figure 2.3: SWAT modeled SWC in the Qu'Appelle River Basin for Historical and Projected (near future and far future) climate. Each climate forcing is from an Earth System Model downscaled using a Regional Climate Model (e.g., MPI-ESM.CRCM5).

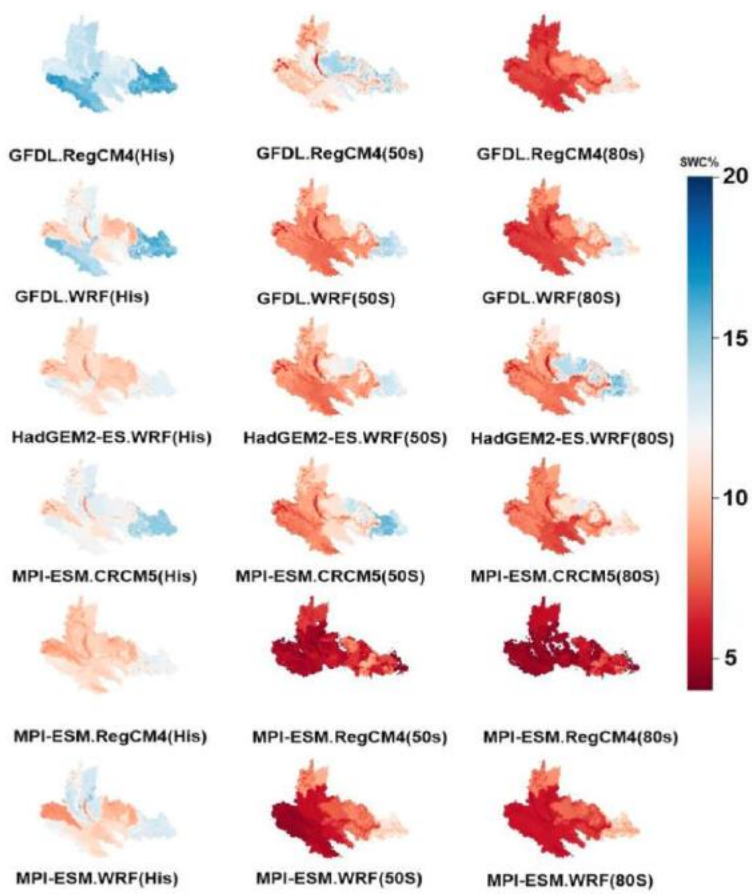

Figure 2.4: SWAT modeled SWC in the Qu'Appelle River Basin for historical (His), near future (50s) and distant future (80s) climate. Each climate forcing is from an Earth System Model downscaled using a Regional Climate Model (e.g., MPI-ESM.CRCM5).

The Changing Nature of Past Excessive Moisture Patterns

As noted above, drought can quickly shift in time and space to wet conditions. Extreme precipitation and resultant flooding can cause considerable damage to agriculture, businesses, communities, infrastructure and ecosystems. Much improved knowledge and awareness of changing patterns of extreme precipitation events with changing climate are needed for successful adaptation. These next sections give a brief overview of past and future expected patterns of extreme precipitation.

Traditionally, excessive wet periods were of less concern in the Canadian Prairies, but recent large-area extreme events such as the Assiniboine River Basin flood of 2011 (Brimelow et al., 2014, 2015) have resulted in considerable impacts including threats to safety, damage to infrastructure, over-topping of reservoirs, and agricultural crop losses. In addition, over the last decade, rapid transitions from extreme dry to wet (and vice versa) conditions over the southern Prairies have occurred (Szeto et al., 2011) and have resulted in damages.

Past excessive moisture periods have occurred to end significant drought periods. For example, a series of storms began in June 2002 after the major drought of 1999 to 2001. Szeto et al. (2011) documented an amazing rainstorm on 8-11 June 2002 that brought 175mm to the Lethbridge, Alberta area and affected an area greater than from Pincher Creek in western Alberta to Winnipeg, Manitoba. The authors found a surprising result that the atmospheric conditions of the extreme drought before the wet period may have enhanced the probability of the storm. Flooding damage occurred in a large area from Alberta across into Manitoba. The return period for such an extreme rainstorm was estimated to range from 258 to 1,486 years (Groeneveld et al., 2004; cited in Szeto et al., 2011).

Then after the drought of 2009 to early 2010 (Table 2.1), the spring of 2010 was the wettest during 1948 to 2012 period, being 64% greater than the areal average for the prairie climate region as documented in the Climate Bulletin (Environment Canada, 2013). The summer of 2010 was also very wet, ranking fourth highest on record.

Spring of 2011 was especially wet with multiple rainfall events of 20mm or greater. The precipitation amounts in southeastern Saskatchewan in April to June 2011 were 150 to 200% or more of their normal amounts prior to an intense 1:100-year event on 17 June 2011 (Hopkinson, 2011). The severe flooding on the prairies was the top weather story for 2011 (Phillips, 2011). More land was flooded than ever recorded. The highest water levels and flows in modern history were recorded across Saskatchewan and parts of Manitoba. Then 2012 was also very wet, with the sixth highest summer areal average precipitation amounts (Environment Canada, 2013).

Although Table 2.1 focuses on major droughts, the gap years are mainly wet years. Even in wet years though smaller pockets of dry conditions can be found and vice versa for dry years. The example of wet to wetter years for Saskatchewan from Table 2.1 includes the years 2000, 2005, 2010 to 2014, and 2019. This frequency is 9 of the 23 years. During these years the Canadian Drought Monitor maps did not show even moderate drought during 2000 to 2022.

The period 2010 to 2013 is an excellent example of a very wet period and may be indicative of near future intense precipitation and wet times. The Canadian Prairies have experienced very extreme wet periods on various time and spatial scales and the region holds some Canadian records. These extreme conditions may represent what may be expected in the future and what society should prepare for.

Patterns of Future Possible Excessive Moisture Conditions

Less research has been conducted regarding the future occurrence of excessive wet periods and flooding across the Canadian Prairies. Much less literature appears to be available for estimates of future extreme precipitation than for drought. This is likely because drought has caused more problems for longer times and larger areas than wet periods, especially for Alberta and Saskatchewan.

An assessment of future flooding risk across Canada was documented in Canada's Changing Climate Report (Bush & Lemmen, 2019). With respect to future Canadian Prairie spring flooding, it was determined that various aspects of a warming climate need to be taken into consideration. For instance, projected increases in winter and spring precipitation will increase flood risk. However, warmer winters and springs will result in more precipitation falling as rain compared to snow and will also cause more periodic snowmelt events and smaller spring snowpacks. This will act to decrease spring flooding risks**.** It is therefore uncertain how projected increases in winter to spring precipitation, higher temperatures and resultant reductions in snow cover will combine to affect the frequency and magnitude of future snowmelt-related flooding. It was determined, however, that projected higher temperatures will result in a shift toward earlier floods associated with spring snowmelt and that projected increases in extreme precipitation are expected to increase the potential for future flooding (Bonsal et al., 2019).

An example of changes in future possible extreme precipitation is from Mladjic et al. (2011). They used ensembles of the Canadian Regional Climate Model for the past and for the future 2040-2071 period. Results for eastern agricultural Saskatchewan are in the range of a 5 to 20% increase in the extreme one-day, three- and five-day precipitation amounts for the 20-year return period. In addition, X. Zhang et al. (2019) found that for the end of century (2081-2100) under the high emission scenario, the extreme 10-year, 24-hour precipitation amount will increase by almost 18%, while the 50-year, 24-hour amount will increase by 21.3% over the Canadian Prairie region.

Future possible excess moisture events are more likely as climate warming increases the moisture-holding capacity of the atmosphere and changes the general circulation. Basic physics, climate model results, and empirical evidence all confirm that climate change will produce more intense precipitation events (Trenberth, 2011). Even though droughts are expected to worsen, substantial inter-annual variability is also expected because of the projected increase in extreme precipitation.

2.6: Discussion and Conclusions

This work addressed several key questions, including: what are the past and future possible patterns of drought and excessive moisture, what is the role of variability, what does this mean for soil water content, what are some implications of these changes and for adaptation in general, including adaptation gaps. The study area is the Canadian Prairies, with examples from Saskatchewan.

New findings about the characteristics of both past and possible future drought and excessive moisture patterns have emerged and are documented. The examination of these extremes from both extremes of the hydrological cycle clearly show the dominance of strong climatic variability. Switching from one to the other in both time and space enhances this variability.

Several past droughts were described, including the ten major severe droughts of the past decades since 1900 were described in terms of life stage evolution and other characteristics. Changes for the near future with the high emission scenario include increases of frequency, duration, rapid retreats and onsets, as well as worst cases of drought persistence. The Canadian Drought Monitor and other sources were used to analyze more recent past droughts during 2000 to 2022. Seven years during that period were found to have been hit with moderate to exceptional drought conditions. Some were multi-year droughts that tend to limit or overwhelm adaptation measures in some cases.

Alternatively, patterns of many years of excessive moisture were also documented. For example, the period 2010 to 2013 is an excellent example of a very wet period, especially for Saskatchewan, and may indicate the nature of future wet times.

Many research findings indicate that several aspects of drought and excessive moisture are projected to increase, including frequency, duration, intensity, and area. The life stages of drought are expected to change, including rapid onset and retreat, and lingering persistence, for example. All of these characteristics cause damage now to ecosystems, agriculture, society, health, and economies. Future damage is expected to increase without considerable attention to the changing nature of drought and excessive moisture, and to enhanced adaptation planning and action.

Work is lacking regarding the impacts of past and future possible drought and excessive moisture patterns for the economy, environment and society. Signs of adaptation gaps exposed by too much and too little water require much more work of many types, including research, planning, communication, evaluation, and implementation. Note that increased variability alone can increase adaptation gaps, as well as the patterns of the wet times and areas getting wetter and the dry times and areas getting drier, with more rapid switches between them. Research regarding the characteristics of changing variability both in the past and future also appears scarce. These extremes are driven by increasing climatic variability at a range of spatio-temporal scales and by climate change. Therefore, these projections and current trends mean further preparation and adaptation are crucial to minimize further damage and loss. Of course, rapid reduction in atmospheric greenhouse gases is also vital for successful adaptation.

Planning for drought and excessive moisture has been accomplished by the provincial and local governments to some extent, yet it is an ongoing requirement of much greater urgency. Both planning and implementation required bolstering. Comprehensive drought and excessive moisture risk assessments are recommended, especially in preparation for prolonged (multi-year) periods of drought and excess moisture. Severe impacts of drought and excessive moisture and projections of climate change clearly demonstrate that our current knowledge of the extremes, their impacts, and adaptation measures are inadequate and must be improved.

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Chapter 3: Risks to water quality and ecosystem health

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Freshwater resources, which are increasingly under stress, are critical for social well-being including human health, development, and food growth. Human use and climate change are driving dynamic changes in water quantity and quality (Rodell et al., 2018). Climate change impacts on water include increased water temperatures (O'Reilly et al., 2015), an increased frequency of extreme events including drought and flood (IPCC, 2021), and increased evaporation (Bonsal et al., 2019). These impacts, together with increased industrial resource extraction (Olive, 2020), and nutrient pollution from runoff from urban and agricultural land (Bergbusch et al., 2021a; Schindler, 2006), further stress water resources, contributing to eutrophication and poor water quality. Other risks to aquatic ecosystems include invasive species and pollution from other substances including mercury and plastic. These risks will be described in more detail in the following sections.

3.1: Effects of climate change on water temperature and lake mixing

It is not surprising that increasing atmospheric temperatures will cause an increase in water temperatures, but the impact of this on lake functioning is complex. Woolway et al. (2022) note that warming water temperatures will cause shorter periods of ice cover, affect lake mixing and water levels, reduce oxygen availability, increase cyanobacterial blooms and reduce habitat of cold-water fish.

The loss of lake ice with climate warming (Lopez et al., 2019; Sharma et al., 2019) may create considerable risk in Saskatchewan (see Woolway & Merchant, 2019 for map of ice loss). If ice roads are open for a shorter period of time, northern areas of the province may lose important transportation (Knoll et al., 2019; Woolway et al., 2022). Shorter ice cover may affect cultural practices and there are demonstrated impacts of climate change in canceling of spiritual ceremonies, recreational ice skating, and ice fishing tournaments (Knoll et al., 2019). Sharma et al. (2020) also found that winter drownings were increasing as winter air temperatures increase in ice-covered regions, including Canada.

Lake warming is also anticipated to affect lake mixing and thermal stratification (changes in temperature with depth) (Woolway & Merchant, 2019), which has consequences for oxygen and nutrient availability and food web dynamics (Woolway et al., 2021). A modeling study of Lake Diefenbaker suggests that climate warming will increase stratification strength in this lake (Morales-Marin et al., 2021), which could impact phosphorus availability in the water column (North et al., 2015).

Evidence for the impact of increased water temperature and effects on lake mixing in Saskatchewan is sparse. The risks of ice loss, shorter ice cover, etc. have been demonstrated elsewhere, and are likely to be a concern here as well. Lakes in southern Saskatchewan in particular are often polymictic (mix several times per year with shorter periods of thermal stratification), but climate warming is likely to shift these systems into a dimictic state. Lakes in northern SK may switch from cold monomictic (one mixing period in summer) to dimictic (stratified during summer and winter, with spring and fall mixing events). These mixing regimes have profound impacts on oxygen availability, nutrient resuspension from the sediments, and subsequently fish populations and algal blooms (Woolway et al., 2021).

Oxygen saturation in water is directly related to water temperature, with warmer water holding less oxygen (Wetzel, 2001), thus there is a general concern that climate warming will reduce lake oxygen concentrations. A study of almost 400 lakes around the world (including six of the Qu'Appelle lakes) found that oxygen concentrations in lakes are decreasing at a rate 2.75 to 9.3 times greater than the oceans (Jane et al., 2021). Low oxygen will be detrimental for fish and invertebrates, alter the availability of nutrients, and increase the toxicity of metals (Golosov et al., 2012). Increased stratification under increasing temperatures can cause a reduction of suitable fish habitat with implications for recreational and subsistence fishing (Missaghi et al., 2017).

3.2: Effects of climate change on prairie lake food webs

Large die-offs of fish known as fish kills, which can occur both in the summer and winter, are not uncommon in prairie lakes (R. I. Hall et al., 1999). Examples of recent summer fish kills include the Qu'Appelle lakes in 2021 (Benson, 2021). While disease sometimes contributes to fish kills, often low oxygen caused by decomposition of algal blooms or high temperatures is the main culprit (Materie, 2021). Climate change is therefore expected to contribute to more summer fish kills in the future (Benson, 2021).

Winter fish kills (aka winterkill) are more common in shallow lakes with high nutrients, such as Wascana Lake (Radford, 2021) and Humboldt Lake, where winterkills occurred in 2005 (Robarts et al., 2005) and 2020 (Woodward, 2020). The effects of climate change on winterkill and fish health are not certain and depend on the characteristics of each lake. On the one hand, as the climate becomes drier, the expected decrease in water depth and increases in salinity, nutrients and temperature would increase the probability of winterkill (Cooper & Wissel, 2012) and/or decrease fish reproductive success (Zalewski et al., 1990). This latter point was supported by a study of 7 fish-bearing lakes where a decrease in zooplankton species from drought years to years with higher precipitation was likely due to decreased fish predation during the drought period (Starks et al., 2014). On the other hand, as winters become milder and the duration of ice cover decreases (Knoll et al., 2019), the shorter duration of ice cover may reduce the threat of winterkill (Cooper & Wissel, 2012).

Changes in climate can also impact important food web processes in lakes. One example is the clear water phase (CWP), which is a period in early summer when water clarity is at its greatest. While several factors can contribute to the CWP, in lakes in the Qu'Appelle River basin in Southern Saskatchewan, the CWP is driven mainly by a type of large zooplankton/invertebrate (called *Daphnia*) feeding on a type of algae (diatoms) (Dröscher et al., 2008). Dröscher et al. (2009) looked at the effects of various factors on the timing and intensity of the CWP over ten years in six lakes in the Qu'Appelle River basin. While transfer of energy (heat) to the lakes and lake volume had the greatest effect, changes in the winter index of the North Atlantic Oscillation (NAO) and precipitation from February to April also impacted CWP timing and intensity, demonstrating how changes in climate can affect food web processes in lakes in Southern Saskatchewan (Dröscher et al., 2009).

3.3: Effects of increasing temperature on water quality (algal growth) in prairie lakes

Lakes in the prairie ecozone of Southern Saskatchewan tend to naturally have lower water clarity and higher algal growth compared to more northern lakes, which can be attributed to naturally high levels of phosphorus from glacier deposits in prairie soils (R. I. Hall et al., 1999; Quinlan et al., 2002). A sediment core taken from the bottom of a prairie lake (Pasqua Lake) demonstrated this by showing that algal species characteristic of poor water quality were present before European settlement in 1890 (R. I. Hall et al., 1999). However, the same core also showed a substantial decline in water quality in Pasqua Lake since ~1930, as shown by increases in pigments acting as proxies for total algal biomass and cyanobacteria (R. I. Hall et al., 1999). This shows how human activities have further degraded water quality in prairie lakes.

In R.I. Hall et al. (1999), resource use (including agriculture and aquatic resource use) and urban factors were the strongest factors explaining the variation in the algal community in the core from Pasqua Lake. Later studies have further illustrated the contributions of nutrient (particularly nitrogen) pollution from urban and agricultural sources in increasing algal growth in prairie lakes. These include urban sewage entering water bodies through point sources (Leavitt et al., 2006) and nitrogen fertilizer, particularly in the form of urea, entering water bodies through surface (rain and snow melt) runoff (Donald et al., 2011; Finlay et al., 2010; Swarbrick et al., 2020).

While climate variables (including air temperature, evaporation, and number of ice-free days) also affected the algal community in the sediment core in R.I. Hall et al. (1999), they had more of an effect when in combination with resource use and urban factors. Later studies have also illustrated that while nutrients are a key factor, changes in climate can also affect water quality in prairie lakes. For example, Vogt et al. (2015) found that the interaction of the Pacific Decadal Oscilliation (PDO) with the El Niño–Southern Oscillation (ENSO) explained 30% of variation in water clarity in a prairie reservoir (Lake Diefenbaker). In other words, the water was more clear in years with drier winters (Vogt et al., 2015).

Another study conducted a scenario analysis predicting how changes in inflow, temperature, and nutrient influx would affect total algae and surface blooms in six prairie lakes over 16 years (Vogt et al., 2018). They found that temperature change had the greatest impact on total algae and surface blooms, followed by changes in nutrients and then changes in inflow (Vogt et al., 2018). To combat the effects of these increases in water temperature, Vogt et al. (2018) recommended reducing nutrient influx to water bodies as the most practical way to reduce algal growth in the immediate future.

Effects of increasing temperature on cyanobacteria in prairie lakes

Another impact of warmer water temperatures is an increase in cyanobacteria or blue-green algae, which tend to proliferate in warmer water temperatures compared to other types of algae (Paerl & Huisman, 2008). Cyanobacteria can also produce toxins such as microcystin, a liver toxin that can negatively impact humans and other animals (Hayes et al., 2020). In a study using summer data over 10 years from six prairie lakes, warmer water temperatures contributed to increased concentrations of microcystin, demonstrating how warmer water temperatures are contributing to an increase in cyanobacterial toxin production (Hayes et al., 2020). Increases in algal blooms due to warmer temperatures are also concerning for fish because decomposition of algae can consume oxygen and reduce habitat for fish and other aquatic organisms (Paerl & Otten, 2013).

Lastly, warmer temperatures may combine with nutrient pollution to lead to unexpected phenomenon. An example of this occurred in March 2021 at Pasqua Lake when ice fishers reported blue staining in the lake ice and water (Haig et al., 2022). Analyses revealed that this staining was due to high concentrations of a cyanobacterial pigment which was released after a cyanobacterial bloom froze into the ice in late October 2020 (Haig et al., 2022). Cyanobacterial blooms of this type occurring in October is rare and may have been related to warmer than normal temperatures at the time (Haig et al., 2022). While concentrations of the cyanobacterial toxin microcystin were low in the March 2021 samples, this incident still raised public concern over the water quality of the lake (Haig et al., 2022).

3.4: Droughts and floods can impact water quality through discharge and associated dissolved and particulate constituents

Increased precipitation will cause higher runoff into aquatic ecosystems and could potentially load more nutrients and contaminants into these systems. In Saskatchewan, climate change has resulted in more precipitation falling as rain, rather than snow, with large impacts on hydrology and increasing runoff efficiency (Pattison-Williams et al., 2018). MacKinnon et al. (2016) found that higher precipitation increased the connectivity of the Saskatchewan River Delta, which raised nutrient concentrations, increased pH, and elevated the salinity of the systems. In a review of the interactions between flooding with land use across Canada (urbanization, agriculture and forestry), St-Hilaire et al. (2016) note that flooding can increase loading of nutrients, pesticides, pathogens and sediments in agricultural watersheds.

On the flip side, the impact of droughts can cause water quality issues in water bodies through alterations in mixing regimes and evapoconcentration of solutes. Hudson & Vandergucht (2015) noted that in a drought year, Lake Diefenbaker had a larger anoxic region, and had larger algal blooms than normal or flood years.

Effects of drought on lake level and ecosystem functioning can be particularly dramatic in closed-basin systems which are common in southern Saskatchewan. With limited inflow and outflow, closed systems only receive water and watershed loading through runoff and water outflows are typically via spillover, rather than through channelized outflows. A paleolimnological evaluation of Kenosee and White Bear lakes in southeastern Saskatchewan demonstrated a lake level decrease of over 8m since 1900. This lake level change affected the mixing, oxygen, and light regimes in the lakes, with a notable increase in purple sulfur bacteria during low lake levels (Bjorndahl et al., 2022). This dramatic change in lake level will also affect recreation in the area as shoreline exposure, boat and water access will be severely impacted with an 8m water level change.

3.5: Invasive species

Climate change is also known to affect the presence and spread of invasive species (A. L. Smith et al., 2012). As the climate warms, and precipitation regimes are altered, habitat suitability often favours the spread of invasive species from south to north. Additionally, increasing frequency of extreme events may make ecosystems more vulnerable to the invasion of new species (A. L. Smith et al., 2012). Of the frequently studied invasive species identified, the major aquatic species of concern are the zebra mussel (expansion northward and to higher elevations, Thorp et al., 1998) and smallmouth bass (northward expansion expected, Sharma et al., 2009). Coldwater fish species such as lake trout, which are present in Lake Diefenbaker and lakes in Northern Saskatchewan, may be vulnerable to invasion of smallmouth bass which are a warmwater species (Jackson, 2002; Vander Zanden et al., 2004; cited in Sharma et al., 2009). Sharma et al. (2009) notes that 12% of lakes with lake trout populations in Canada are at risk of invasion by smallmouth bass.

In Saskatchewan, several species have been identified as potential and real invasive species of concern. A 2015 MSc thesis by Zhang at the University of Saskatchewan (Z. Zhang, 2015) evaluated the risk of 16 potential aquatic invasive species in a few watersheds in the province, and found that purple loosestrife, zebra mussel, and saltcedar are at very high risk of invading and impacting ecosystems. Curly-leaved pondweed, common carp, narrow-leave cattail, reed canary grass, Eurasian water-milfoil, faucet snail, New Zealand mudsnail, spiny waterflea, round goby and silver carp are all considered medium risk. Interestingly, an evaluation of residents' knowledge of, and therefore vigilance for aquatic invasive species indicated that residents were more aware of non-native fish species, compared to invasive plant species, indicating a need for education (Nanayakkara et al., 2018). Prussian carp has also started to invade Saskatchewan lakes, entering the province via Alberta and is anticipated to continue to spread and outcompete other native species (Hamilton, 2021; Hamilton & Somers, 2019).

3.6: Mercury in fish

Larger fish and fish that eat other fish usually have higher mercury concentrations compared to smaller fish and fish that only eat plankton (Donald et al., 2015; Government of Saskatchewan, 2015). The Government of Saskatchewan may issue advisories if mercury levels of fish in certain lakes reach high levels that may negatively impact children or people who are pregnant (CTV News, 2009). Lakes in southern Saskatchewan tend to have both high mercury concentrations in fish and high algal growth, which is unusual compared to other lakes (B. D. Hall et al., 2020). One study suggests that large invertebrates may be transferring mercury from the bottom of the lake to fish at the surface via a "mercury elevator" at night (B. D. Hall et al., 2020).

3.7: Plastic pollution

Pollution from substances in municipal waste is another concern, including microplastics (plastic with a diameter < 5mm) and microfibers from textiles. Plastic pollution is present in marine and freshwater environments all around the world, but it is still unclear what risks it poses to aquatic organisms and their ecosystems (Bujaczek et al., 2021). Baseline studies in Western Canada have found microplastics and microfibers in the North Saskatchewan River near Edmonton (Bujaczek et al., 2021), effluent from the Saskatoon's wastewater treatment plant (Prajapati et al., 2021) and in both water and fish samples in Wascana Creek both upstream and downstream of Regina's wastewater treatment plant (S. H. Campbell et al., 2017).

3.8: Agricultural Pond water quality under a changing climate

Concerns about water quality in agricultural ponds (wetland ponds and dugouts) are common in Saskatchewan, and climate change is likely to exacerbate these issues. Most of the above mechanisms noted for natural lakes will also apply to smaller systems, with increasing algal blooms, cyanobacterial toxicity, nutrients, and decreased water levels being major concerns (Andresen et al., 2015). In addition, given their use for livestock watering in particular, concerns about salinity and sulfates in dugouts are common and increasing in frequency. Sulfate concentrations in agricultural dugouts and wetland ponds are currently one of the largest threats to water quality for cattle health on the Canadian Prairies (J. Campbell, 2017, 2018; Glen, 2019) and are likely to become more commonly problematic with climate change.

3.9: Indigenous views of water quality and climate change

It is estimated that at any given time, one in five Indigenous communities in Canada is under a boil water advisory (Patrick et al., 2019). A map of current and past drinking water advisories in Saskatchewan and their proximity to Indigenous communities is shown in Figure 3.1, which is taken from Awume et al. (2020). There are many reasons for the high number of drinking water advisories in Indigenous communities, including inadequate technology, changing land use, and lack of federal funding. Climate change is expected to exacerbate these issues as well by contributing to deteriorating source water quality, as described above. The above review focuses almost entirely on a western view of water quality, whereby water is a resource to be used for and by humans. Indigenous perspectives provide a more holistic view of water related issues and concerns, including the need to view water as a life form, the relationship between water and the spirit world, women as water-keepers, water and human ethics, and water in Indigenous culture (Awume et al., 2020).

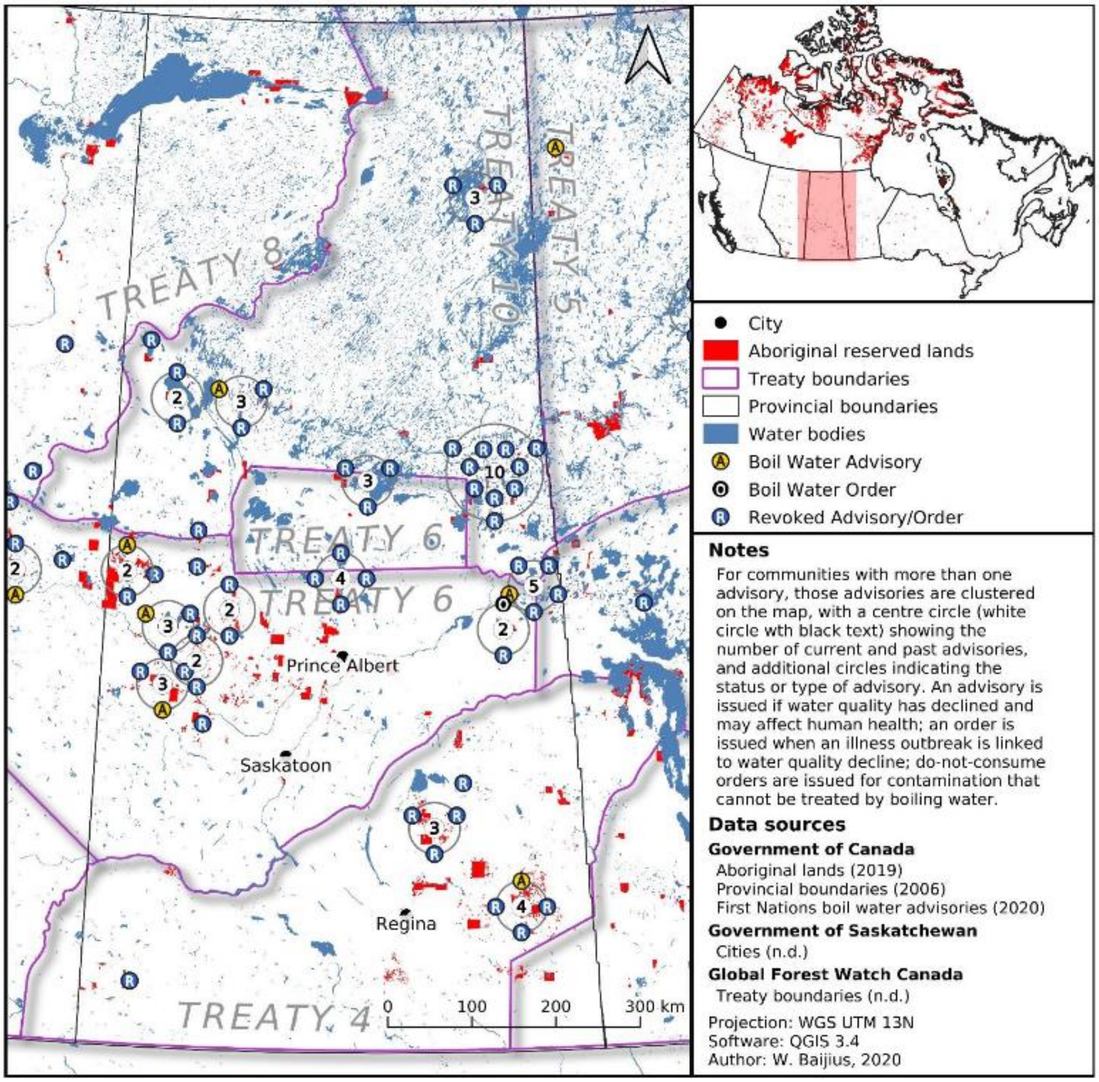

Figure 3.1: Treaty areas, Aboriginal reserved lands, and current and past boil water advisories in Saskatchewan. This figure comes from Figure 1 in Awume et al. (2020).

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Chapter 4: Risks to primary economic sectors

Oscar Zapata and Gabriela Beltrán

4.1: Introduction

The importance of water for the economy.

The economic importance of the South Saskatchewan River (SSR) and the South Saskatchewan River Basin (SSRB).

4.2: Water as an input and consumption good

Water is a precious economic resource whose uses present fundamental economic characteristics. In general, economic goods fall into four categories depending on two characteristics: rivalry and excludability in consumption. Rivalry in consumption (use) consists of competing uses for water that prevents an activity from using it once another has used it. For example, once a water bottle is purchased and consumed by a consumer is no longer available to be consumed by someone else. In this sense, this good is rival in consumption. Excludability refers to the economic, technical or natural feasibility of excluding water users from accessing the resource. A common excludable mechanism is the price of a good, which can be acceptable to some consumers and too expensive to others. The latter group is automatically excluded from consuming or using the resource.

The combination of the characteristics of rivalry and excludability yields four possible categories for the uses of water, as shown in the table below:

	Excludable	Non-excludable
Rival	Private goods	Common pool/open access resources
Non-rival	Club goods	Public goods

Private goods are rival and excludable in consumption (use) and provided through markets where prices function as an exclusion mechanism. Examples of water as a public good include household water consumption and irrigated water in agriculture. The opposite category corresponds to public goods that are non-rival and non-excludable. Some examples of water as a public good include the benefits of water conservation or the protection of water sources and hydrological services (e.g., mitigation of climate change that reduces glacier melting and preservation of river basins). Intermediate categories include open-access resources and club goods. Open access resources are rival and non-excludable, which presents congestion problems when many users want to enjoy water resources. An example of water use as an open-access resource is leisure activities in a lake. If too many swimmers, fishermen and sailors come to the lake simultaneously, the enjoyment of their activities will reduce due to congestion. Club goods are excludable and non-rival, implying that once users have access to the resource, their uses do not affect others' consumption. Examples of water use as a club good include swimming pools with membership or an entry fee and golf club members that enjoy well-irrigated fields.

Except for water uses as private goods that can be efficiently allocated through market mechanisms, the other three categories involve market failures requiring public interventions to allocate water resources efficiently. Market failures, such as externalities, uncertainty and asymmetric information, promote either over-exploitation or insufficient sustainable practices and conservation of water resources.

4.3: Economic sectors in Saskatchewan

Canadian agriculture is a spatially heterogeneous industry and therefore, climate change currently does and, in the future, would have different impacts in different regions. At a regional level, these impacts are related not only to different climate characteristics but also to differing enterprise combinations.

A review of studies suggests a wide range of impacts on crop production.

Agricultural impacts

Crops / Irrigation

- Canada's SK Prairies family farms are generally "corporate farms" but there are some "smaller corp farms" - they manage large-scale dryland rainfed agriculture; Irrigation is employed in <5% of the land (very water scarce) so irrigated agriculture uses 22% of the river water (highest water use).
- Irrigation is set to expand, but is very expensive and requires federal, provincial, local farm producer funding. Groundwater is deep below the surface, and too salty to use for crop production as it is highly mineralized.

Units of analysis:

- Size of agricultural producer.
- Types of crops and water requirements.

Table 4.1: Saskatchewan’s Share of World Export Market 2021:

Saskatchewan's Share of World Export Market 2021:

56% Canary Seed	**35%** Durum Wheat	**19%** Canola Seed
51% Lentils	**27%** Canola Meal	**19%** Mustard Seed
36% Peas	**23%** Oats	**16%** Flax Seed

Canola

The biggest crop in Saskatchewan was canola. In 2021, farms in Saskatchewan reported the largest canola area in Canada with 12.0 million acres, up 8.2% from 2016. The province accounted for over half (53.8%) of Canada's canola area.

Cereal grain

Cereal grain includes wheat, barley and oats, among other crops. In 2021, Saskatchewan accounted for 44.3% of Canada's total spring wheat area.

The province also made up a significant share of the country's durum wheat area. In 2021, the province accounted for 81.4% of Canada's total durum wheat area, with 4.7 million acres.

Saskatchewan reported the second largest barley area in Canada, with 3.6 million acres of barley, up 45.8% since 2016. The province accounted for 43.7% of Canada's total barley area.

In 2021, farms in Saskatchewan reported 1.7 million acres of oats, the province reported the largest oats area; it accounted for 46.0% of Canada's total oats area.

Pulse crop

Lentils, faba beans and chickpeas are classified as pulse crops. In 2021, farms in Saskatchewan reported the largest lentil area, with 3.8 million acres, the province accounted for 89.3% of Canada's total lentil area.

In 2021, farms in Saskatchewan also reported the largest faba bean area, with 61,301 acres, which accounted for 50.5% of Canada's total faba bean area. Farms in that province also reported the largest chickpea area, with 168,654 acres in 2021, the province accounted for 76.0% of Canada's total chickpea area.

The wide range of estimated impacts of climate change on crop yields may be a result of studies employing different methodologies, assumptions related to the following variables:

- Regional precipitation
- Projection period
- CO_2 fertilization effect
- Shift of agro-ecosystems.
- Water pollution
- Insect pests and diseases.

In 2020, farms classified as oilseed and grain accounted for more than three-quarters ($13.6 billion) of the province's total farm operating revenues. This was followed by farms classified as beef and feedlots ($1.8 billion) and other crops ($454.3 million).

In 2020, farms in Saskatchewan reported $16.8 billion in total farm operating revenues, accounting for 19.3% of Canada's total farm operating revenues.4

Livestock, empirical studies related to climate change impacts on livestock are lacking, although conceptually, impacts are negative due to adverse impacts on forage, pastures, and feed grain production, and on livestock productivity.

4.4: Water allocation

Efficiency is one of the most important criteria to determine and assess water allocation considering the multiple competing uses. The opportunity costs of using water shows the economic sectors where water brings the largest benefits to society. These benefits refer to society's wellbeing that captures households' benefits and profits for economic activities. From a normative perspective, water uses with the lowest opportunity costs should access the resource with priority since they contribute to social wellbeing more.

Competing uses of water in Saskatchewan include sectors such as households, municipalities, industries and ecosystems. An efficient allocation of the resource occurs across and within sectors even when water resources are abundant. For example, Cutlac and Horbulyk (2011) model water allocations among farmers in the Alberta portion of the SSRB and determine that reallocations of water can increase the social benefits by 21% (from $930 million to $1,123 million per year), even under conditions of relative water abundance. However, the assumption behind these results is that water can be freely moved across farmers, which place these estimates as potential gains from reallocation.

An alternative way to define efficiency is by pointing out the gap between the potential water efficiency and its actual use. Ali and Klein (2014) employing an input-output agricultural model determine that the average efficiency in irrigation districts of Alberta in the SSRB region reaches 84%. The interpretation of their findings is that an efficient allocation of water implies that irrigated farms in the region could on average use 16% less inputs, and that available water using the existing farming technology would be enough to expand the irrigated land by 58% (Ali and Klein, 2014).

Using a system dynamics approach, an integrated water resources system model is developed for scenario analysis of the Saskatchewan portion of the transboundary Saskatchewan River Basin in western Canada. Results reveal that the water re-sources system in Saskatchewan becomes increasingly sensitive to the selection of evapotranspiration algorithm as the irrigation area increases, due to competition between hydropower and agriculture. Preliminary results suggest that irrigation expansion would decrease hydropower production, but might increase the total direct economic benefits to Saskatchewan. However, indirect costs include reduction in lake levels and river flows (Hassanzadeh et al., 2014).

Efficiency gains from improved water use can also occur within a specific activity through recycling and reusing water. One important water user in Saskatchewan is the mining industry. Specifically, the SSR constitutes the main water source for the potash industry, where water losses reach 40% of the water intake (Reid, 1984). It is loss levels that opens an opportunity to increase water efficiency in the potash industry through water reuse during the production process, which will reduce potential competition for water between the industry and agriculture (Reid, 1984).

4.5: The economic value of water

Water resources can be directly or indirectly used. Direct consumption includes household uses of water (e.g., human consumption and hygiene, laundry and dishwashing, garden watering) and leisure activities in water bodies (e.g., swimming, sailing, fishing, and landscape viewing). Other uses related to spirituality and culture are also direct consumption of water. Preferences and the demand function for water provide the information needed to establish the economic value of water for direct consumption. The specific measure of value is the willingness to pay (WTP).

A series of studies look at the economic value of water from the SSR in the city of Saskatoon. The first study determines the total value of uses of the river for different uses and users (Kulshreshtha and Gillies, 1993a). Using the concept of economic surplus (i.e., consumer and producer surplus) the authors establish a value estimated between $8.1 to $11.1 million per year for domestic water use, between $12.3 to $16.7 million per year for waste assimilation and aesthetic benefits to residents valued at $1.2 million per year (Kulshreshtha and Gillies, 1993a). Additional benefits occur outside the city limits, specifically for irrigation and power generation, valued at $2.36 million per year (Kulshreshtha and Gillies, 1993a).

A similar study looked at residents' and businesses' perceptions in Saskatoon about the SSR about economic, aesthetic and recreational uses of water. Gillies et al. (1989) find that 78% of residents did not consider the river as a factor to decide to live in Saskatoon. Additionally, around two-thirds of residents (between 57%-77%) agree that the SSR contributes to recreational opportunities and quality of life. A smaller share of businesses (32-42%) consider that the river contributes to attracting or retaining employees (32-425) and to their quality of life (69%) (Gillies et al., 1989). This study suggests that more information for Saskatoon residents about the contribution of water to life in the city will improve perceptions about the economic value of the resource.

Recreation and leisure activities are also direct uses of water. In a different study, Kulshreshtha and Gillies (1993b) find that 80% of the surveyed residents (i.e., a contingent valuation application) and less than 20% of businesses use the SSR for recreational activities. The economic value of the river for leisure purposes, based on WTP, reached $2.6 million for individuals and $0.25 million for local business in 1989 (Kulshreshtha and Gillies, 1993b). Taken the two studies by Kulshreshtha and Gillies (1993a, 1993b) together, the estimated total economic value of the SSR for Saskatoon residents reaches values between $27 to $34 million per year.

Changes in water availability measured by river flows can alter the economic value and the cost of accessing the resource. Kulshreshtha and Gillies (1994) evaluate the value consequences of increases and decreases in river flows and find that gains from flow increases are smaller than those from flow decreases. The former, relatively small, were valued at $375.2 thousand per year, whereas the latter reached a value of $2.3 million per year (Kulshreshtha and Gillies, 1994). Specifically, these authors consider changes in the economic value of water supply, waste assimilation, river-dependent businesses, river water related recreation, and aesthetic enhancement of the city that result from changes in river water flows.

An important economic use of water for recreational purposes occurs in tourist destinations, including protected areas and natural parks. Kulshreshtha (1991) determines the value of water-related outdoor in 21 recreation sites in Saskatchewan in 1986 using two methodologies (i.e., the travel-cost method and contingent valuation) to calculate WTP. The estimated average value per visitor day is $3.90, an estimate ranging from $0.71 to $14.67 per visitor day (Kulshreshtha, 1991).

An essential direct water use is human consumption at home. Although this type of consumption has been long considered as a human right and promoted through Sustainable Development Goal 6 (Clean water and sanitation), the satisfaction of this basic need is unequal in society. In Saskatchewan, access to safe drinkable water depends on one is located. The situation in remote and Indigenous communities, that depend on small drinking water systems, is inadequate compared to what happens in urban centres. McLeod et al. (2020) study the problem of water advisories in Saskatchewan and report 384 communities reporting advisories during 2012 – 2016. The authors find that median number of advisories per community is 3, while their median length is 8 days and the median total length during the study period reaches 52 days (McLeod et al., 2020).

Indirect water consumption refers to using the resource as an input in production processes. Agriculture, industry (e.g., mining and energy), tourism/recreation and water utilities are some sectors utilizing water to produce other goods and services. Productivity and contributions to total output determine the value of water as an input. Water enters the production function of economic activities contributing to output directly and in interaction with other factors of production, such as land, seeds and technological alternatives (i.e., water-saving technologies, including climate-resistant crops or precision irrigation systems). The substitutability between water and other factors of production (i.e., trade-offs and opportunity costs) can also reveal the economic contribution of water to production processes.

A study comparing the average economic value of irrigation in the SSRB of Alberta (four sub-basins) and Saskatchewan (one sub-basin) identifies the crops with the highest net return to water use (i.e., profitability), placing alfalfa silage use primarily to feed cattle on top, followed by potato, corn silage, alfalfa, wheat, and timothy (Samarawickrema and Kulshreshtha, 2008a). The estimated values range between $16.95 per dam3 in Alberta sub-basin of the SSRB and $24.90 per dam3 in the Oldman River Sub-basin, whereas in Saskatchewan this value was estimated to be $9.58 per dam3 in the southwest Saskatchewan region and $61.74 per dam3 in the Lake Diefenbaker Development Area (LDDA) (Samarawickrema and Kulshreshtha, 2008a). This study suggests that the mix of crops and irrigation practices determine the profitability of farming in the region, specifically the high economic value of water in LDDA, relative to the Alberta sub-basins, results from differences in irrigated crops mix between the two regions (Samarawickrema and Kulshreshtha, 2008a).

Irrigation constitutes not only a production technology in agriculture but also a mechanism to smooth farming income in the face of climate disasters. In Saskatchewan, droughts constitute costly climate events. Samarawickrema and Kulshreshtha (2008b) compare the profitability of irrigated and dryland production systems for crop production in the Alberta sub-basin of the SSRB to establish the benefits of irrigation during drought years. Short-run value estimates ranged from $37 per dam3 in the Bow River sub-basin to $42 per dam3 in the Oldman River sub-basin (Samarawickrema and Kulshreshtha, 2008b). These results suggest that water used for irrigation provides additional benefits beyond enhanced producer income in crop production during periods of water scarcity (i.e., soil moisture deficits).

For the allocation of water resources occurring through markets, prices and quantities constitute the elements to find the economic value of water employing methods based on market conditions (i.e., revealed-preference methods including productivity changes, avoided costs, hedonic pricing and travel cost). For other water allocations, especially under market failures, nonmarket methodologies (i.e., stated-preference methods, such as contingent valuation and choice experiments) help determine the economic value of water resources.

4.6: Remaining questions

- How does the economic value of water change when weather conditions vary?
- How does the benefit of water use for users (consumers and producers) vary when weather conditions change?
    - What is the effect of changes in weather patterns on farming profits?
- What are the economic benefits of specific adaptation measures to changes in water availability?
    - What are the profits associated with changes in production technologies in agriculture and crop mix?
- What is the trend of crop insurance coverage over time in Saskatchewan?
    - How do insurance purchases affect other adaptation strategies in agriculture (e.g., moral hazard and adverse selection)?
- How do new infrastructure projects (e.g., dams and reservoirs) discourage farmers from adopting water efficient production technologies and behaviour?
- How equal is the access to adaptation strategies (e.g., insurance, water-saving technologies, information) across and within economic sectors?
- What is the benefit/cost analysis of different adaptation strategies?

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Chapter 5: Land use and water-related climate risk in Saskatchewan

Barbara Kishchuk

5.1: Context

Agricultural water management in Saskatchewan includes, but is not limited to, surface drainage of agricultural land including natural wetlands, and irrigation (e.g. Baulch et al., 2021; Minnes et al., 2020). Some agricultural water management practices, as well as other land use changes and practices, may directly and indirectly affect water-related climate risks in Saskatchewan. Agricultural drainage is a specific case of land use change, because the diverted water is not the ultimately sought product or commodity (e.g. Breen et al., 2018). Instead, drainage increases the extent of arable land and facilitates agronomic operations, thereby increasing net economic accruals from crop production (Cortus et al., 2011; Olson, 2021; Pattison-Williams et al., 2018).

The history, motivations and drivers for agricultural drainage in Saskatchewan and its effects on watershed function, water quality, biodiversity, carbon, and economics have been comprehensively reviewed elsewhere (e.g. Baulch et al., 2021; Breen et al., 2018; Cortus et al., 2011; Minnes et al., 2020; Olson, 2021; Pattison-Williams et al., 2018). Overall, there are both direct and indirect effects on spatial and temporal water distribution and volume, land and substrate, nutrient and carbon fluxes, infrastructure, and habitat.

In addition to drainage, other land use changes include conversion of any existing land use such as wetlands or grasslands to cultivated crops, for the purpose of increasing arable area and associated revenue streams. Cropping practices on converted lands may exacerbate existing issues of nutrient export and water quality (Baulch et al., 2021) and shifts in carbon sink-source relationships, and increase the land area subject to agricultural water management practices.

5.2: Implications of land use change for climate risk

Bonsal et al. (2019), Sauchyn et al. (2020), and Bonsal & Sauchyn (2022) describe changes and anticipated trends in temperature and precipitation in the prairie region, which include the form and timing of precipitation, and changes in seasonal freshwater availability. At a regional scale, if a primary effect of agricultural drainage is the disruption of watershed function and water storage (e.g. Olson, 2021), then watershed ability to absorb current and predicted climatic changes is altered. At local scales, key issues include variability and uncertainty of water supply, drought and excess water, and continuity and productivity of surface vegetation cover. At all scales, uncertainty of response to climate variability is increased when the biophysical landscape on which past observation and planning has occurred is altered, and the reliable prediction of future conditions is diminished. There is additional risk in not quantifying the additive and cumulative effects of land use change and climate-driven changes on water regimes.

Another form of land use change is reversion to a previous state, such as wetland restoration (e.g. Cortus et al., 2011). Such reversals should mitigate or reduce risks to land and watershed function. However, in the absence of pre-intervention baselines, such as how undrained landscapes would respond to currently observed changes in precipitation, determining the net effect of land use change, whether positive or negative and by what metrics, is challenging.

5.3: References

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Appendices

Appendix A: Impacts of water security risks on four sectors (livelihoods, primary economic activities, ecosystems, and infrastructure) in Southern Saskatchewan.

The table below summarizes risks to water security in Southern Saskatchewan, as identified by our partners during the September 20, 2022 partners meeting and by the Canadian researchers in chapters 2-5. Table A is a two-page summary of this appendix. Our definitions of risk and water security are in Chapter 1. The citations for Corkal (2018) draw from synthesised summaries from workshops in six different regions of Saskatchewan. Additional details for present and future impacts (2050s climate scenario) are provided in Corkal (2018) for these six regions (Yorkton, Saskatoon, Prince Albert, La Ronge, Swift Current, and Regina).

	Sectors			
Risk categories	**Livelihoods**	**Primary economic activities**	**Ecosystems**	**Infrastructure**
Risks related to water scarcity • Recurring drought is characteristic of the southern areas of the Canadian Prairie provinces (Bonsal, Wheaton, Chipanshi, et al., 2011), as shown by instrumental records and supported by paleoclimate records such as tree rings (Sauchyn & Kerr, 2016). • Droughts in this area are projected to increase in intensity, duration, and frequency (Axelson et al., 2009; Bonsal et al., 2013). • Tree-ring records also project longer and more severe droughts than those recorded since	• Social and institutional impacts (water use competition & priorities, loss of trust; impaired and unequal coping by people) (Corkal, 2018 Table A). • Droughts tend to cost more, cause more damage last longer and cover larger areas than other weather extremes, making impacts worse (Bonsal et al., 2020). • Drought impacts water for household use (urban and rural), including water for household food production and rural subsistence	• Sector impacts (e.g. agriculture, energy) and economic downturn; severe impacts to agricultural land and farm production (crops, livestock), and off-farm impacts to Saskatchewan communities (Corkal, 2018 Table A). • Agriculture is a prominent part of Saskatchewan's economy. In 2020, farms in Saskatchewan reported $16.8 billion in total farm operating revenues, accounting for 19.3% of Canada's total farm	• Land, water & ecosystem impacts (poor water quality; plant, animal, and wildlife diseases; impairment of agricultural land resources; impaired ecosystems including grasslands, wetlands, and other aquatic ecosystems, wetland loss, soil erosion and degradation, increasing grassland and forest wildfire risks, and habitat destruction) (Bonsal, Wheaton, Chipanshi, et al., 2011; Corkal, 2018	• Community and Municipal Water (quality, supply, community evacuation) (Corkal, 2018 Table A). • Improved opportunities for road maintenance (Corkal, 2018 Table A). • Impacts on water infrastructure (including hydropower generation) (Wheaton et al., 2005). • Water is needed for other critical infrastructure

	Sectors			
Risk categories	Livelihoods	Primary economic activities	Ecosystems	Infrastructure
settlers occupied the Prairies (Axelson et al., 2009). • Evapotranspiration is projected to increase more than precipitation (Bonsal et al., 2019; Trenberth, 2011), leading to an increased risk of water supply shortages in the summer. • Under a high emissions scenario for 2081-2100, summer precipitation is projected to decrease in the southern areas of the Canadian provinces (Figure 4.18 in Bush & Lemmen, 2019).	economies (September 2022 partners meeting). • Concerns with overconsumption and combined number of users of water: how much water is available for the environment vs for human use? (September 2022 partners meeting). • Lack of control: what happens upstream (in Alberta) affects the prairies (September 2022 partners meeting). • Restricted water quality and quantity for northern communities (September 2022 partners meeting). • Movement of people (e.g., 1930s, 2001/2002: cattle industry moved from Alberta to Manitoba) (September 2022 partners meeting). • Water governance (September 2022 partners meeting). • Crop insurance dependency	operating revenues (St. Pierre & Mhlanga, 2022). • Impacts of drought on agriculture include decreased crop, grassland, and hay yields, decreased on-farm water supplies, poor soil moisture, soil erosion, outbreaks of pests (ex. grasshoppers), and concerns regarding water quality and feed for livestock (AAFC, 2022). • The greatest impacts of drought often occur during the growing season, as shown in nine out of ten major droughts in the Canadian Prairies from 1900-2014 (Bonsal et al., 2020), which impacts the agricultural sector. • During the 2001 and 2002 drought years, Canada's Gross Domestic Product fell by an estimated $5.8 billion, while previously reliable water supplies such as	Table A). • A challenge with studying drought is that drought impacts are mostly invisible (e.g., soil moisture, plant stress) compared to other impacts such as wildfires and thus require comparisons, monitoring, and evaluation over time (E. Wheaton, personal communication). • Droughts can interact with other extreme events. For example, hail can be more damaging to crops during or after a drought as the plants are less able to protect themselves and recover from hail damage. Drought is often concurrent and exacerbated by heat waves. Also, rainfall can produce more damaging runoff after or during a	(e.g. education, health) (September 2022 partners meeting). • Lack of water storage for agriculture (September 2022 partners meeting).

	Sectors			
Risk categories	Livelihoods	Primary economic activities	Ecosystems	Infrastructure
	and coverage are expected to grow as climate change progresses. For example, the drought in 2021 in Saskatchewan, which increased crop losses and feed shortages for producers, led to the highest program liabilities and indemnities in the Saskatchewan Crop Insurance Corporation's history (SCIC, 2022). • Decreased fish populations during drought (Starks et al., 2014) may impact subsistence fisheries, including those in Indigenous communities.	streams, wetlands, dugouts, reservoirs, and groundwater were placed under stress and often failed (Wheaton et al., 2005, 2008). • Potential financial distress for the Saskatchewan Crop Insurance Corporation as insurance dependency and coverage is expected to grow over time, as shown in 2021 (SCIC, 2022). • Risk of not getting crop insurance (more research needed on the impacts of drought on this risk.) • Drought also impacts greenhouses (September 2022 partners meeting). • Other economic sectors impacted by drought include water supplies, industry, forestry, recreation, municipalities, and human health (Bonsal, Wheaton, Chipanshi, et al., 2011). • Drought impacts other industries that use water,	drought (see example in Szeto et al., 2011). • In southern Alberta and Saskatchewan, most rivers are projected to decrease in annual and summer streamflow (Bonsal et al., 2019). By the end of the 21st century, natural river flow in the South Saskatchewan River Basin may be reduced by 4% to 13% (Martz et al., 2007). • Streamflow reductions can reduce habitat for fish (protected by the Fisheries Act,) migratory waterfowl (protected under the Migratory Bird Convention Act,) and endangered species including the Piping Plovers and Northern Leopard Frogs (protected by the Species at Risk Act) (Leavitt, 2021). • Lake level change:	

	Sectors			
Risk categories	Livelihoods	Primary economic activities	Ecosystems	Infrastructure
		such as mining. Water losses reach 40% of water intake for potash mining (Reid, 1984). • Cost of drought to urban centers (ex. effects on increased droughts on reservoirs, may have to bring in bottled water) (September 2022 partners meeting). • Drought may decrease fish populations by decreasing fish recruitment, particularly in closed-basin lakes (Starks et al., 2014), which could have negative impacts on recreational fisheries. • The decrease in lake levels of over 8m since 1900 at Kenosee and White Bear lakes (Bjorndahl et al., 2022) affects recreation as shoreline exposure, boat and water access are severely impacted. Other closed-basin lakes may experience similar water	decrease during drought, increase during years of precipitation (Bonsal et al., 2017, 2019). This may lead to dramatic ecosystem changes in closed-basin lakes, which have limited inflow and outflow and are common in southern Saskatchewan (Bjorndahl et al., 2022). • Lake salinization: as lake levels decrease, salinity will increase. In closed basin lakes that already have relatively high salinity, increasing salinity may affect which fish species can survive in the lake (Wissel et al., 2011). • Algal blooms and low oxygen concentrations may increase during drought years, as shown in Lake Diefenbaker (Hudson & Vandergucht, 2015).	

	Sectors			
Risk categories	**Livelihoods**	**Primary economic activities**	**Ecosystems**	**Infrastructure**
		level changes and recreational impacts in the future. • Drought may increase fish winterkill in shallow closed-basin lakes (Cooper & Wissel, 2012; see ecosystems for more information.) Fish winterkill negatively impacts recreational fisheries (Durling, 2021) and may decrease property values of lakeside cottages.	• Droughts can increase the risk of wildfires (grasslands or forest) and affect aquifer groundwater recharge (Wheaton et al., 2005). • There are uncertain impacts of drought on fish in shallow closed-basin lakes during the winter: while lower lake water levels may increase the possibility of fish winterkill, a shorter duration of ice cover would reduce the time available for depletion of oxygen and therefore may decrease winterkill (Cooper & Wissel, 2012).	
Risks related to excessive moisture and flooding in the Canadian Prairie provinces • Annual precipitation increased 7.0% from 1948-2012 (Table 4.4 in Bush & Lemmen, 2019). • Annual precipitation is projected to	• Social impacts (individual and community stress/anxiety during event and prolonged recovery periods; displacement of people, communities, industry; post flood recovery	• Livestock losses, agricultural land damages (Corkal, 2018 Table B). • Economic activities stopped, reduced, or impaired (Corkal, 2018 Table B). • Impaired Tourism (Corkal,	• Contaminated water in lakes, rivers, wells; erosion, slumping, river and shoreline alteration; pollution from animal carcass disposal, human and animal waste (Corkal,	• Damages to a range of infrastructure, including: agricultural land, railways and highways (Halliday, 2018), bridges (Wittrock et al., 2018),

	Sectors			
Risk categories	Livelihoods	Primary economic activities	Ecosystems	Infrastructure
increase in the range of 5.0% - 6.5% (2031-2050) and 5.9% - 15.3% (2081-2100), mostly during the winter with smaller increases projected for the summer (Table 4.5 in Bush & Lemmen, 2019; ranges refer to different future emissions scenarios). • A significant decrease in the snow to rainfall ratio is projected; i.e. less snow and more rain (Bush & Lemmen, 2019). • Daily extreme precipitation is projected to increase across Canada, which may increase the likelihood of flooding (Bush & Lemmen, 2019).	stress and human toll (Corkal, 2018 Table B). • First Nation Community displacement/ relocation (Corkal, 2018 Table B). • Institutional impacts (taxed human resources, emergency responders, programs/chaos; lack of coordinated responses) (Corkal, 2018 Table B). • Policy impacts (zoning non-compliance, insurance; agricultural drainage) (Corkal, 2018 Table B). • Loss and damage of household assets: for example, in 2011 (Wittrock et al., 2018) (see Appendix B for more examples of flood impacts.) • Threats to human health and safety, including safety around dams (Corkal, 2018). • From 2005 to 2014, Saskatchewan received the largest per capita payment	2018 Table B; see CTV News, 2011; Mceachern, 2013 for an example from Regina Beach of 2011 flooding impacts). • Policy implications with zoning, insurance, agricultural drainage (Corkal, 2018 Table B). • Loss and damage in productive agriculture due to heavy rains and floods Brimelow et al., 2014, 2015). • Loss and damage in other industries (like mining or hydroelectricity) (September 2022 partners meeting). • Costly impacts of the 2012-2018 Quill Lakes flooding, including lost crop/livestock production ($74 million), lost farmland and buildings (over $100 million), local government and infrastructure losses, including repairing and upgrading highways and one rail line ($79 million) and	2018 Table B). • Floods associated with spring snowmelt will occur earlier in the year due to projected higher temperatures (Bonsal et al., 2019). • However, it is uncertain how the frequency and magnitude of future snowmelt-related flooding will be affected by the combination of projected increases in winter/spring precipitation versus higher temperatures and resultant reductions in snow cover (Bush & Lemmen, 2019). • More rainfall vs snow will also cause higher runoff into aquatic ecosystems and could potentially load more nutrients and contaminants into these systems. For example, MacKinnon et al. (2016)	dams, landfill and waste management sites, water and wastewater facilities (including overtopping of reservoirs and sewage lagoons), buildings and structures, property (rural and urban, private, recreational, commercial), critical facilities (hospitals, care homes, seniors residences), homes, rural roads, storm drainage, and urban drainage (Corkal, 2018 Table B). • Community access may be limited or isolated (Corkal, 2018 Table B). • Impaired utilities inc. energy, gas, water, wastewater (Corkal, 2018 Table B). • Wastewater treatment plants may need

	Sectors			
Risk categories	**Livelihoods**	**Primary economic activities**	**Ecosystems**	**Infrastructure**
	from the federal Disaster Financial Assistance Arrangements (DFAA). Most of these payments were due to flooding, showing that flooding is a major problem in Saskatchewan (Wittrock et al., 2018). • Projected increases in extreme precipitation are expected to increase the potential for future urban flooding (Bonsal et al., 2019; see Salman & Hurlbert, 2022 regarding floods in Yorkton). • Forced evacuation of homes due to flood risk (ex. City of Moose Jaw in April 2011; see Corkal, 2018 in Appendix B). • Rainfall floods, which will become more common, are more immediate and difficult to prepare for compared to snowmelt floods (September 2022 partners meeting). • Impact on subsistence economies (September 2022 partners meeting).	realized net farm income losses (over $17 million) ((Warren, 2018). • In 2011, "governments at all levels spent close to $1 billion on flood fighting and victim compensation" (Environment and Climate Change Canada, 2011). • In 2014, total costs from flooding exceeded $1 billion, including lost crops and damages to communities (Environment and Climate Change Canada, 2014).	found that higher precipitation increased the connectivity of the Saskatchewan River Delta, which raised nutrient concentrations, increased pH, and elevated the salinity of the systems. This is an example of high precipitation leading to loss and damage in ecosystems and their services (September 2022 partners meeting). • Less research has been carried out on excessive moisture compared to droughts in the Canadian Prairies (E. Wheaton and B. Bonsal, personal communication).	upgrades to increase capacity to deal with intense rainfall events (Bergen, 2022; Gousseau, 2015a, 2015b) which are projected to become more frequent and intense in the prairies (Bush & Lemmen, 2019; Mladjic et al., 2011; Trenberth, 2011). • Green spaces are at risk because of irrigation (September 2022 partners meeting).

	Sectors			
Risk categories	**Livelihoods**	**Primary economic activities**	**Ecosystems**	**Infrastructure**
	• Impacts on rural towns and villages: including the Southey Basin flooding disaster, where repair costs were estimated to be close to $1 million. The village of Elfros declared a state of emergency in July 2016 due to localized flash flooding, which caused substantial damage to nearly half of the village's 57 private properties (Wittrock et al., 2018).			
Risks related to climatic variability, including extreme seasonal storms and weather and changes in climate systems. • The Canadian prairies have high variability in precipitation, including seasonal variability (Bonsal et al., 1999) and inter-annual (year-to-year) variability (McGinn, 2010). • There has been substantial inter-annual and inter-decadal variability in the frequency of droughts and excessive moisture events, with	• Heat and convective storms with extreme temperatures affecting people, plants, animals, energy (Corkal, 2018 Table A and D). • Rapid weather changes, extreme winds, tornados, hail in summer (Corkal, 2018 Table D). • Winter ice storms, wet snow, more intense blizzards affecting people, homes, energy systems,	• Changing plant, tree, and animal diseases and disease vectors impairing agricultural production of crops and livestock, with potential increased disease vectors to human populations (Corkal, 2018 Table D).	• Slumping or swelling of land due to excessive moisture; cascading effects of rapid changes from drought to flood and vice versa resulting in natural hazard shocks; increased risk of pollution (Corkal, 2018 Table D). • Excessive moisture periods may occur at the end of significant drought periods and lead to	• Cascading infrastructure risks and damages from rapid changes and extreme conditions (such as drought, extreme heat, excess moisture, flood, wind, hail, ice, snow) all affecting private, public, and commercial property, industry, transportation

	Sectors			
Risk categories	Livelihoods	Primary economic activities	Ecosystems	Infrastructure
decadal variations being more prominent (Bonsal et al., 2019). • Climate variability in the Canadian prairies is expected to continue in the future, with an increase in intensity, duration, and frequency of droughts (Axelson et al., 2009; Bonsal et al., 2013). While less research has been conducted on projecting flood risks, future increase in extreme precipitation are expected to increase the potential for future urban flooding (Bonsal et al., 2019).	transportation, etc. (Corkal, 2018 Table D). • Human health risks from changing diseases and disease vectors (Corkal, 2018 Table D).		flooding damage, as occurred in June 2002 in the Lethbridge, Alberta area (Szeto et al., 2011). • Changes in the North Atlantic Oscillation (NAO) and February to April precipitation had an impact on food web dynamics (zooplankton clear water phase timing and intensity) in the Qu'Appelle lakes (Dröscher et al., 2008). • The Pacific Decadal Oscilliation (PDO) interacting with the El Niño–Southern Oscillation (ENSO) explained 30% of variation in water clarity in a prairie reservoir (Lake Diefenbaker), suggesting that the water was more clear in years with drier winters (Vogt et al., 2015).	systems, energy and transmission lines (power, gas, oil) and utilities (waters, wastewater, landfill infrastructure, etc.) (Corkal, 2018 Table D).

	Sectors			
Risk categories	Livelihoods	Primary economic activities	Ecosystems	Infrastructure
Risks related to water quality • Although many lakes in Southern Saskatchewan naturally have high algal growth, human activities have increased algae and cyanobacteria since 1930 (R. I. Hall et al., 1999). These human activities include nutrient pollution from urban (Leavitt et al., 2006) and agricultural sources (Donald et al., 2011; Finlay et al., 2010; Swarbrick et al., 2020) and changes in climate (R. I. Hall et al., 1999; Vogt et al., 2018).	• While human fatalities from cyanotoxins are rare, dog fatalities occur more often (Wood, 2016), including in Saskatchewan (Hammer, 1968) and elsewhere in Canada (Cummings, 2020). High levels of cyanotoxins may lead to swimming advisories for dogs and humans, like at Buffalo Pound Lake (Sharpe, 2016). • Poor source water quality affects drinking water quality, particularly in remote and Indigenous communities. At any given time, one in five Indigenous communities in Canada is under a boil water advisory (Patrick et al., 2019). In Saskatchewan, 384 Indigenous or rural communities reported drinking water advisories from 2012-2016 (McLeod et al., 2020). Indigenous ways of knowing include	• Algal and cyanobacterial blooms can have large economic costs. For example, recurring cyanobacterial blooms in Lake Taihu in China and Lake Erie in Canada and the US have led to drinking water advisories and negative impacts on tourism (Huisman et al., 2018), including decreased property values for lakeside properties at Lake Erie (Bingham et al., 2015). • In Saskatchewan in 1986, Kulshreshtha (1991) determined that the value of water-related recreation in 21 recreation sites in Saskatchewan was $3.90 value per visitor day. • Cyanobacterial toxins have killed cattle in all the prairie provinces, so copper is used to control cyanobacteria (Andresen et al., 2015). Sulfate	• Negative impacts of cyanobacterial blooms include increased turbidity, oxygen depletion, and cyanotoxins which can cause "liver, digestive and neurological diseases when ingested by birds, mammals and humans" (Huisman et al., 2018). • Nutrient pollution and climate effects can combine to have synergistic effects on different aspects of lake ecosystems, including cyanobacterial growth in shallow, nutrient-rich lakes (Huisman et al., 2018), which are common in southern Saskatchewan. • In addition, as water levels decrease, it is expected that salinity, water temperatures,	• Drinking water treatment plants may struggle with poor water quality in their source water and require upgrades. For example, the Buffalo Pound water treatment plant, which provides drinking water to Regina and Moose Jaw, requires $222 million in upgrades to its infrastructure (Silverthorn, 2021). • Wastewater treatment plants also often require expensive upgrades to meet governmental regulations, such as the $550 million upgrades announced in Winnipeg (Bergen, 2022) and the $175 million in upgrades to Regina's wastewater treatment plant, which

	Sectors			
Risk categories	Livelihoods	Primary economic activities	Ecosystems	Infrastructure
	recognition of water as a life form, which helps Indigenous communities to adapt to drinking water challenges (Awume et al., 2020). However, drinking water advisories also often demonstrate where the most vulnerable are the people that pay the biggest price: see Figure 3.1 for a map of boil water advisories in Saskatchewan from Patrick, Grant, and Bharadwaj (2019). • To a lesser extent, poor water quality also impacts drinking water in non-Indigenous communities. For example, complaints of odour in household water in Regina in November 2022 were connected to a change in filtration at the water treatment facility that deals with removing cyanobacteria from the source water in Buffalo Pound Lake (Quon,	concentrations in agricultural ponds are also a concern (J. Campbell, 2017, 2018; Glen, 2019) and are likely to become more commonly problematic with climate change.	and nutrients will rise, which increases osmotic and temperature stress for fish. Lakes that currently have fish that feed on smaller fish will likely be affected the most by these changes (Cooper & Wissel, 2012). • Ecological surprises, such as late-season cyanobacterial blooms freezing into the ice in the fall and releasing blue-coloured pigments in the winter, may become more common as human population, nutrient pollution, resource use and atmospheric temperatures increase (Haig et al., 2022). • Mercury: lakes in southern Saskatchewan tend to have both high mercury concentrations	were completed in 2016 (CBC News, 2016). Upgrades such as these increase capacity during storms with high rainfall (Bergen, 2022; Gousseau, 2015a) and improve removal of nutrients such as P and N that negatively impact downstream water quality (Bergbusch et al., 2021b). Regina's upgrades, which greatly reduced N in the treated wastewater, have already shown improvements in downstream water quality in the Qu'Appelle River, as shown by several factors including a decrease in algal abundance (Bergbusch

	Sectors			
Risk categories	Livelihoods	Primary economic activities	Ecosystems	Infrastructure
	2022). High levels of lead in drinking water from lead pipes has also been a concern in Regina (Ackerman, 2021). This goes against the expectation that providing high quality safe potable water is a human right, and within Sustainable Development Goal 6 (clean water and sanitation.) • Late-season cyanobacterial blooms, such as a bloom in late October 2020 in Pasqua Lake (Haig et al., 2022), are becoming more common. Blue staining reported in March 2021 by ice fishers came from cyanobacterial pigment released by this bloom when it froze into the ice. Fortunately, concentrations of the cyanobacterial toxin microcystin were low in the March 2021 samples, which was communicated to the public using traditional and		in fish and high algal growth, which is unusual compared to other lakes (B. D. Hall et al., 2020). Larger fish and fish that eat other fish usually have higher mercury concentrations compared to smaller fish and fish that only eat plankton (Donald et al., 2015; Government of Saskatchewan, 2015). The Government of Saskatchewan may issue advisories if mercury levels of fish in certain lakes reach high levels (CTV News, 2009). • Pollution from municipal waste, including microplastics (plastic with a diameter < 5mm) and microfibers from textiles. Plastic pollution is present in marine and freshwater environments all around the world, but	et al., 2021b).

	Sectors			
Risk categories	**Livelihoods**	**Primary economic activities**	**Ecosystems**	**Infrastructure**
	social media platforms (Haig et al., 2022). However, as this was the first occurrence of this phenomenon, it initially raised public concern about pollution in the lake amongst recreational anglers and Indigenous rights-holders (Haig et al., 2022).		it is still unclear what risks it poses to aquatic organisms and their ecosystems (Bujaczek et al., 2021). Baseline studies in Western Canada have found microplastics and microfibers in the North Saskatchewan River near Edmonton (Bujaczek et al., 2021), effluent from the Saskatoon's wastewater treatment plant (Prajapati et al., 2021) and in both water and fish samples in Wascana Creek both upstream and downstream of Regina's wastewater treatment plant (S. H. Campbell et al., 2017).	
Risks related to warming air temperatures in the Canadian prairie provinces • Annual mean air temperatures	• Effects of increased temperature on urban areas prone to heat (September 2022 partners	• Evidence that warmer water temperatures are reducing oxygen concentrations in lakes	• Warmer temperatures increase the risk of droughts (Meehl et al., 2007).	• Changes to climate will impact water use (e.g., hot dry periods) will put strain on

	Sectors			
Risk categories	Livelihoods	Primary economic activities	Ecosystems	Infrastructure
increased by about 1.9°C from 1948-2016. Winter temperatures increased by 3.1°C, spring by 2.0°C, summer by 1.8°C, and autumn by 1.1°C. (Bush & Lemmen, 2019). • Projected that air temperatures will continue to increase, with the greatest changes projected for the winter (Bush & Lemmen, 2019).	meeting). • Heat waves can increase water use. • Shorter periods of ice cover may cause the cancellation of cultural practices, including spiritual ceremonies, recreational ice skating, and ice fishing tournaments (Knoll et al., 2019). • Evidence of winter drownings increasing as winter air temperatures increase in ice-covered regions, including Canada (Sharma et al., 2020). • Summer fish kills in the Qu'Appelle lakes in July of 2021, which negatively affected those living near the lake, may have been affected by low oxygen caused by high temperatures and/or decomposition of algal blooms (Materie, 2021). • Reduction in fish habitat	(Jane et al., 2021), which may reduce fish habitat, particularly for cold-water species. • Increases in algal blooms due in part to warmer temperatures are also concerning for fish because decomposition of algae can consume oxygen and reduce habitat for fish (Paerl & Otten, 2013). • Reduction of fish habitat noted above could negatively affect the recreational fishing tourism industry in Saskatchewan. According to a survey completed by people who purchased fishing licenses, approximately $555 million was spent on goods and services directly related to sport fishing (including boats, lodging, transportation, and fishing packages) in 2015 in	• Increased risks from Prairie wildfires in the agricultural zone (bushes, grasslands, etc.) (Corkal, 2018). • Prairie wildfires share risks to northern forested wildfires (limited access to surface water for fighting Prairie wildfires (Corkal, 2018 Table C). • While it is expected that projected changes in temperature and precipitation will affect groundwater, "the magnitude and even direction of change is not clear." Groundwater recharge is projected to occur earlier in the spring in the future due to an earlier snowmelt (Bonsal et al., 2019). • Warmer surface waters are associated with changes in lake thermal	infrastructure. • Shorter periods of ice cover: ice roads are open for a shorter period of time, which may reduce transportation in northern areas of the province (Knoll et al., 2019; Woolway et al., 2022). • Prairie wildfires share risks to northern forested wildfires (cascading infrastructure losses, energy and power supplies, homes, buildings industry, commercial infrastructure fire damages (Corkal, 2018 Table C).

	Sectors			
Risk categories	**Livelihoods**	**Primary economic activities**	**Ecosystems**	**Infrastructure**
	may also negatively impact subsistence fishing in Indigenous communities (Missaghi et al., 2017). • In a study using summer data over 10 years from six prairie (Qu'Appelle) lakes, warmer water temperatures contributed to increased concentrations of the cyanotoxin microcystin, showing negative impacts on public human health (Hayes et al., 2020). • Prairie wildfires share risks to northern forested wildfires (law and order, looting, crime, employment loss, evacuations, coordination of disaster responses, challenges to evacuated parks and recreational sites, etc. (Corkal, 2018 Table C)	Saskatchewan (Saskatchewan Ministry of Environment, 2016). • Prairie wildfires share risks to northern forested wildfires (individual and industry economic losses and shut-downs, agricultural losses inc. livestock (Corkal, 2018 Table C)	stratification (change in temperature with depth; Huisman et al., 2018), nutrient availability (as shown in Lake Diefenbaker by North et al., 2015), oxygen availability (Jane et al., 2021), and food web dynamics (Woolway et al., 2021). These changes can impact fish populations and algal blooms (Woolway et al., 2021). • Lower oxygen is detrimental for fish and invertebrates, alters the availability of nutrients, and increases the toxicity of metals (Golosov et al., 2012). • Cyanobacteria often reach maximum growth rates at warmer water temperatures compared to other types of algae (Huisman et al., 2018;	

	Sectors			
Risk categories	Livelihoods	Primary economic activities	Ecosystems	Infrastructure
			Paerl & Huisman, 2008). In six of the Qu'Appelle lakes over 10 years, warmer water temperatures contributed to increased cyanotoxin concentrations (Hayes et al., 2020). • Warmer surface waters contribute to cyanobacterial blooms occurring during less productive times of the year, including the fall (Shcherbak et al., 2019; Wejnerowski et al., 2018; cited in Haig et al., 2022)	
Risks from invasive species • Invasive species can dramatically alter ecosystems, including decreasing the abundance of native species and increasing their risk of extinction (Pyšek et al., 2020).	• Invasive species such as dreissenid mussels, smallmouth bass and Prussian carp may negatively impact native fish populations, which could impact subsistence fishing.	• Invasive species such as dreissenid mussels, smallmouth bass and Prussian carp may negatively impact native fish populations, which could impact the recreational fishing	• Invasive species of concern include microbial species, viruses, parasites, bacteria (Corkal, 2018 Table D). • Warmer water temperatures and changes in precipitation	• Invasive dreissenid (zebra and quagga) mussels can severely impede the function of a variety of infrastructure, including facilities with water intake pipes

	Sectors			
Risk categories	**Livelihoods**	**Primary economic activities**	**Ecosystems**	**Infrastructure**
	• West Nile Virus has impacted people and their health (Corkal, 2018) and future transmission of West Nile Virus should consider the effects of climate change (Paz, 2015).	industry. • High economic cost of removing dreissenid mussels from infrastructure. In the Great Lakes region of the US, the cost of preventing and removing zebra mussels from intake pipes, power plants, and water filtration equipment was estimated at $3.1 billion over 10 years (Cataldo, 2001; as cited in Lovell et al., 2006). • In Saskatchewan, zebra mussels could also increase costs for irrigators and other water-related infrastructure (Ludwig, 2011). Alberta has estimated an annual cost of $75 million if zebra mussels were to invade (Neupane, 2013). Businesses may have to close if these costs become too high. • The Pine Beetle has	may favour the spread of invasive species from south to north (A. L. Smith et al., 2012). For example, smallmouth bass, a warmwater fish species, are expected to threaten cold-water lake trout populations (Sharma et al., 2009), which are present in Lake Diefenbaker and Northern Saskatchewan. • Additionally, increasing frequency of extreme events may make ecosystems more vulnerable to the invasion of new species (A. L. Smith et al., 2012). • Purple loosestrife, zebra (and quagga) mussels, and salt cedar are all at very high risk of invading and impacting aquatic ecosystems in Saskatchewan (Z. Zhang,	(including power generation and water treatment facilities), canal and dock walls, and watercraft and motors (MacIsaac, 1996).

	Sectors			
Risk categories	Livelihoods	Primary economic activities	Ecosystems	Infrastructure
		impacted forestry (Kurz et al., 2008).	2015). • Zebra and quagga mussels can drastically change many aspects of a lake, including nutrient cycling, underwater light penetration, and food web interactions, which can negatively affect fish at the top of the food web (Evans et al., 2011; Ofosu, 2022). • Prussian carp have also invaded southern Saskatchewan via Alberta (Hamilton, 2021). Their spread to Alberta was likely either through aquaculture or the aquarium industry (Elgin et al., 2014).	
Land use changes, which include: • Surface drainage of agricultural land including natural wetlands (e.g. Baulch et al., 2021; Minnes et al., 2020).	• Draining wetlands reduces flood and drought protection (Washington State Department of Ecology, n.d.), leading to	• Agricultural drainage has been practiced and promoted (even funded by government) since 1949 as a land management	• Agricultural drainage removes many benefits (or ecosystem services) provided by wetlands, including providing	• Wetlands may be considered 'natural infrastructure' since they reduce the severity of floods and

	Sectors			
Risk categories	Livelihoods	Primary economic activities	Ecosystems	Infrastructure
• Irrigation • Converting grasslands to cultivated land. • Reversion to a previous state, such as wetland restoration (e.g. Cortus et al., 2011).	livelihood risks (see the first two rows for examples of these risks). • Reducing wetlands reduces recreational opportunities (ex. hunting, hiking, fishing, bird watching, photography; Cortus et al., 2011; Olmstead et al., 2021).	adaptive technique to reduce flood risk impairing agricultural production and lands to improve economic security, rural livelihoods, and rural communities (S. N. Kulshreshtha & Pearson, 2002; see also Saskatchewan Conservation and Development Organization, 2023). • The Province of Saskatchewan (Auditor and WSA) recognize all drainage must be licensed and responsible to protect downstream producers and the environment and are promoting the Agricultural Water Management Strategy to achieve more responsible drainage (WSA, n.d.).The Provincial Auditor of Saskatchewan recognized this as a need along with a	plant and wildlife habitat, increasing biodiversity, carbon storage (greenhouse gas retention), groundwater recharge, water flow regulation and flood control, water storage for agriculture, filtering of nutrients, and improved water quality (Cortus et al., 2011; Minnes et al., 2020; see Baulch et al., 2021; and Breen et al., 2018 for more on impacts of wetland drainage in the Canadian Prairies). • If agricultural drainage disrupts the function of a watershed (Olson, 2021), then the watershed has a reduced ability to absorb current and predicted climatic changes. • Difficult to separate land	may be more cost-effective than other engineered solutions (Olmstead et al., 2021). • Increased urban sprawl/ pavement increases water flow in urban drainage system and rivers during precipitation events (Qin et al., 2013).

	Sectors			
Risk categories	Livelihoods	Primary economic activities	Ecosystems	Infrastructure
		need for a new wetland protection policy and regulation (Provincial Auditor of Saskatchewan, 2018). • Draining wetlands reduces flood and drought protection (Washington State Department of Ecology, n.d.), leading to economic risks (see the first two rows for examples of these risks). • However, drainage also increases the extent of arable land and facilitates agronomic operations, thereby increasing net economic accruals from crop production (Cortus et al., 2011; Olson, 2021; Pattison-Williams et al., 2018).	use and climate change effects since they are occurring at the same time (September 2022 partners meeting.) • Some land use and climate changes are irreversible (September 2022 partners meeting.) • Land use changes and wetland protection are occurring and are anticipated to continue well into the future. The Provincial Auditor of Saskatchewan has called for improved policies for wetland retention and water quality, including improved regulation of drainage to help protect ecosystems and downstream users (Provincial Auditor of Saskatchewan, 2018, 2021).	

Appendix B: Hazards related to water and hydro-climatic events, including droughts, floods, severe storms, fires, and heat, in Saskatchewan from 2000-2022.

NOTES:

1. The **Canadian Disaster Database** search in this table was a selection for "Saskatchewan, all natural disasters, period 1900-2022, start date descending), Public Safety Canada website, Feb 20, 2023 (although it appears the table may have been last updated in 2018). See: https://www.pub-licsafety.gc.ca/cnt/rsrcs/cndn-dsstr-dtbs/index-en.aspx Most items during 2000-2020. Most hydro-climatic hazard events are listed in the following table (most pandemics and wildfires are not listed). Note that, severe weather, storms, and floods often move from Alberta to Saskatchewan to Manitoba and economic impacts are often estimated for the entire Prairie region. Often Federal Government Disaster Financial Assistance Arrangements (DFAA pay-ments) occurred for a portion of the damages.
2. **Saskatchewan's Provincial Disaster Assistance Program or PDAP** (Corrections, Policing and Public Safety) and **Emergency Management Flood Damage Reduction Program** (EFDRP) have much more data on claims and costs, for many communities not shown in this table. PDAP is currently being audited by KPMG for the Government of Saskatchewan. Should greater detail be required, a request would need to be made to PDAP for a summary of claims paid over the years (this would yield a better record summary of actual flooding and storm damages in Saskatchewan).
3. This table includes some hydro-climatic risk examples impairing farms (land, crops, livestock, buildings, etc.); however, the examples are depicted in broad regions and not specific to farm locations nor communities.

Hazard	Year	Area	Description / Impacts	Sources
Flood	2000	Vanguard, SK	•On July 3, 2000, up to 375 mm of rain fell in eight hours from an intense and slow-moving thunderstorm complex, inundating the Vanguard area of southern Saskatchewan. •The Village of Vanguard and seven surrounding municipalities experienced a severe flood, causing extensive damage to private property and public infrastructure. •The storm was centred primarily over a single basin, the Notekeu Creek watershed. •Home and farm buildings in and near Vanguard were inundated; roads and rail lines were washed out; drinking water supplies were compromised for two weeks because the village's water treatment plant and sewer system were submerged during the flood. No deaths or injuries were reported. •Agricultural productivity for the region was reduced. Saskatchewan Government Insurance reported commercial and package policy claims of $2M in covered damages.	(Hunter et al., 2002) (Armstrong et al., 2013) (Government of Canada, 2018)
Drought	2001	Central-west and southwestern SK	•Severe to extreme drought covers much of SK. Creating severe and long-lasting impacts on many sectors.	

		(Palliser Triangle area, Stewart Valley, and Cabri)	•Some locations, such as Saskatoon, had their lowest annual precipitation on record in 2001. •The higher temperatures accompanied by a lack of precipitation resulted in several biophysical impacts, such as wind erosion, reduced stream flows, dry droughts, and groundwater reductions. •The overall impact was a loss in gross farm cash receipts of $925.3 million in 2001. •Net losses in livestock and crop production were $655 million in 2001. •Eleven months of below-average precipitation, and seven of those months were less than 50% below average. * •The Palmer Drought Severity Index (PDSI) values were below -5. ** •Changes in Net Farm Income -$652 million. ** •Hydroelectric power generation was reduced to 66% of the previous four-year average. **	(S. Kulshreshtha et al., 2016) (Diaz et al., 2009)* (Wheaton et al., 2010)**
Flood	2002	Regina and the southwest SK	•June 8-12, 2002, a catastrophic rain event during a major drought. The storm brought record-breaking rains and major flooding events. •The severity of the June 2002 system is partly a result of the rare co-occurrence of these features during the period. •Results show that the atmospheric conditions associated with the extreme background drought enhanced the likelihood of the co-occurrence of these features during spring 2002, hence facilitating the development of the extreme rain event. In return, the tremendous precipitation from the storm alleviated the drought conditions in the southern Prairies.	(Szeto et al., 2011)
Drought	2002	Palliser Triangle area (Shaunavon, Coronach, Gravelbourg, Kindersley, Maple Creek and	•Severe and long-lasting impacts for many sectors. •26.52 drought losses on agricultural production as a percentage of the average 1998-2000 value of productions. •Crop yields and harvested areas were below average for 2001 and 2002. •The overall impact was a loss in gross farm cash receipts of $1,520.1 million in 2002. •Changes in Net Farm Income -$652 million. **	(S. Kulshreshtha et al., 2016) (Diaz et al., 2009)*

		Maidstone) (Stewart Valley and Cabri)	•Net losses in livestock and crop production were $1,001 million in 2002. •Reduction in the amount of hydroelectric power generated, requiring Saskatchewan Power Corporation to purchase additional power from other sources. •Employment losses in the agricultural sector and associated industries. •Low water supplies resulted in water restrictions on the agricultural communities. •In addition to impacts on communities, the drought of 2001-2 impacted individuals' well-being. •A decline in crop process and an increase in input costs were identified as specific stressors increasing the economic vulnerability of local agricultural producers. * •PDSI with values of -4 to -5 during spring. * •Estimated impacts on the livestock sector were 29.3 (% of Western Canada) **	(Wheaton et al., 2010)**
Drought	2001 - 2002	Southern Prairies	•The Canadian drought of 2001-2002 affected more land than the 1931 drought, and caused a $3.6 billion drop in Canadian agriculture, a $5.8 billion drop in Canada's Gross Domestic Product and 41,000 job losses. Many adaptations implemented since 1931 helped safeguard the prairie and its population. • Crop production losses were devastating; livestock production was impacted, and herds were reduced due to water and feed scarcity. • Water supplies were scare and adaptation measures were severely challenged. • Long-lasting impacts affected soil health, wind erosion of soil, and deterioration of grasslands also resulted in livestock herd reductions. • Multi-sector effects were associated with the 2001 and 2002 droughts, unlike many previous droughts that affected single to relatively few sectors. Impacts were felt in areas as wide-ranging as agricultural production and processing, water supplies, recreation, tourism, health, hydro-electric production, transportation, and forestry. • Blowing dust was associated with traffic accidents on the Prairies and linked to some fatalities. Routine monitoring of wind erosion and dust storms - required to determine the effectiveness of adaptation measures - is now non-existent, contributing to increased risks.	(Marchildon, 2009) (Corkal et al., 2011) (Wheaton et al., 2005)

			• Many adaptations proved insufficient to deal with such an intense, large-area, and persistent drought, underlining Canada's vulnerability to such events. • The risk of drought is greater than previously thought. Indicators of this increased likelihood include the recent knowledge of great decadal droughts before 1900, the increasing societal demands for water and food production, preliminary understanding of drought causal factors, and climate change. Evidence indicates that droughts may become worse as a result of climate change, requiring a far greater adaptive capacity in all areas.	
Drought	2003	East and south-central SK	• Mostly E and S central SK in moderate drought with smaller areas of severe drought. •Much of the rest of SK is abnormally dry.	(AAFC, 2022)
Frost	2004	SK	•On August 30, 2004, southern portions of Saskatchewan and Manitoba had a widespread killing frost, the earliest in 50 years. •Low-temperature records spanning 100 years were broken in Saskatoon and •Yorkton. Broadview was the coldest spot at -2.9°C.	(Prairie Adaptation Research Collaborative, 2023)
Flood	2005	Cumberland House, SK	•The prairie regions of Saskatchewan and Alberta experienced an unusually wet autumn in 2004, resulting in abnormally high soil moisture conditions and nearly filled reservoirs during spring runoff in 2005. •In June 2005, the headwater tributaries of the Saskatchewan River Basin were struck by four heavy rain events. Runoff from the rainfalls resulted in three floods which extended from Alberta through the provinces of Saskatchewan and Manitoba, causing at least four deaths and property damages of CAD $ 400 million. •Flood 1. The heaviest precipitation, up to 253 mm, fell in the headwaters of the Oldman and Bow basins. The heaviest precipitation in the upper Bow Basin fell in the southern portion. •Flood 2. The event was caused by up to 149 mm of precipitation, the greatest accumulations were in the upper Red Deer and North Saskatchewan basins. •Flood 3. The third flood event was caused by up to 87 mm of precipitation in the Bow and Oldman basins.	(Shook, 2016) (N. D. Smith & Pérez-Arlucea, 2008) (Government of Canada, 2018)

			Flooding was reported in communities in the Saskatchewan River Delta in Saskatchewan and Manitoba and caused the village of Cumberland House to be evacuated. •Over $3.4 million impacts at Cumberland House, Cree First Nation SK, June 23, 2005. Approximately 2000 residents of Cumberland House were evacuated to Prince Albert after the Saskatchewan River began flooding. Saskatchewan Environment issued a boil water advisory for the residents. Movement of most ferries on the North and South Saskatchewan rivers was suspended.	
Storms and Severe Thunderstorms	2005	Northern Saskatchewan	•An intense low-pressure system caused heavy rainfall from July 23-25, affecting an area of northern Saskatchewan already saturated by snowmelt between Meadow Lake to the south and Stony Rapids to the north. •The closure of Highway 905 due to flooding in several locations resulted in the disruption of services to northern communities, including Stony Rapids and Black Lake, until the road was re-opened on July 31. •Preliminary eligible costs were estimated at $3,200,000, which would result in a federal share of approximately $1,100,000.	(Government of Canada, 2018)
Drought	2006	South SK	•South SK in moderate drought. •Sharp transition from abnormally dry to severe drought.	(AAFC, 2022)
Flood	2006	Red Earth First Nation, SK	•Over $7.2 million impacts April 13,2006. In northeastern Saskatchewan, the Red River First Nation scrambled to avoid the threatening Carrot River as leaders ordered a general evacuation of the band of 1,100.	(Government of Canada, 2018)
Flood	2007	Red Earth First Nation, SK, Fishing Lake, SK	•Over $125.8 million impacts April 19, 2007. •The band council's decision to evacuate 691 residents from the northern reserve, mainly children, elderly residents and pregnant women, came as water covered one-third of a main access road, which divides the reserve. •Fishing Lake SK, April 28, 2007. An Estimated 300 homes and cabins have been damaged by flooding from higher-than-average snowfall and runoff at Fishing Lake.	(Government of Canada, 2018)

			•Fishing Lake SK, May 25, 2007. An estimated 300 homes and cottages (approximately 600 individuals) were damaged by flooding that was caused by a higher-than-normal snowfall and subsequent ice melt runoff. •Fishing Lake, located two hours east of the Saskatoon area, received 50 to 75 mm of rain.	
Drought	2007	SW SK	•SW SK in moderate drought. •Poor pasture production and some livestock water shortages.	(AAFC, 2022)
Drought	2008	S SK	•Moderate to severe drought in S SK. •Water and forage shortages, poor crop and forage production •Mainly split between N AB and S SK droughts	(AAFC, 2022)
Flood	2008	Paddockwood, SK Regina, SK	•The Rural Municipality of Paddockwood declared a state of emergency on April 14, after floodwaters rose more than one metre. •Floodwaters covered main access roads leaving approximately 400 people stranded in their homes. Two families were forced to leave their homes due to flooding. •Water levels receded within a day, but the flooding caused damages to roads and residential homes. •Regina SK, July 22, 2008. Wicked weather wreaked havoc across Regina, with wind gusts up to 92 km/h and 11.2 mm of rain. The squall left about 5000 customers (15,000 individuals) in parts of north and east Regina without power.	(Government of Canada, 2018)
Drought	2009	W SK	•Central western SK has mostly moderate drought with smaller areas of severe drought to extreme drought. •Crop and forage yields decreased. •Water hauling and new wells needed. •Saskatchewan and Alberta, March 1 to July 1, 2009. The Canadian Wheat Board projected lower crop prospects by 20 per cent across the Prairies. Saskatoon had less than one-quarter of the usual amount of spring precipitation, making the months of March, April and May the driest since record-keeping began in 1892.	(Wittrock et al., 2010) (Government of Canada, 2018)

			•The soil moisture recharge period between September 1, 2008, and March 31, 2009 had less than 60 per cent of normal precipitation. •The flow of the North Saskatchewan River was at its third lowest level in nearly a century.	
Flood	2009	Denholm, SK	•The summer 2009 drought ended in a typical fashion with intense summer rains caused, for example, flash floods and the closure of the Yellowhead Highway near Denholm, SK on July 15.	(Sauschyn et al., 2010)
Severe Storms	2010	Maple Creek & Medicine Hat	•Record rainfall resulted in extensive flooding in Saskatchewan, washing out a portion of the Trans-Canada highway and shutting down part of the Canadian Pacific rail line. •Forty people from the Blood Tribe reserve, 75 homes in Maple Creek, and 600 households in Medicine Hat were forced to evacuate. •Disaster financial assistance was provided for over $1 billion damages in SK.	(Government of Canada, 2018)
Severe Storms and Tornado	2010	Prince Albert, Saskatoon, Davidson, Kawacatoose First Nation, Central/Southern North Battleford, SK	•Saskatoon was struck by severe weather on June 29. The following day numerous municipalities from Prince Albert to Davidson were affected by heavy rain. •On July 1, the storm moved south while another system moved in from the north. •On July 2, an F3 tornado touched down at approximately 17:30 CST in Kawacatoose First Nation, near the town of Raymond. The tornado produced wind speeds of up to 330 km/h and left a path of destruction that was 500 metres wide and 45 kilometres in length. The tornado destroyed 18 homes in the small First Nations community. There were no fatalities or reported injuries, although 85 people were left homeless in the wake of the tornado. •Over $13.2 million damages June29-July2. •A sudden and severe downpour of rain caused extensive flooding in the city of North Battleford with over $112,000 damages in North Battleford SK, •On July 22 a local state of emergency was declared, and 97 homes were flooded. The Red Cross provided food and accommodations to 45 people from 11 families.	(Government of Canada, 2018)

Flood	2010	Maple Creek, SK and area	•Wet weather through April and May of 2010 combined with a moderately severe rainstorm produced record flooding in the Maple Creek area in June. • The rainstorm of June 17 to 18, 2010 with over 100 mm of rain that fell on the Maple Creek drainage basin caused widespread damage to roads and public and private infrastructure throughout southwest Saskatchewan. • The rainfall frequency analysis indicates that the average was close to a 1:100 year event with some areas possibly as high as 1:200 years. The best estimate of the frequency of the Maple Creek flood peak is to assume the return period is similar, 1:3700 years, to that for Junction Reservoir. AESB estimates the return period of the runoff to be 1:250. •Severe flood damages in the Town of Maple Creek, the surrounding rural area and Highway 1 resulted with about 175m of westbound lanes being entirely washed away.	(Saskatchewan Watershed Authority, 2011) (Pentland et al., 2011)
Flood	2010	Yorkton, SK	•Resulted of inadequate stormwater drainage, a state of emergency was declared in Yorkton as the city experienced the highest recorded flood, with 70% of homes impacted. •Rainfall estimations ranged between 64 mm and 150 mm of rain. •The storm caused power outages, uprooted trees, destroyed homes and businesses, trapped 70 people in their houses and 170 people were displaced. •After this flood, the city adopted a multi-year, multi-million-dollar drainage plan that included, among other things, building two stormwater ponds and purchasing homes on one particular avenue that experienced some of the worst flooding.	(Salman & Hurlbert, 2022)
Flood	2011	Weyburn and Estevan, SK	•Over $33.2 million damages June 17-28, 2011. •A local state of emergency was issued on June 17, because of extensive flooding in the City of Weyburn and Estevan, Saskatchewan. •Throughout the province, 19 municipalities declared local states of emergency. •Approximately 200 homes were known to be affected in Weyburn, where there was 112 mm of rain. •On June 17, Estevan received 27 mm of rain over night and 383 residents were evacuated from a mobile trailer park.	(Government of Canada, 2018)

			•On June 18, officials reported that the capacity of the treatment plant had exceeded its limit, and Environment Canada granted permission to pump sewage directly into the Souris River. •Repairs were conducted at the treatment plant to address the capacity issue. •SaskPower reported scattered and localized power outages throughout the region. •Residents in most areas were given permission to return to their homes on June 28.	
Flood	2011	Southern Saskatchewan	•Heavy rainfall in 2010 and an unusually high snowpack through winter 2010-11 led the Authority to anticipate widespread flooding across southern Saskatchewan for spring 2011. •In 2011, in many southern areas of the province, there was a spring runoff peak, followed by a second flood peak caused by rains in May and June, some of the areas in the province received more than 200 mm of precipitation over the 30-day period. Widespread flooding occurred in many regions of southern, central and southeastern portions of Saskatchewan. •"Governments at all levels spent close to $1 billion on flood fighting and victim compensation." •On February 22, 2011, the Government of Saskatchewan announced the Emergency Flood Damage Reduction Program (EFDRP) aimed at providing grants for flood prevention work to communities, RMs and businesses as well as to rural homeowners. •In April 2011, the City of Moose Jaw issued an evacuation order for the occupied residences in the low-lying area of the Wakamow Valley.* •The Wakamow Valley was affected by flooding in both 2011 and 2013. * •In 2011 the RMs of Lakeside and Lakeview, with a combined total of 206 locations damaged, required support from the Provincial Disaster Assistance Program (PDAP).* • From 2009-2011, the Prairies experienced extreme variability from drought to flood; in 2011 damages in the Assiniboine River Basin (ARB) exceeded $1billion. •"Primary factors controlling the distribution and amount of precipitation included the location and persistence of key surface and upper-air features, as well as their interaction.	(Environment and Climate Change Canada, 2011) (Water Security Agency, 2013) (Brimelow et al., 2014) (International Joint Commission, 2021) (Corkal, 2018)*

			•Additionally, multiple events—rather than individual extremes—were responsible for the flooding over the Saskatchewan River Basin and the ARB. Very heavy rainfall events (≥25 mm d^{-1}) accounted for up to 55 % of warm season rain at some locations, and the frequency of heavy rainfall events was critical for determining whether a region experienced drought or pluvial conditions. • The Souris River basin experienced unprecedented flooding that far exceeded any other flood event for the 100 years of instrumental records. What was particularly unique was that spring snowmelt runoff flooding was followed by summer rainfall runoff flooding in a saturated basin, causing extensive damages to infrastructure (roads, railways, buildings, communities), to riparian landscapes and ecosystems, and causing immense social disruption. •In Saskatchewan, several major roads were closed, states of emergency were declared in the cities of Estevan and Weyburn, and more than 4,000 people were forced from their homes.	
Flood	2013	Cumberland House, Moose Jaw, Indian Head, Regina, Weyburn Central and Southern Saskatchewan	•Over $43.3 million impacts from Apr 29-July3. Cumberland House SK, April 29 to July 03, 2013. Higher-than-normal snow fall, and lower temperatures delayed the annual spring melt until the end of April. •Over 15 communities declared states of emergencies between April and June as flood waters rose throughout the province. •Overland flooding occurred between Moose Jaw and Indian Head, including parts of Regina and south past Weyburn to the U.S border. •Significant damage occurred on parts of Highways 2 and 3 that were washed out by the flood waters. Flood waters flowing east on the South Saskatchewan River from Alberta following the June 19 flash floods reached a peak flow of 6000 cubic metres per second, the highest ever recorded, flowing into the Lake Diefenbaker Reservoir. •Between June 23 and 28 the Saskatchewan Water Security Agency began releasing water from the reservoir at a rate of 2000 cubic metres per second, leading to a two-metre rise	(Government of Canada, 2018) (Pomeroy et al., 2016) (Wittrock et al., 2018)

			in the river downstream. As a result, 2,200 residents of Cumberland House were evacuated to Prince Albert and Saskatoon. •On July 3, 2013 the evacuation order was lifted and residents began to return to the community. *Note: A request for federal assistance through the DFAA program has been made.	
Flood	2014	Central and South Saskatchewan	•Over $19.3 million damages in Southern Saskatchewan, June 25 to July 14, 2014. •Heavy rain across southeastern Saskatchewan led to localized overland flooding, road washouts, highway closures, and local power outages. •The affected basins were the Souris, Lower Qu'Appelle and Assiniboine. •Some areas in southeastern Saskatchewan reported up to 240 mm of precipitation in less than two days. •Over 68 municipalities declared local states of emergency. •In Melville, St. Peter's hospital evacuated 150 acute care patients due to rising flood waters. •The Trans-Canada Highway was washed out in several sections and CN rail was heavily impacted on its regional lines. Peak flow levels on the Assiniboine and Qu'Appelle rivers exceeded that of the 2011 flood.	(Government of Canada, 2018)
Flood	2014	Yorkton, SK	•Due to years of excess precipitation, Yorkton's soil was saturated. •More water seeped into the sewer system, significantly increasing the volume of water travelling through the system. •Many people had incorrectly attached sump pumps to the sewer system instead of the stormwater drainage system, putting enormous pressure on the sewer system and causing it to back up. •Sump pumps at some low-lying locations had to work nonstop, they failed eventually, and caused flooding in those basements.	(Salman & Hurlbert, 2022)
Fire	2015	Northern Saskatchewan	•Over $92.1 million damages in Northern Saskatchewan, July 1-18, 2015.	(Government of Canada, 2018)

			•The 2015 wildfire season in Saskatchewan featured an unprecedented number of wildfires that consequently caused the biggest fire evacuation effort in Saskatchewan's history to date. •More than 13,000 people from 54 different communities had to be evacuated from their homes in Northern Saskatchewan due to over 720 wildfires that burned nearly 1.8 million hectares of land. •The two most severely impacted communities were La Ronge and Montreal Lake. Approximately 7,900 residents of La Ronge Indian Band were forced to evacuate, while in Montreal Lake approximately 1,500 residents evacuated due to several wildfires that destroyed six buildings in the area. •Up to 1,500 members of the Canadian Armed Forces were sent to the La Ronge area to assist firefighters.	
Severe Storms and Thunderstorms	2015	Central and Southern Saskatchewan	•Over $98.1 million damages from June 12, 2015 prairie storms in AB,SK, MB. •A massive storm from AB later moved into Saskatchewan near maple Creek with hail and estimated wind gusts of up to 120 km/h. As the storm travelled eastward, Assiniboia and Weyburn sustained damages from hail. •Over $45.6 million damages in AB and SK July 22, 2015. •Severe storms moved from AB into Saskatchewan, where the town of Kerrobert was hit with severe hail, prompting a state of emergency to be declared. Other communities in Saskatchewan such as Anglin Lake, Francis, Sedley and Regina were impacted by strong winds, heavy rain, hail and lighting. •Golf-ball sized hail caused the most significant damages during the storm, including damages to roofs, windows and vehicles.	(Government of Canada, 2018)
Flood	2015	Moose Jaw River	•During the 2015 spring runoff, several bridges along the Moose Jaw River were damaged.	(Wittrock et al., 2018)
Flood	2016	Yorkton, SK Village of Elfros, SK	•This flood was due to excessive stormwater and the inability of the system to drain. •60 mm of rain in less than an hour flooded Yorkton. •Many public buildings experienced damage.	(Salman & Hurlbert, 2022)

		Red Earth First Nation	•In July 2016, the village of Elfros suffered damage because of localized flash flooding, with substantial damage to nearly half of the 57 private properties. •Approximately 140 mm of rainfall hit the village in under two hours, causing streets to flood and the village's sewer system to back up. Elfros declared a state of emergency and emergency response equipment was deployed to the area.* •Red Earth First Nation SK, July 14-18, 2016. Heavy rain resulted in the flooding of the Carrot River in northern Saskatchewan. The community of Red Earth Cree Nation, located 75 kilometres east of Nipawin, declared a state of emergency and was forced to evacuate 576 residents. •The majority of evacuees stayed in Saskatoon at the Henk Ruy's Soccer Centre, while others stayed in hotels or with family. •The communities of Carrot River and the rural municipalities of Moose Range and Arborfield also declared states of emergency but were less impacted by the flood.	(Government of Canada, 2018) • (Wittrock et al., 2018)
Severe Storms and Thunderstorms	2016	Southern Saskatchewan	•Over $35.5 million damages in Alberta, Saskatchewan, Manitoba and Ontario, June 24-25, 2016. •A large storm system caused bad weather throughout the Prairies and parts of northern Ontario. •On June 24, widespread and severe thunderstorms caused heavy rain, strong winds, hail, and lighting in southern Saskatchewan uprooted trees and downed power lines, while flooding caused damages to roads, homes, and businesses. •Prairie Provinces storms June 28-30 (over $89.0 million damages), July 8 (over $54 million damages), July 15-16 (over $70.4 million damages) and July 18-20, 2016 (over $102.7 million damages) occurred. •On June 29, the [Alberta] storm began to move into southern Saskatchewan and southern Manitoba where hail and heavy rain accompanied by strong winds caused localized flooding. •On July 10, the bad weather continued [from Alberta] into Saskatchewan where 130 mm of rain fell causing significant flooding in Estevan prompting the declaration of a local state of emergency. There were also reports of numerous funnel clouds in Saskatchewan,	(Government of Canada, 2018)

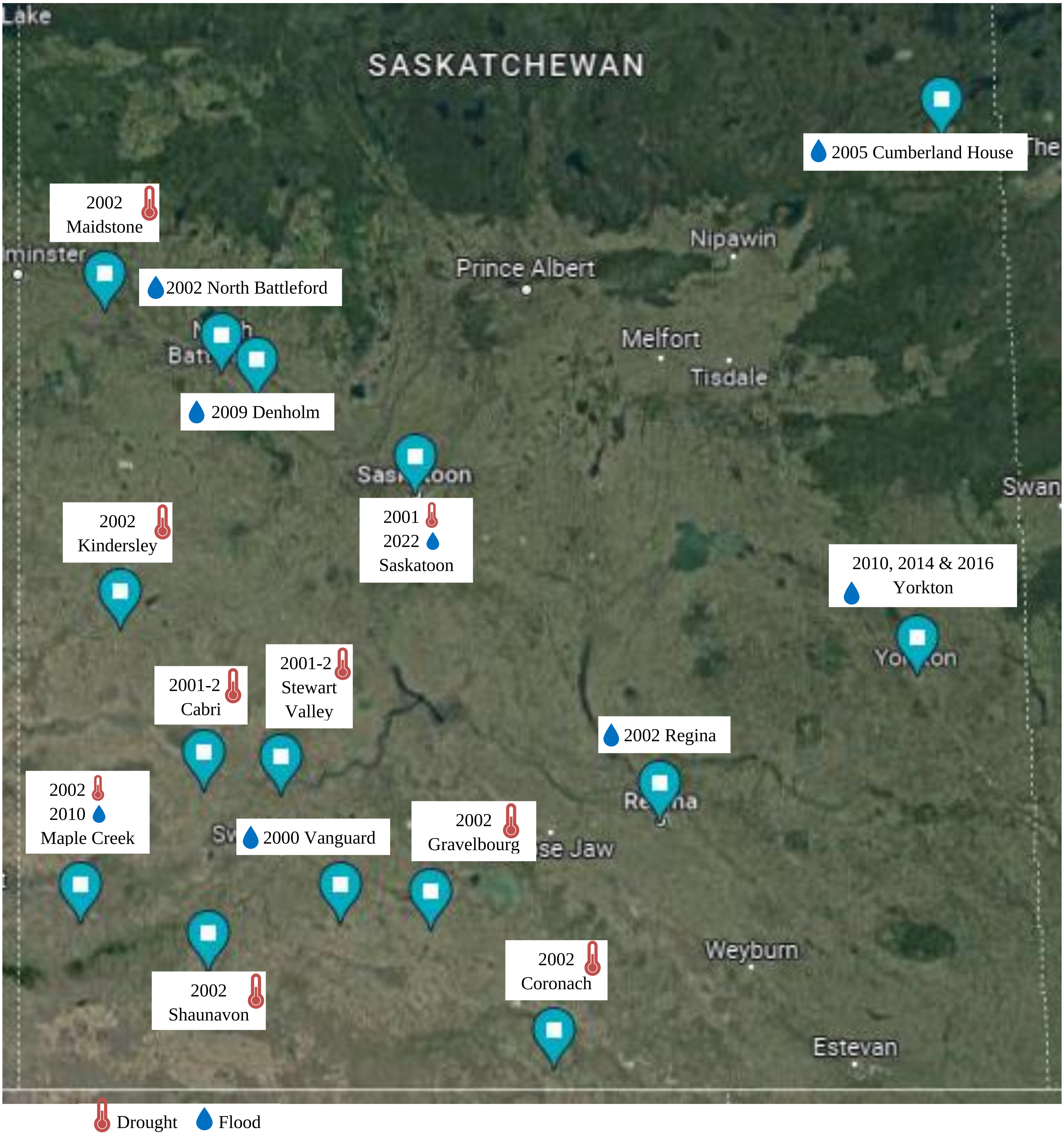
			including in Battleford and in Humboldt, where a small tornado briefly touched down for roughly 20 seconds. •On July 16, a torrential down pour consisting of 60 mm of rain in less than one hour hit the town of Swift Current, Saskatchewan, which caused flash flooding. In Swift Current, flash flooding overwhelmed the city's storm water system, which resulted in flooded basements and submerged vehicles. •Southern regions of the Prairie provinces were overwhelmed by severe storms after weeks of bad weather. •In Saskatchewan, near softball sized hail pelted Stewart Valley and Davison, where a tornado briefly touched down resulting in minimal damages.	
Flood	*2010* - *2017*	Southern and Southeastern Saskatchewan	•Heavy rains often with very wet antecedent conditions caused extensive flood damages to numerous Saskatchewan cities, rural communities, rural municipalities, and farms, with impacts to homes, buildings, roads, streets, landfills, water/wastewater facilities, energy systems, farmland, farm animals and crops, etc. •Saskatchewan's Emergency Flood Damage Reduction Program expended $81.6M from 2010-2014. •The Saskatchewan Provincial Disaster Assistance Program paid $372.47M to claimants from 2010-2017 (flood disasters likely the largest payouts). •The 2011 flooding was extensive across the Prairies (esp. SK and MB) "swamping three million hectares of farmland" – "Governments at all levels spent close to $1 billion on flood fighting and victim compensation". •In 2014. summer flooding in the eastern prairies in SK and MB drowned over one million acres of seeded fields, while two million acres were left unseeded. •Many communities suffered flood damages; total 2014 costs from flooding exceeded $1billion for farmers and numerous communities. (N.B Excessive snow conditions/runoff in 2010, 2011, 2014 followed by severe, often widespread, and frequent spring and summer rains resulted in extreme wet years and very large runoff volumes over	(Provincial Auditor of Saskatchewan, 2014) (Environment and Climate Change Canada, 2011) (Environment and Climate Change Canada, 2014) (Szeto et al., 2015) (Wittrock et al., 2018)

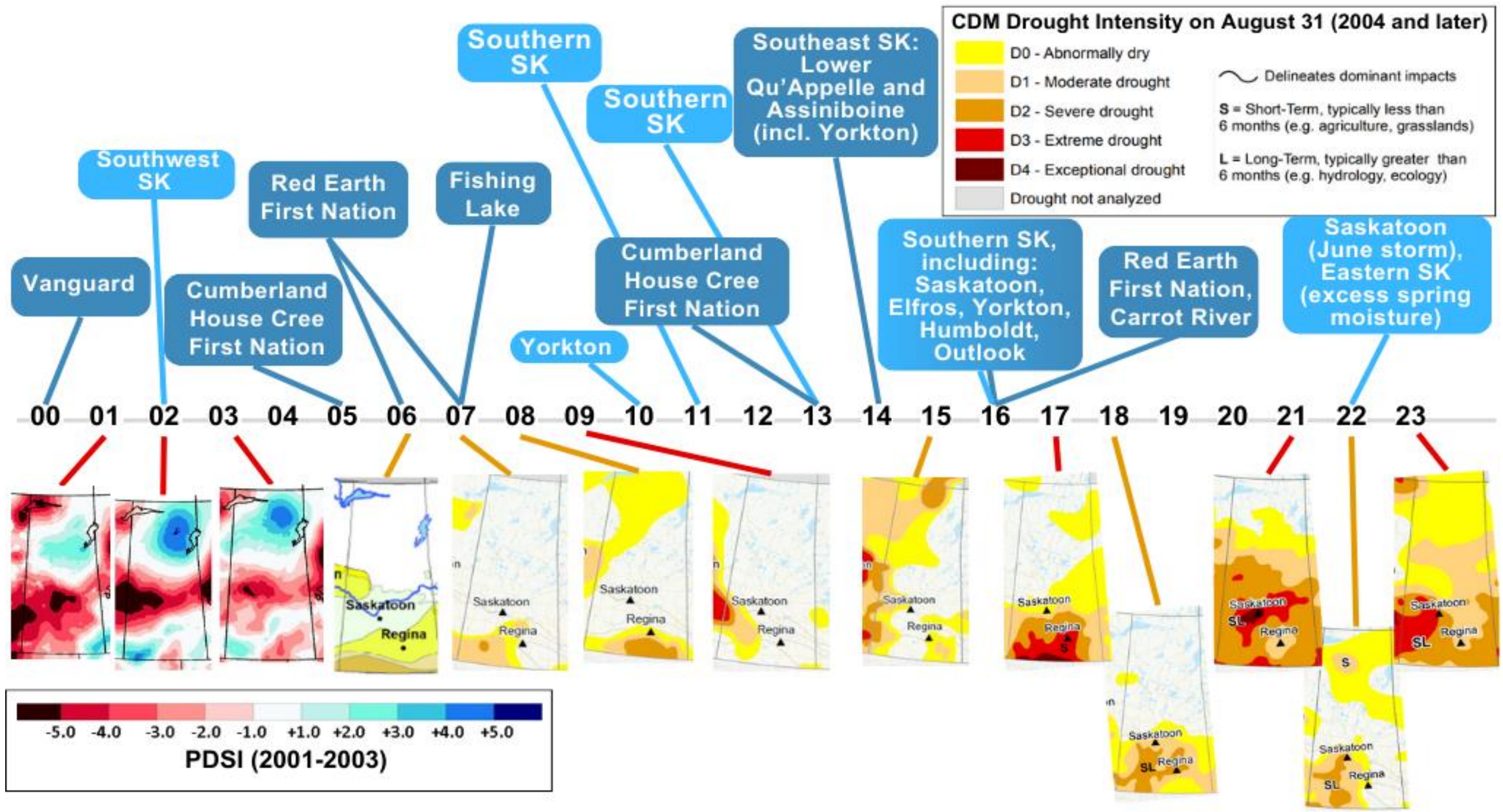
			significant regions of Saskatchewan, North Dakota, and Manitoba during back-to-back wet years during 2010-2017).	
Drought	2017	Southern Saskatchewan	• Severe drought covers much of SK to exceptional drought in the south. •Southern Saskatchewan experienced a wide range of drought impacts to both crops and livestock. •The agricultural sector faced the most severe impacts throughout the region; however, the 2017 drought impact went far beyond agriculture. Drought conditions continued to intensify throughout the summer with many regions recording less than half of normal rainfall during the growing season with a large region being below the 10th percentile. •Southern agricultural regions, especially in southern Saskatchewan, experienced rapidly deteriorating conditions throughout the spring and early summer resulting in severe drought and a wide range of impacts. •Total rainfall in Regina from April to October was 119.3 mm compared to the previous record of 151.5 mm in 1961. •More than 42 percent of the province's agricultural area was experiencing drought conditions, of which 11 percent was in the D3-Extreme Drought or D4-Exceptional Drought classifications. •Serious damage to electrical services and over 1,200 electrical supply repairs were required. •The Saskatchewan government announced that they would match donations of up to $100,000 for producers affected by wildfire.	(AAFC, 2022) (Hadwen & Schaan, 2021)
Severe Thunderstorms	2017	Saskatoon	•June 2, 2017, $46 million damages. •A fast-moving severe storm with ping pong-sized hail struck the Saskatoon area. •At least 6,000 insurance claims were processed with a total of over $46 million in insured damages. Nearly half of the losses were in vehicle damages.	(Government of Canada, 2018)
Fire	2017	Burstall, SK	•An estimated 400 livestock were killed in the fires. •Over the Burstall, Sask. area, a prairie fire covered more than 30,000 hectares. A fire at Tompkins burned 4,000 hectares.	(Lesko, 2017)

Drought	2018	SK	•Severe drought in central and south SK. •Many moderate to severe impacts. Surface water, hay, and pasture shortages. •Crop conditions declined	(AAFC, 2022)
Normal to wet	2019	SK	•Without the more "normal to wet" year of 2019, the drought sequence would have been the longest in a long time. Even with 2019 as a relief of the drought, the sequence was still difficult. *This is a useful case, also for future possible conditions.* •Saskatchewan experienced the greatest improvement of the Prairie provinces having received 150 percent (60 to 100 mm) of normal precipitation during 30 days in most southern regions. •August 2019 is a distinct lack of drought and even only small abnormally dry conditions in the more northern agricultural region of SK. •Only small pockets of Abnormally Dry (D0) conditions remain around Kindersley, between North Battleford to Prince Albert and along parts of the eastern border due to long term conditions.	.
Drought	2020	SW SK and central N to S corridor in SK	•Moderate drought in north-central to south SK. •Dry conditions and heat resulted in some yield losses, reduced water supplies and fire risk.	(AAFC, 2022)
Intense Ice Storm and Rain	2021	Melville, SK' East and SE SK	•$1.2 million damages in Melville with PDAP covering $835,000."An ice storm hit east and southeast Saskatchewan, and Melville was one of the hardest hit areas. •There were 48 SaskPower employees and 6 Vegetation Management crews dispatched to the Melville area to help with the cleanup. •Approximately 56-thousand 987 SaskPower customers in east and southeast Saskatchewan were affected by the ice storm."	(Young, 2022)
Heat Dome	2021	Saskatchewan	•Intense rare heat dome covers North America.	(BBC News, 2021)
Drought	2021	SK	•Severe to extreme drought dominated the prairies, including areas of exceptional drought, the highest category. •Crop yields dropped about 20-40%, and quality dropped also. •Surface water supplies a concern.	(AAFC, 2022)

			•Grasshopper problems.	
Drought	2022	Central and SW SK	•Severe drought areas increased in central and SW SK. •Poor crop yields in SW SK, grasshopper, and flea beetle outbreaks. •Water quality and livestock feed concerns in south central SK.	(AAFC, 2022)
Ice Storm	2022	Southeast Saskatchewan	•April 24, 2022 SE Saskatchewan receives intense storm, wind, ice downing electrical generation lines. •Southeast Saskatchewan is cleaning up after yet another spring storm which left 24,460 customers without power Sunday morning.	(Saskatoon Star Phoenix, 2022)
Flood	2022	Saskatoon, North Battleford, Eastern SK	•June storm brought 75mm in just a few hours flooding homes and a new storm retention pond. •The exceptionally dry western half of the province was drenched by rain in mid-June. Nearly 100 millimetres of rain fell in North Battleford in less than 24 hours breaking the previous one-day rainfall record of 92.7 mm in 1965. •In eastern SK, Excess spring moisture caused delayed seeding and harvesting of crops.	(Williams, 2022) (AAFC, 2022)

Appendix C: Map of droughts and floods in Southern Saskatchewan from 2000-2





Appendix D: Timeline of floods and severe or worse (D2 or higher) droughts from 2000 (00) to 2023 (23) in the BWAG watersheds in Southern Saskatchewan (SK).

For 2004 and later, drought maps show drought intensity as of August 31 from the Canadian Drought Monitor (CDM; AAFC 2023; see legend in upper right corner). For 2000-2003, the maps show August PDSI (Palmer Drought Severity Index) values because CDM maps were not available (see legend under 2001-2003; maps adapted from Bonsal et al. 2011). Red lines signify years with extreme drought (D3 or PDSI between -5.0 and -4.0) or exceptional drought (D4 or PDS1 < -5.0), while tan lines show years with severe drought (D2) as the highest intensity. Dark blue squares = flood locations up to 2017 found by searching 'floods' and 'storms and severe thunderstorms' in the Canadian Disaster Database (Government of Canada 2018). Light blue = additional sources for floods for Southwest SK in 2002 (Szeto et al. 2011); Yorkton in 2010 (Salman and Hurlbert 2022); Southern Saskatchewan in 2011(Environment and Climate Change Canada 2011) and 2013 (Pomeroy, Stewart, and Whitfield 2016); Saskatoon and Outlook in 2016 (Baird 2016); Elfros in 2016 (Wittrock et al. 2018); Saskatoon in 2022 (Williams 2022) and Eastern SK in 2022 (CDM info for Aug 31, 2022 from AAFC 2023). More information on the impacts from these and other hazards from this period can be found in Appendix B of the Objective Two Risk Report (see link in References).

Appendix E: Information on multi-year droughts in SK (2000 to 2022).

Bonsal et al. (2011) was used for 2000-2002 and the Canadian Drought Monitor (AAFC, 2022) was used for 2003-2022. See **Table 2.1** and **Appendix B** for more details on droughts during these time periods.

Multi-year severe drought or worse (D2+): Consecutive years with severe drought or worse in SK are 2001-2002, 2017-2018, 2020-22.

Therefore, three sets of consecutive severe droughts (or worse) two years long have occurred during 2000-2022. The last set was just separated by one year, that is 2019, so recovery would be limited.

Multi-year moderate droughts (D1) are 2001-2004, 2006-2009, 2017-2018, 2021-2022.

Four sets of multi-year moderate droughts have occurred during 2000-2022. The first two sets were four years long. The last two sets were two years long, but only separated by one year.

In a multi-year drought, the environmental, economic, and social effects are multiplied every year by management decisions made during previous years. Because we do not know in advance whether drought will become a multi-year event, the potential for prolonged droughts requires greater preparedness and resiliency.

Appendix F: Provincial Auditor of Saskatchewan Key Reports (disaster compensation for storms, flooding, etc.)

1. **2021 Report Volume 1 – Chapter 4 Corrections, Policing and Public Safety – Providing Provincial Disaster Assistance** (Provincial Auditor of Saskatchewan, 2021)**:** the Auditor describes the importance of disaster relief in Saskatchewan and documents PDAP claims over ten years (many if not most are related to storms and flooding, but other disasters are also included; PDAP reports are likely available to categorize).

Figure 1—Provincial Disaster Assistance Claims Paid from 2010–11 to 2019–20

Fiscal Year	Total Amount Paid to Claimants	Non-Claim Related Program Expenditures (e.g. Salary and Administration Costs)	Claim-Related Program Expenditures (e.g., Adjuster, Engineering Services)
	(in millions)		
2010–11	$ 15.08	$ 1.36	$ 3.47
2011–12	**112.65**	7.35	7.00
2012–13	63.64	5.56	3.98
2013–14	39.05	4.90	2.36
2014–15	61.76	5.17	5.91
2015–16	50.56	4.60	3.91
2016–17	29.73	3.98	1.88
2017–18	12.45	3.71	0.70
2018–19	9.78	3.17	0.44
2019–20	**3.93**	2.82	0.20

Source: Derived from Ministry records.
Bold font shows the year of the lowest and highest total amount paid over the 10-year period.

The Auditor adds: "The Provincial Disaster Assistance Program claims and receives Government of Canada disaster financial assistance under the Federal Disaster Financial Assistance Arrangements. Under this Arrangement, the Government of Canada reimburses provincial governments when the provincial eligible expenditures exceed an established initial threshold (threshold established based on provincial population). Provincial governments must complete all provincial restoration activities before submitting a final claim for federal reimbursement. The Ministry can seek advances of reimbursements from the Government of Canada."

Figure 2 shows the amount of federal funding the Ministry received over the last ten years for expenditures submitted under the Disaster Financial Assistance Arrangements. In this 10-year period, the amounts recovered vary considerably from as low as $0 million in 2010, 2011, 2012, 2019 and 2020, to as high as $166 million in 2013.

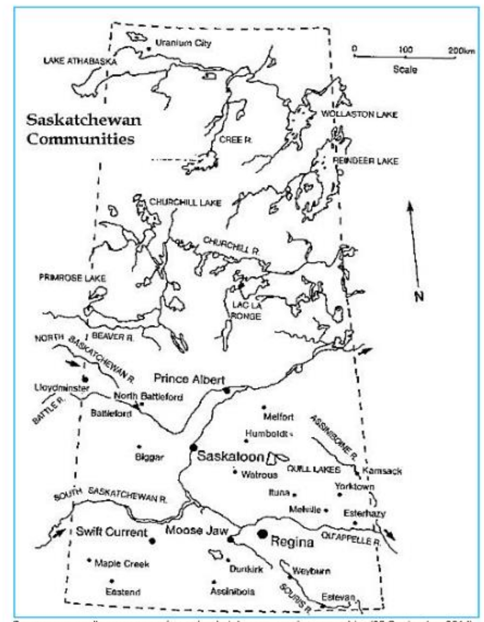
Figure 2—Eligible Provincial Expenses Recovered Under the Federal Disaster Financial Assistance Arrangements from 2010 to 2020

Calendar Year	Eligible Provincial Expenses Recovered Under the Federal Disaster Financial Assistance Arrangements (in millions)
2010	$ 0.00
2011	0.00
2012	0.00
2013	**166.00**
2014	**165.00**
2015	**29.70**
2016	**50.30**
2017	**43.31**
2018	6.89
2019	0.00
2020	0.00

Source: Derived from Ministry records.
Bold font shows the year of the highest total amount paid over the 10-year period.

2. **2019 Report Volume 1 Chapter 43 Water Security Agency – Co-ordinating Flood Mitigation** (Provincial Auditor of Saskatchewan, 2019): the Auditor reports: **"**We found that the Agency determined 98 communities had ongoing flood risks. It further assessed these risks and evaluated where additional flood mitigation activities would be beneficial for the 98 communities. As of early April 2019, the Agency evaluated 86 of the 98 communities. Management indicated it planned to complete its assessment of the remaining 12 communities during 2019."
3. **2014 Report Volume 2 Chapter 40 Water Security Agency – Co-ordinating Flood Mitigation** (Provincial Auditor of Saskatchewan, 2014)**:** the Auditor reports on WSA's key roles and states: "Floods in Saskatchewan occur along water sources, including three of its major river systems: the South Saskatchewan River, the Souris River, and the Qu'Appelle River (see Figure 1 for the location of these rivers). Many of Saskatchewan's municipalities, 7 including the cities of Saskatoon and Prince Albert, are located adjacent to these major river systems and hence are in flood-risk areas."

Figure 1—Map of Saskatchewan Including Major River Systems



Source: www.yellowmaps.com/maps/saskatchewan_province_map.htm (25 September 2014).

Floods can also be costly to the provincial government as it provides assistance to those affected (e.g., through the Provincial Disaster Assistance Program – see Figure 3). Reducing or preventing flood damage can reduce the cost of cleanup and reduce potential negative impacts on the health and safety of residents. The Agency plays a key role in coordinating flood mitigation.

Figure 3—Four Years of Provincial Disaster Assistance Program (PDAP) Expenses

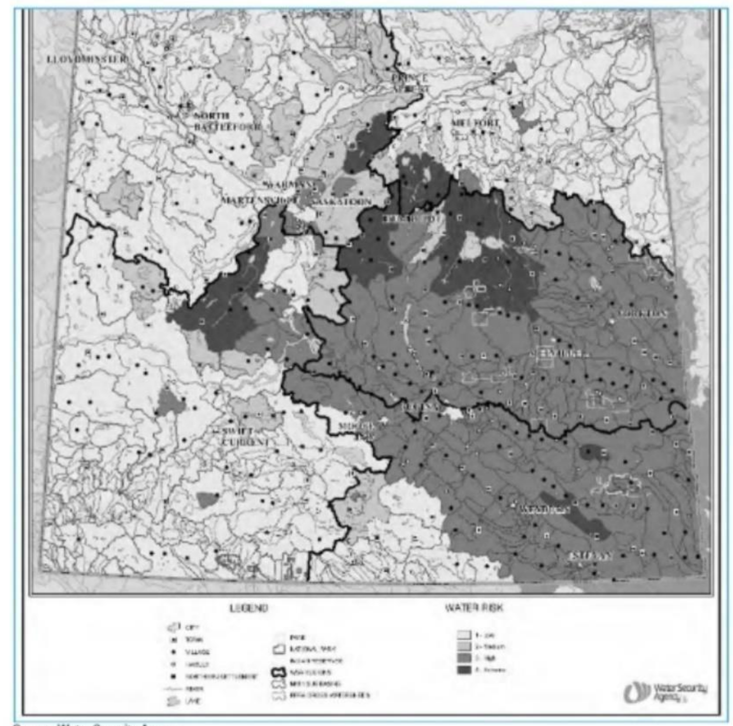
Fiscal Year	PDAP Expenses* (in millions)
2013-14	$ 46.8
2012-13	72.6
2011-12	157.1
2010-11	48.2
Total:	$ 324.7

*Source: *Public Accounts Volume 2*, 2010-11 to 2013-14. The PDAP expenses include expenses related to flood damage and other disasters; flood damage makes up most of the expenses.

4. **Provincial Auditor of Saskatchewan 2018 Report Volume 1 Chapter 12 Water Security Agency-Regulating Drainage** (Provincial Auditor of Saskatchewan, 2018)**:** Flooding Risk is related to natural topography, and may be exacerbated by land drainage The Auditor writes:

“It is now understood that flooding your neighbour is not the only drainage issue, and that drainage has a cumulative effect on flooding further downstream, water quality, wetland loss, and increased greenhouse gas emissions. In addition, the drainage network as a whole must be considered when approving drainage works to avoid unintended consequences. The Agency [WSA] has identified areas in the province at risk of flooding. See Figure 1 for areas in the province with a naturally higher risk of flooding, water quality issues, and erosion. Drainage can further increase these risks. Flooding can affect farmland, residential areas, and infrastructure (e.g., roadways). The darker shading in Figure 1 shows the eastern portion of Saskatchewan is at higher risk of flooding and drainage issues (i.e., water risk is assessed as high and extreme). The Agency’s Yorkton and Weyburn regional offices are responsible for regulating drainage in this area.

Figure 1—Saskatchewan Watershed Vulnerability Map at April 2018



Source: Water Security Agency.

Appendix G: WSA listing of Watershed Association Boards (WABs)

Notes:

i. **All WABs are formally constituted by local government to construct, own and operate water infrastructure to address specific water management issues - most commonly WABs are formed to address flooding and excessive water management, and/or drainage.** Most were formed following specific or multi-year flooding or excessive water problems in a targeted region. Some WABs will be responsible for water flooding issues related to land use development where drainage is required to prevent flooding problems. Background on their formation to determine the specific rational for flood management would be available from WSA.

ii. **WABs are not the stewardship watershed associations; WABs are focussed on specific water management at a localized or regional scale (WABs do not usually incorporate planning or water management at a watershed scale – the one exception is the Quill Lakes WAB). WABs typically have elements of water infrastructure.**

iii. **Many of these WABs are in the prospective BWAG study Basins. It will eventually be useful to ask WSA for background information, so we can add the Hydro-climatic Events to the BWAG hydro-climate Risk Table (i.e. the flooding events/issues that triggered the formation of these WABs. N.B. These groups should also be included in the BWAG Focus Groups**

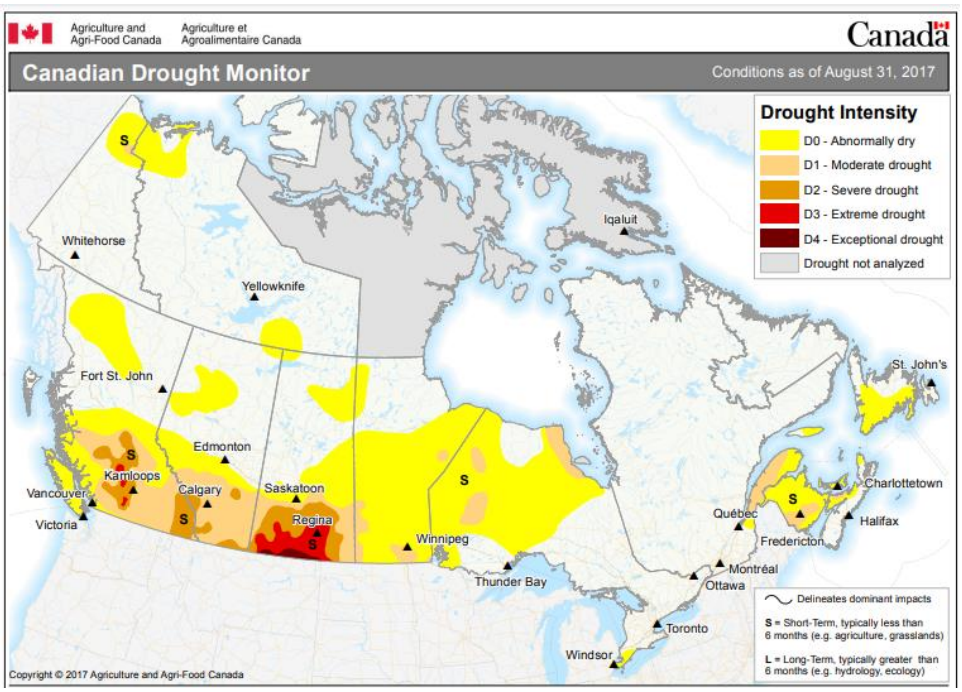
Ministerial Name of Watershed Association Boards (abbreviated as WA including its Number)	*City, Town, Village or Hamlet*	*Status*	*SCDA Member*
Jackfish Lake WA No. 1	North Battleford	Active	Yes
Moose Jaw Creek WA No. 2	Moose Jaw	Inactive	No
Nut Lake WA No. 3	Kelvington	Active	Yes
Yorkton Creek WA No. 5	Yorkton	Active	Yes
Lanigan Creek-Dellwood Brook WA No. 4	Humboldt	Active	Yes
Good Spirit Lake WA No. 6	Canora	Active	Yes
Fishing Lake WA No. 7	Foam Lake	Active	Yes
Smith Creek Regional WA No. 8	Calder	Active	Yes
Lake Roy WA No. 9	Lampman	Active	Yes
Opimihaw Creek WA No. 10	Saskatoon	Active	Yes
Wallace Creek WA No. 11	Yorkton	Active	Yes
Amsterdam South Creek WA No. 12	Amsterdam (Canora)	Inactive	No
Thickwood Hills WA No. 13	Shellbrook	Active	Yes
Quill Lakes WA No. 14	Wadena	Active	Yes
Lake Lenore Goose Hunting Creek WA No. 16	Humboldt	Active	Yes
Pense-Cottonwood Creek WA No. 17	Pense	Active	No

Moose Mountain-Pipestone Creek WA No. 20	Kipling	Active	No
East Cottonwood Creek WA No. 21	Regina	Active	No
Kaposvar Creek WA No. 22	Stockholm	Active	Yes

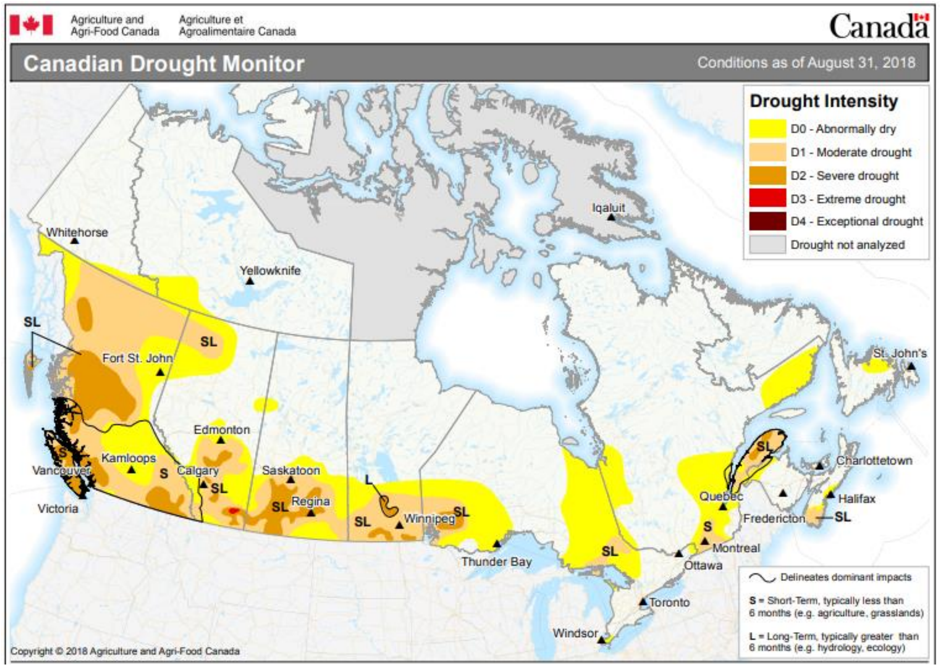
Land Use Changes and Modifications: Drainage at the farm scale have also affected flooding risk. Saskatchewan Conservation and Development Association https://scda.ca/index.php/home/history/ provides a history of the 1949 Conservation and Development Act (to preserve and protect agricultural land with water management adaptations using drainage.) These land use changes are widespread across the province, and significant in the BWAG study basins, where many producers have altered the landscape to help their livelihoods and farm economics, but with changes to ecosystems and water management which are now being addressed with increased regulation by WSA's Agricultural Water Management Strategy.

Appendix H: Canadian Drought Monitor Maps **(AAFC, 2022)** for August (2017-2022) and for the end of each of the four seasons (for 2020-2021).

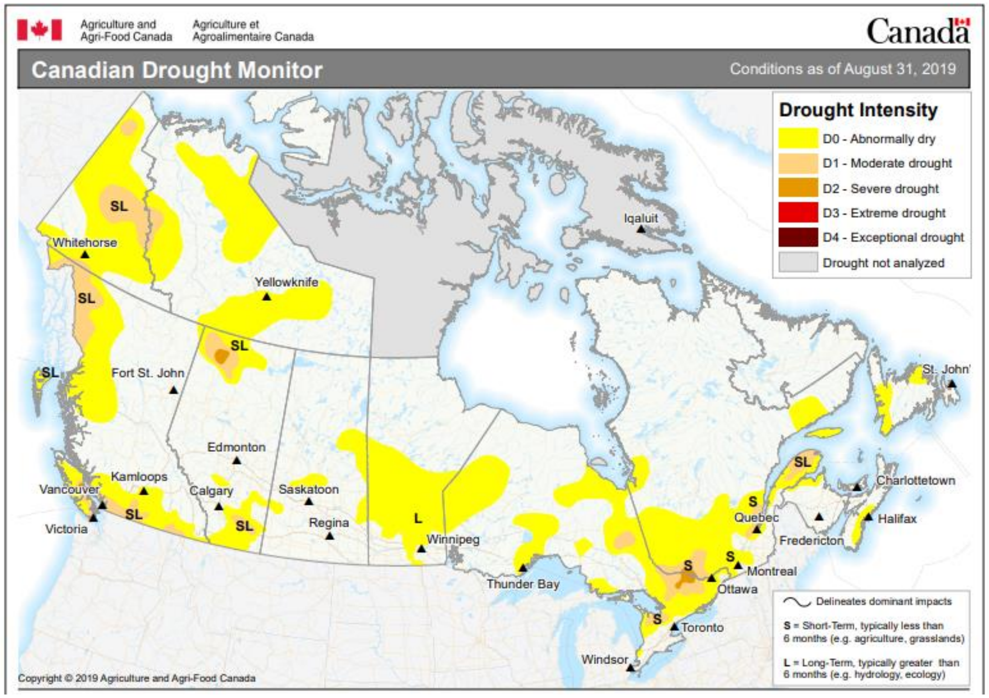
a) 2017 August



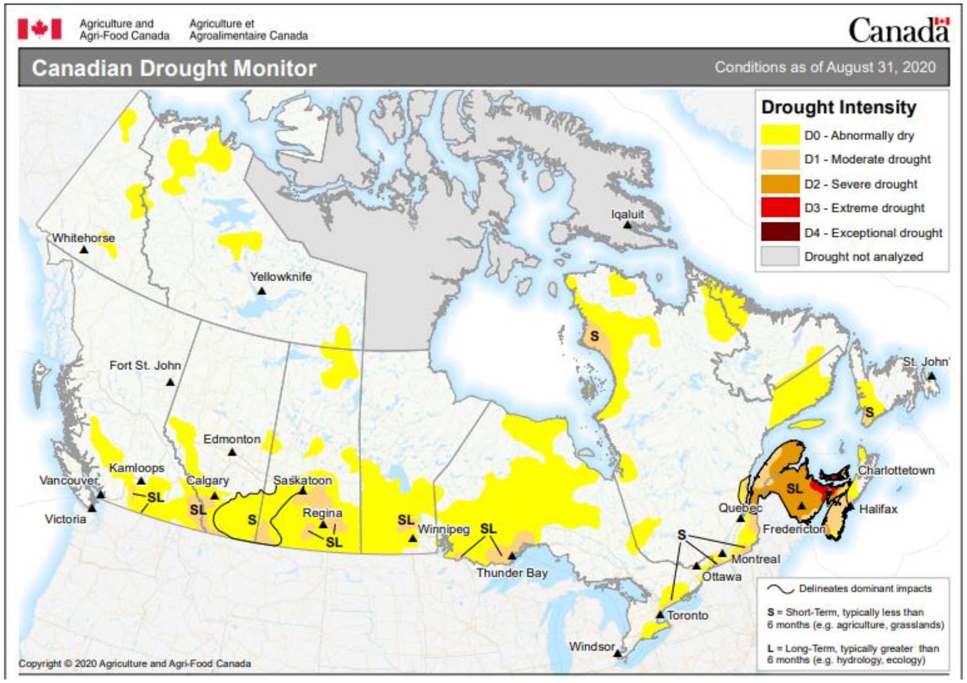
b) 2018 August



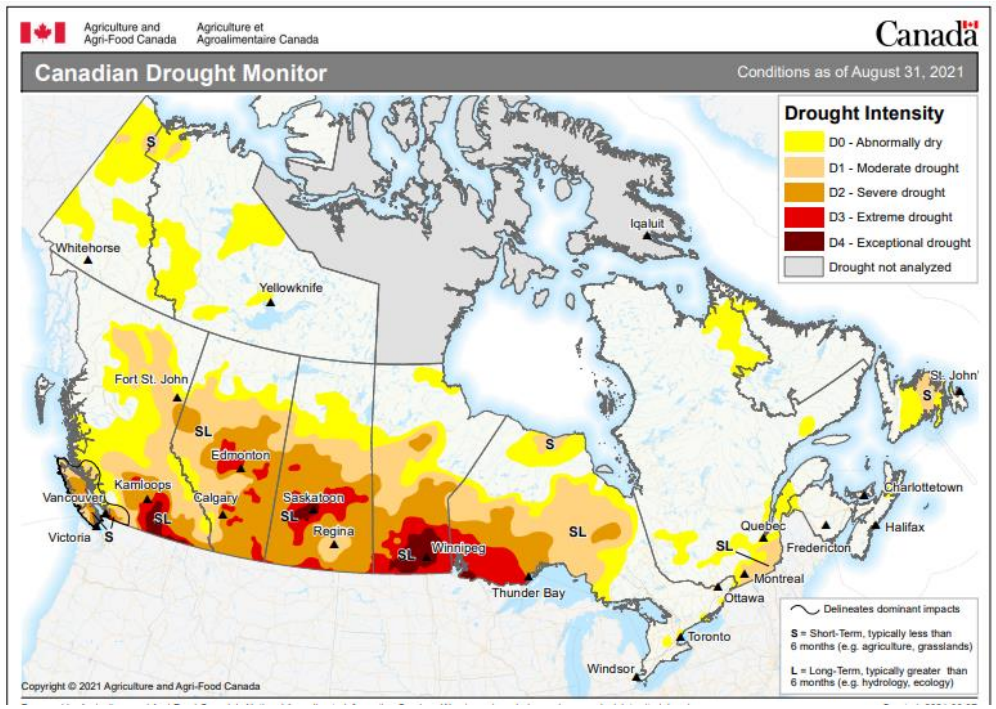
c) 2019 August



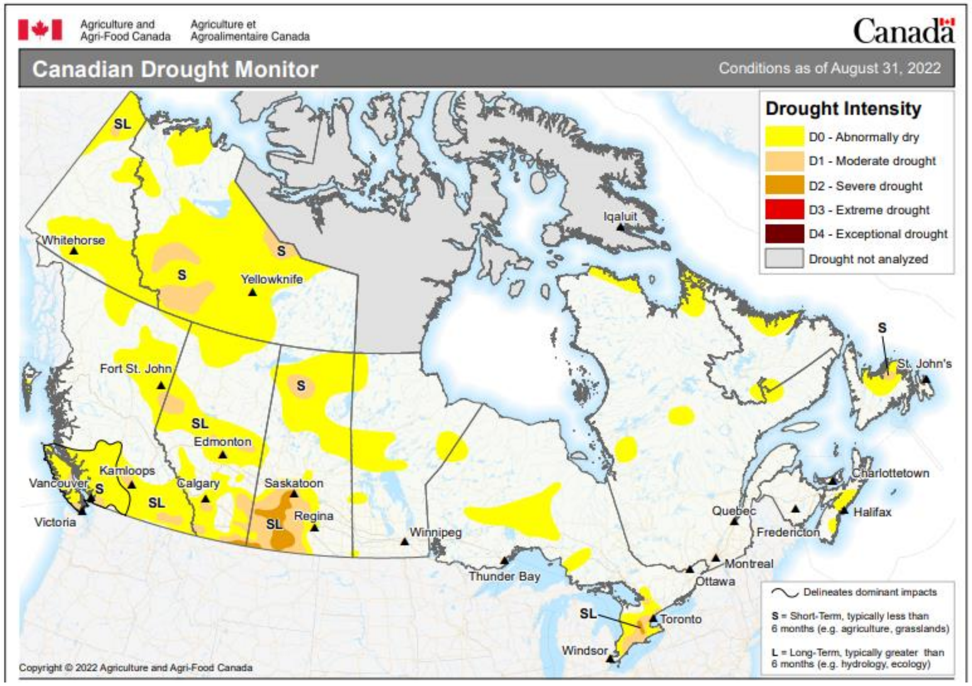
d) 2020 August



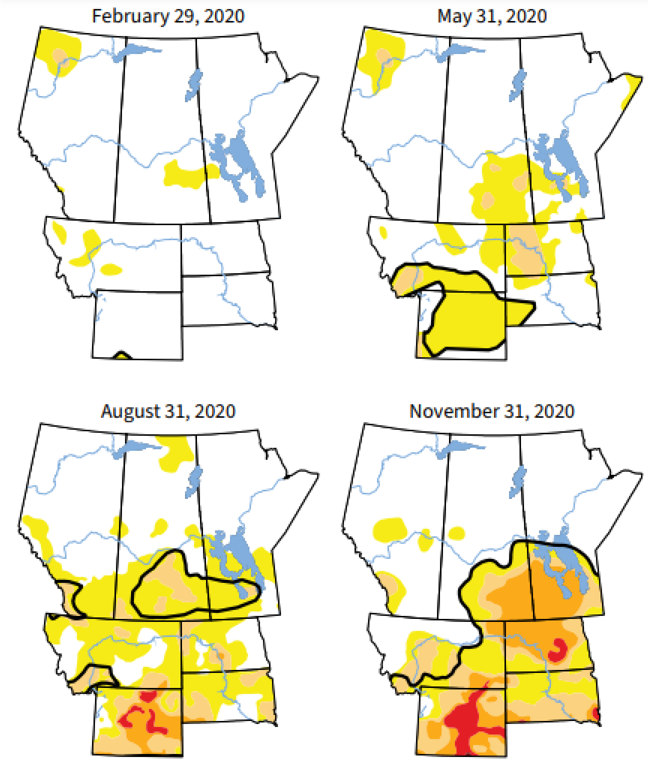
e) 2021 August



f) 2022 August

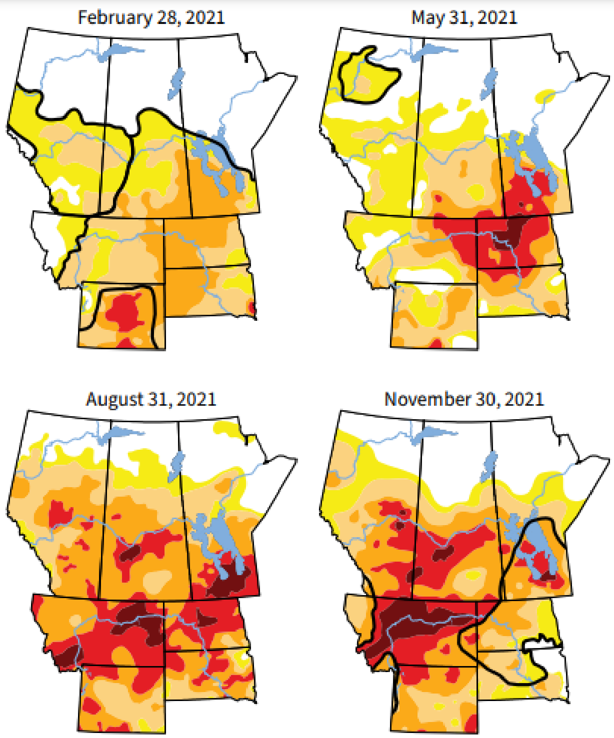


g) 2020 end of February, May, August, and November



◄ Figure 5: **North American Drought Monitor (NADM) Maps at the end of each climatological season in 2020, showing the progression of the drought across the U.S. Northern Plains and Canadian Prairies. Source: NOAA/NCEI, NDMC**

h) 2021 end of February, May, August, and November



◄ **Figure 10: NADM Maps at the end of each climatological season in 2021, showing the progression of the drought across the U.S. Northern Plains and Canadian Prairies. Source: NOAA/NCEI, NDMC**

Appendix I: The likelihood of natural hazards occurring in Saskatchewan (Table A) and changes in these likelihoods resulting from climate change in the 2050s (Table B).

These tables are from the Saskatchewan Flood and Natural Hazard Risk Assessment Report (Wittrock et al., 2018). (Tables were also produced for Human Health and Safety Impacts, Social Impacts, Public Administration Impacts, Economic Impacts, and Environmental Impacts).

Table A Comparison of Plausible Worst-Case Natural Hazard Scenarios

Natural Hazard	Case Study Location	Likelihood of Occurrence	Impact Categories					Aggregate Risk
			Human Health & Safety	*Social*	*Public Administration*	*Economic*	*Environment*	
Mountain Runoff Flooding	Prince Albert	Rare	Moderate	Minor	Moderate to Major	Minor	Minor	Low to Moderate
Plains Runoff Flooding	Regina	Unlikely	Moderate	Minor to Moderate	Major	Major	Moderate	Moderate
Lake Flooding	Fishing Lakes Last Mountain Lake	Unlikely	Moderate	Minor	Minor	Minor	Moderate to Major	Moderate
Overland Flooding	Agricultural region of Saskatchewan	Unlikely	Minor	Minor to Moderate	Minor	Major	Moderate	Moderate
Groundwater Flooding	Highly localized	Unlikely	Insignificant to Minor	Insignificant to Minor	Insignificant to Minor	Insignificant to Minor	Insignificant to Minor	Low
Drought – All Types	Agricultural region of Saskatchewan	Unlikely	Major to Catastrophic	Major to Catastrophic	Catastrophic	Catastrophic	Moderate to Major	High
Forest Fire	Human-caused forest fires close to communities; forested zone of province	Unlikely	Major	Moderate to Major	Major	Moderate	Minor to Moderate	Moderate to High
Grass Fire	Grass fire > 1,000 ha; agricultural region of Saskatchewan	Unlikely	Major	Moderate to Major	Minor	Minor to Moderate	Minor	Moderate
Convective Summer Storms	Regina and area	Unlikely	Catastrophic	Major to Catastrophic	Major	Major to Catastrophic	Major to Catastrophic	High
Winter Storms	Southern Saskatchewan	Unlikely	Major	Minor to Moderate	Moderate to Major	Major	Moderate	Moderate to High
Earthquake	Highly localized along the Saskatchewan and Montana border	Unlikely	Insignificant	Insignificant	Moderate	Moderate	Insignificant	Low

Table B Natural Hazard Comparison of Plausible Worst-Case Scenario with Projected Climate of the 2050s

Natural Hazard	**Case Study Location**	**Likelihood of Occurrence**	**Impact Categories**					**Aggregate Risk**
			Human Health & Safety	*Social*	*Public Administration*	*Economic*	*Environment*	
Mountain Runoff Flooding	Prince Albert	Rare to unlikely	Moderate	Minor	Moderate to Major	Minor	Minor	Low to Moderate
Plains Runoff Flooding	Regina	Unlikely to possible	Moderate	Minor to Moderate	Major	Major	Moderate	Moderate
Lake Flooding	Fishing Lakes Last Mountain Lake	Unlikely	Moderate	Minor	Minor	Minor	Moderate to Major	Moderate – less shoreline ice damage
Overland Flooding	Agricultural region of Saskatchewan	Unlikely to possible	Minor	Minor to Moderate	Minor	Major	Moderate	Moderate to High
Groundwater Flooding	Highly localized	Unlikely	Insignificant to Minor	Insignificant to Minor	Insignificant to Minor	Insignificant to Minor	Insignificant to Minor	Low
Drought – All Types	Agricultural region of Saskatchewan	Unlikely to possible	Major to Catastrophic	Major to Catastrophic	Catastrophic	Catastrophic	Moderate to Major	High to Extreme
Forest Fire	Human-caused forest fires close to communities; forested zone of province	Unlikely to possible	Major	Moderate to Major	Major	Moderate	Minor to Moderate	Moderate to High
Grass Fire	Grass fires > 1,000 ha; agricultural region of Saskatchewan	Unlikely to possible	Major	Moderate to Major	Minor	Minor to Moderate	Minor	Moderate to High (depending on biomass availability)
Convective Summer Storms	Regina and area	Unlikely to possible	Catastrophic	Major to Catastrophic	Major	Major to Catastrophic	Major to Catastrophic	High to Extreme
Winter Storms	Southern Saskatchewan	Unlikely	Major	Minor to Moderate	Moderate to Major	Major	Moderate	Moderate to High (with greater risk of freezing rain)
Earthquake	Highly localized along the Saskatchewan and Montana boundary	Rare	Insignificant	Insignificant	Moderate	Moderate	Insignificant	Low

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