

FOREST VULNERABILITY TO FIRE IN THE NORTHERN ROCKY
MOUNTAINS UNDER CLIMATE CHANGE

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ABSTRACT

Forest fires are an increasing concern under climate change. Substantially increased fire vulnerability could become a reality for many areas, including the Rocky Mountains. Forest fire hazard was examined in the upper North Saskatchewan and St. Mary watersheds for the period of 1960 to 2100. Ensemble climate scenarios were chosen to represent a wide range of possible future climates. The GENGRID meteorological model and the Canadian Forest Fire Weather index System were combined to assess possible changes in forest fire hazard in the Rocky Mountains. A wind model was developed to estimate daily wind speed variation with elevation. It was found that under most climate scenarios, fire hazard is predicted to increase. If future temperatures are warm, as expected, it could offset future precipitation increases, resulting in greater severity of fire weather and an increase in the number of days per year with high fire hazard.

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KEY EXPRESSIONS

Abbreviations

BUI	Buildup Index
CFFWIS	Canadian Forest Fire Weather Index System
DC	Drought Code
DMC	Duff Moisture Code
DSR	Daily Severity Rating
FFMC	Fine Fuel Moisture Code
FWI	Fire Weather Index
GENGRID	Grid simulating meteorology model
GCM	General Circulation Model
ISI	Initial Spread Index
NSW	North Saskatchewan Watershed
SMW	St. Mary Watershed
SSR	Seasonal Severity Rating
TC	Terrain Category

Variables

T	Air temperature (°C)
T _d	Dewpoint temperature (°C)
T _N	Minimum air temperature (°C)
T _X	Maximum air temperature (°C)
T _{d NOON}	Dewpoint temperature at noon (°C)
T _{NOON}	Air temperature at noon (°C)
RH	Relative humidity
RH _{NOON}	Relative humidity at noon (%)
WS	Wind speed (km·h ⁻¹)

Terms

Historical Period	1960-2010
Base Period	1961-1990
2020s	2011-2040
2050s	2041-2070
2080s	2071-2100

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CHAPTER 1:

Introduction

1.1 Introduction and Rationale

Fires are among the prevalent disturbances of forests, capable of changing landscapes throughout Canada (Dale et al., 2001; Flannigan et al., 2005b). Climate in the Canadian Rockies is known to affect forest fire activity (Johnson and Larsen, 1991; Schoennagel et al., 2004). Forest fires are becoming an increasing concern under climate change (Flannigan et al., 2009; Running, 2006; Westerling et al., 2006). Substantially increased fire vulnerability could become a reality for many areas including the Rocky Mountains of North America. Global warming has already been linked to increases in forest fire occurrence and the area burned by fire in Canada in recent decades (Gillett et al., 2004). Future projections of climate change predict further increases in forest susceptibility to fire, and increases in the severity of forest fire activity throughout the next century (Flannigan et al., 2000; Nitschke and Innes, 2008; Running, 2006; Westerling et al., 2006).

This thesis aims to simulate fire hazard at a fine spatial scale over the past half-century and predict possible future fire weather severity patterns through the year 2100. The headwaters of the North Saskatchewan and the St. Mary watersheds were chosen as the study regions. Both basins are located along the eastern slopes of the Rocky Mountains. Fire hazard variables are studied at incremental 100 m elevation bands to better represent fire hazard in topographically diverse alpine environments. Two study watersheds were chosen for the purpose of doing a comparative study to analyze how the

fire hazard, both historically and in future projections, can vary in similar landscapes with somewhat close proximity.

1.2 Research Objectives

The purpose of this thesis work was to determine a range of possible fire weather regimes under climate change. It was built upon existing knowledge of fine-scale modelling, climate change, and forest fire hazard. This study has two general research objectives:

1. Refine the GENGRID meteorological model in order to determine the necessary meteorological variables for calculating fire hazard at a fine-scale spatial resolution. This involved constructing a model for estimating wind speeds at 100 m elevation bands throughout the study watershed and improving existing routines for simulating relative humidity.
2. Integrate the Canadian Forest Fire Weather Index System model with the GENGRID output to determine daily fire hazard values at 100 m resolution over complex mountain terrain for the historical period of 1960 to 2010. The results were then projected to estimate possible future daily fire hazard values under a range of climate change scenarios.

1.3 Thesis Format

This thesis is separated into five chapters. Chapter 1 serves as an introduction to the thesis offering a rationale and the research objectives. Chapter 2 is a literature review pertaining to the impacts of a changing climate on forest fire hazard regime. In addition, special attention is given to climate change, factors other than climate that may impact forest fires, and the impacts that forest fires have on societal and environmental variables. Chapters 3 and 4 are organized as a two-part paper to be submitted for publication in an academic journal. As such, some overlap in content is present between the literature review and Chapters 3 and 4. Chapter 3 describes the methods used to spatially represent the meteorological variables required for determining fire weather at high spatial resolution for the historical period of 1960 to 2010. In this chapter, the historical fire weather patterns are assessed for the North Saskatchewan and St. Mary watersheds. Chapter 4 uses the methods from Chapter 3 and applies future climate change scenario modelled output to project a range of possible fire hazard regimes for the two study regions through 2100. Chapter 5 serves as an overall summary of the work, and presents key conclusions, study limitations, and provides recommendations for future studies in this area.

CHAPTER 2:

Literature Review

2.1 Introduction

This chapter will serve as a review of current literature on the topic of global climate change, the impacts that climate change can have on forest fire hazard, and the resulting impacts on water quantity and quality. A more comprehensive review will be given to mountainous watersheds in western North America. This will be done to further establish an understanding of the potential impacts of climate change on the hydrologic cycle in the upper North Saskatchewan and St. Mary watersheds. Further consideration in this literature review will be given to General Circulation Models (GCMs) coupled with emission scenarios that give projections of future climate change.

2.2 Fire Weather Variables and Environmental Change

Fire weather variables are the meteorological elements that influence a forest's vulnerability to fire. The main elements of fire weather include air temperature, precipitation, relative humidity, and wind speed. They are used to determine the likelihood and extent of fire (Lawson & Armitage, 2008). Additionally, lightning is occasionally seen as a fire weather variable as it serves as an ignition source (Flannigan et al., 2005b).

2.2.1 Climate Change and Air Temperature

Globally, average air temperatures increased in the past century by approximately 0.1 °C per decade (IPCC, 2007) and close to 0.2 °C per decade during

the last 30 years (Hansen et al., 2006). An increase was also observed in extreme air temperature indices worldwide between 1951 and 2003 (Alexander et al., 2006; Booth, 2011). The frequency of extreme high temperatures has risen slightly in recent decades, and the frequency of extreme low temperatures recorded globally has declined (Houghton et al., 2001). It is well known that the global warming experienced over the last few decades of the twentieth century has been linked and attributed to anthropogenic causes (Easterling and Wehner, 2009; Houghton et al., 2001; IPCC, 2007) mostly from the burning of fossil fuels but also by changes in land-use, primarily deforestation (Houghton et al., 2001; IPCC, 2007). From 1970 to 2004, carbon dioxide (CO₂) emissions increased by 80% worldwide (IPCC, 2007). The IPCC's Fourth Assessment Report predicts a temperature increase of 0.6°C by the end of the century if current CO₂ concentrations stay constant through 2099. However, if CO₂ concentrations continue to rise as expected, a greater increase of 1.8 °C to 4.0 °C is expected, depending on the climate change impact scenario used (IPCC, 2007; Randall et al., 2007).

Regionally, minimum and maximum air temperatures have increased in Canada throughout the twentieth century (Bonsal et al., 2001). Over the last one hundred years, the mean air temperature for the Rocky Mountains increased by 1.5°C (Luckman and Kavanagh, 2000). In the Northern Hemisphere, average annual air temperatures are predicted to increase in most high latitudinal areas in upcoming decades (Cubasch et al., 2001), suggesting that a warming will continue in the Rocky Mountain region.

2.2.2 Climate Change and Precipitation

Over the past century, increases in precipitation were observed throughout

much of North America (Booth, 2011; Houghton et al., 2001; IPCC, 2007). The total number of days with precipitation across Canada steadily grew throughout the twentieth century, while the number of dry days declined (Vincent and Mekis, 2005). There is greater uncertainty in precipitation projections compared to future air temperature estimates (Branković et al., 2010). On the global scale, average precipitation is expected to increase in most areas in the future (Branković et al., 2010; Houghton et al., 2001). Severe precipitation events are expected to increase worldwide by mid to late century (IPCC, 2007), including an increase in the frequency and intensity of heavy rainfall events (Houghton et al., 2001; IPCC, 2007; Kunkel, 2002).

2.2.3 Soil Moisture and Evapotranspiration

Lower summer streamflows, falling lake levels, retreating glaciers, and increasing soil- and surface-water deficits are predicted as climate change advances (Easterling et al., 2000). Streamflow records in the Northern Rocky Mountains already indicate declines in flow partially attributable to global warming (Schindler and Donahue, 2006; St. Jacques et al., 2010). Streamflow decreased by 0.14% from 1912 to 2007 in the North Saskatchewan River at Edmonton, and by 0.46% per year in the in the St. Mary River at the United States border (St. Jacques et al., 2010). Warmer spring temperatures result in earlier snowmelt. This extends the period of soil moisture depletion by evaporation, resulting in a landscape more susceptible to forest fires (Westerling et al., 2006). The majority of land masses in Canada became drier between 1950 and 2002, which was partially attributed to higher air temperature (Dai et al., 2004), and soil moisture values may continue to decline as temperatures rise (Cubasch et al., 2001; Gregory et al., 1997; Schindler and Donahue, 2006). Precipitation may

increase or decrease in the coming decades. However, it is likely that increased evapotranspiration will offset increases in precipitation, resulting in further drying of the soils (Schindler and Donahue, 2006).

2.2.4 Climate Change Effects on Vegetation

Rising temperatures can impact vegetation growth in the Rocky Mountains and in alpine environments worldwide. Higher levels of CO₂ in the atmosphere and warmer temperatures may increase plant productivity. However, this could be offset by declining soil moisture content (Sauchyn and Kulshreshtha, 2008). Forested areas under a warming climate could see a rise in the elevation of tree lines, followed by further upward extent of grasses (Soja et al., 2007). New tree species introduction could also result from a warming climate. For example, aspen trees are known to be very sensitive to extreme cold weather. Areas that were once too cold for aspen tree growth, such as the upper foothills of the Rocky Mountains, are now warm enough to support these trees (Landhausser et al., 2010). Some studies demonstrate that species such as the lodgepole pine could possibly benefit from global warming (Cortini et al., 2001). Chhin et al. (2008) found that climate warming may cause a decline in lodgepole pine growth in forests in Alberta's foothills, but an increase in growth at higher elevations in the Rocky Mountains where climates are cooler. The radial growth of lodgepole pine is dependent on the weather. Growth typically increases following a warm dry winter but could decrease if summer climates get warmer and drier (Chinn et al., 2008a). This same warming could potentially be deadly for white spruce trees, due to drought stress in the future (Cortini et al., 2011).

2.2.5 Lightning Frequencies and Densities

Foothills along the eastern slopes of the Rocky Mountains are affected by an average of 18.25 hours of lightning activity per year, where a single lightning flash is assigned a time of one second, and a series of lightning flashes are timed from the first flash to the last flash (Burrows et al., 2002). Lightning strikes along the eastern slopes of the Rocky Mountains occur mostly in areas less than 1800 m above sea level, with almost no lightning near the continental divide (Burrows et al., 2002). In the IPCC's Third Assessment Report, it was noted that no changes were found in the frequency of thunder and lightning days in recent decades (Houghton et al., 2001).

The IPCC's Fourth Assessment Report (2007) does not provide predictions for future lightning activity. However, the IPCC does report that the number of extreme events could rise in coming decades. This could increase lightning frequency, due to warmer temperatures and a higher frequency and severity of extreme precipitation events. At mid-latitudes, the strength of convective storms that would cause lightning are dependent on the individual storms even under a warmer climate, however, it is projected that considerable increases in lightning frequency could be seen in future decades if the climate warms as expected (Peterson et al., 2010; Price and Rind, 1994). Under a doubled CO₂ concentration scenario, the northern hemisphere would likely experience the greatest rise in lightning activity in June, July, and August (Price and Rind, 1994). As these are typically the warmest months in the Rocky Mountains, an increase in lightning activity could increase the risk for forest fires.

2.3 Forest Fires in Mountainous Environments of Western Canada

2.3.1 Weather and Climate Impacts on Forest Fires

Warm temperature is among the most important driving factors with respect to forest fires, due to the higher likelihood of dry fuels as a result of increased evapotranspiration (Flannigan et al, 2005b; Hély et al., 2001; Westerling et al., 2006). Precipitation and humidity also determine the fuel moisture, while wind affects forest fire spread, and lightning serves as a source of ignition (Flannigan et al., 2005b). In the Canadian Rocky Mountains specifically, the climate and the climate's effect on fuel moisture and ignition frequency, were found to be the determining factors in forest fire frequency (Johnson and Larsen, 1991; Schoennagel et al., 2004) and severity (Schoennagel et al., 2004). Changes in weather conditions can alter both the pattern and extent of fire disturbance (Li et al., 2000), because the probability that a fire will burn as a high severity crown fire increases as fuels become progressively dry (Holden et al., 2007).

Lightning-induced fire requires both lightning and dry fuel. The drying of litter and standing dead biomass usually requires at least three days with minimal precipitation (Nash and Johnson, 1996). Fires initiated by lightning accounted for approximately eighty-five percent of area burned in Canada between 1959 and 1997 (Stocks et al., 2003). Lightning storms that occur with little precipitation are more effective at igniting fires than storms with greater precipitation (Peterson et al., 2010). Late spring and summer fires are more often initiated by lightning, while fires in the early spring and fall are more likely to be started by human impacts (Stocks et al., 2003). Fires initiated by lightning are expected to increase by 80% by 2080-2089 relative to the number of observed from 1975-1985 (Krawchuk et al., 2009).

A link exists between fire occurrence and temperature anomalies, such as the Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO) in parts of western Canada (Fauria and Johnson, 2006; Meyn et al., 2010). During the positive phase of the PDO in western Canada (1959 – 1999), areas east of the Rocky Mountains experienced weather suitable for fire (Fauria and Johnson, 2006). The effects of PDO and ENSO on forest fires varied by region, with a stronger influence on fires in western Canada compared to eastern Canada (Fauria and Johnson, 2006). Strongly positive PDO and ENSO years were correlated with larger and more numerous fires in western Canada than in eastern Canada (Fauria and Johnson, 2006; Meyn et al., 2010), indicating that these anomalies were strongly related to fire weather in the west. However, summer drought is more indicative of large fire size than climate oscillations (Meyn et al., 2010). By contrast, the correlation between burned areas and the mean annual PDO index was negative in Northwestern Canada attributable to lower pressure systems at higher latitudes (Wallenius et al., 2011).

2.3.2 Fire Necessity

Fires are a force that rapidly alters yet conserves and promote healthy ecosystem function in the forests of Canada (Flannigan et al., 2005b). Forest fires are important in maintaining biodiversity and landscape variety, and are essential to forest ecosystems (Flannigan, 1991; Girardin, 2007; Stocks et al., 2003). Small, relatively frequent fires prevent advanced aging of trees in forest stands (Barclay et al., 2009). Fewer fires could result in an abundance of mature trees which challenges the sustainability of a forest (Barclay et al., 2009). Feedbacks exist between vegetation, soil properties, and fire behavior, in ways that increase vegetation recovery after a fire (Johnstone et al., 2010).

Some plants, such as the lodgepole pine, require smoke and heat from fires in order for the cones to open and seed dispersion to take place (Despain et al., 1996). In older forest stands, spruce trees tend to dominate, and once burned, give the faster growing pine and aspen species' an opportunity for germination and growth (Herring, 1999).

2.3.3 Hydrological Impacts of Forest Fires

Forest fires can affect hydrological processes on the surface, by altering the physical characteristics of the soils. Extreme heating results in more unstable, easily eroded soils (Shakesby and Doerr, 2006). Burles (2010) found that even six years after a fire, little development of new soil had taken place, thereby increasing the soil density, and decreasing soil porosity. An important impact of fire on soil hydrology is that fire can change soil that was once non-repellent into soil that is highly water repellent (Shakesby and Doerr, 2006). This soil water repellency is greatest at the surface of the soil after moderate or severe fires. However, after one year, burned regions return to the water-repellency characteristics of unburned areas (MacDonald and Huffman, 2004). When the soils become more water repellent, more overland flow takes place (Shakesby and Doerr, 2006) as soil wetting and water infiltration into the soil decrease (MacDonald and Huffman, 2004). This can greatly increase the amount of water flowing into stream channels during and immediately following rainfall (Shakesby and Doerr, 2006).

Forest fires temporarily decrease streamflow during a fire because of the vapourisation from the high heat (Berndt, 1971). Immediately after a fire, streamflow increases (Berndt, 1971). Post-fire catchments have higher runoff ratios and streamflow volumes (Smith et al., 2011). Runoff, peak-flow, and total streamflow is even higher in catchments that were salvage-logged post-fire (Smith et al., 2011). High severity fires

were also associated with greater soil-water repellency (MacDonald and Huffman, 2004). The moisture content of soils reaches a threshold when water repellent soils become hydrophilic. There is an uncertainty in the soil moisture threshold after a fire, partially attributable to the difficulty in measuring this value, due to inconsistencies in the immediate weather conditions post-fire (Castro, 2011). Additionally, following a forest fire, hydrological variables such as interception and transpiration are reduced (Shakesby and Doerr, 2006).

Little data are available for the Northern Rocky Mountains on the impacts of forest fires on water quality (Mast and Clow, 2008). Generally the amount of suspended sediments in streams increases after a fire (Silins et al., 2009; Smith et al., 2011). Even greater increases of sediment are observed in streams in areas that were salvage-logged post-fire (Silins et al., 2009). Increased accumulation of nitrates, sulphate, and chloride has been found in streams in burned regions (Mast and Clow, 2008). Forest fires can increase mercury deposition, which can end up in streams, rivers, and lakes, further reducing the quality of the water (Witt et al., 2009).

Forest fires are among many disturbances that can greatly affect snowmelt energy balance. Burned forest stands have considerably less canopy than healthy stands. Thus, burned areas have more energy available for snowmelt leading to a higher rate of snowmelt and a shorter snowmelt period (Burles, 2010). Burned stands also experience greater snow accumulation (Winkler, 2011; Burles, 2010), higher rates of snow ablation (Winkler, 2011) and capture greater snow water equivalency (Silins et al., 2009) than nearby healthy stands, due to reduced canopy cover. This reduced canopy cover, and the fact the healthy stands have more litter, explains higher albedo in burned sites (Burles, 2010).

2.3.4 Negative Effects of Forest Fires

Forest fires can temporarily destroy wildlife habitat (Dale et al., 2001).

Mercury deposition from forest fires accumulated into water bodies can be harmful to aquatic life (Witt et al., 2009). An increase in forest fire activity can also have a negative impact on human health by the hardships caused from the smoke alone (Dale et al., 2001). In addition, an increase in forest fire frequency can negatively impact the carbon cycle by releasing greater amounts of CO₂ into the atmosphere while having fewer trees to serve as carbon sinks (Westerlint et al., 2006).

Shifts in vegetation patterns can occur in regions disturbed by forest fires (Flannigan et al., 2001). Forest composition, meaning the age and type of trees, is changed after a forest fire, with an accompanying decrease in the density of the forest (Westerling et al., 2006). Fire has a greater direct effect on species distribution than does global warming (Flannigan et al., 2000; Johnstone et al., 2010). Fire can in some cases even cause extirpation of certain species (Flannigan et al., 2000).

Forest fires can result in serious negative economic consequences (Flannigan et al., 2005). The burning of forests affects their value for timber and for recreational use (Dale et al., 2001), both of which are economically important (Flannigan et al., 2000). Human communities can expect to be threatened by the increase in projected forest fires, resulting in considerable management challenges (Westerling et al., 2006). Five hundred million dollars is spent each year on average for suppressing wildfires across Canada alone (Flannigan et al., 2009). As fire activity increases with anticipated climate warming, more negative impacts to the economy will be seen, including greater fire suppression costs (Flannigan et al., 2009).

2.3.5 Mountain Pine Beetle Infestation and Wildfire

Little research has been done on the theme of mountain pine beetle effects on fire hazard. In past decades, rising temperatures have caused an increase in the number of mountain pine beetle outbreaks in the Rocky Mountains (Shoemaker, 2010). As of 2010, aerial photographs from Alberta Sustainable Resource Development (SRD) of the upper North Saskatchewan watershed (NSW) did not show a current infestation of mountain pine beetles (Mountain Pine Beetle in Alberta [MPB], 2010). The same can be said for the southern-most portion of Alberta near the outlet of the upper St. Mary basin (MPB, 2010). However, with milder winters in recent decades, aging forest stands, and large numbers of beetles coming in from British Columbia, unprecedented numbers of mountain pine beetle outbreaks have occurred in Alberta, with the potential for further spreading (SRD, 2011; MPB, 2010).

The drying of trees damaged by mountain pine beetles and the further drying of soils and fallen needles by greater evaporation from the open understory results in increased risk of forest fire (R. Arthur, Alberta Sustainable Resource Development, personal communication, April 7, 2011). Surface fire spread rate, fire-line intensity, and crown fire potential in both currently infested stands and post- mountain pine beetle infested stands are greater than in a healthy green stand (Page and Jenkins, 2007). Page and Jenkins (2007) partially attributed observed fire increases in mountain pine beetle forest stands to the increased fuel loading during an epidemic and the change in vegetation cover in post-epidemic stands.

New research being done by Monica Turner and Phil Townsend at the University of Wisconsin is contrary to the popular belief that a forest stand infested with mountain

pine beetles will burn more readily than a healthy stand. Preliminary results by Turner and Townsend indicate that beetle infested stands may actually be less likely to burn than a healthy stand in some cases for two reasons: healthy green needles have flammable oils that are not present in dead needles, and dead needles on the forest floor decompose quickly so there is little litter on the forest floor to act as kindling (Shoemaker, 2010). This is in agreement with findings in Yellowstone National Park that: when a fire approached a forested area that was already dead with only standing trunks and very small amounts of litter, the fire would often stop because of a lack of fuel to keep the fire going (Shoemaker, 2010).

2.4 Trends in Climate Change and Forest Fires

2.4.1 Forest Fire Hazard

Fire is one of the most important major disturbances to impact forests (Dale et al., 2001). Since the return of forests after the last Ice Age, forest fires have been a predominant force in shaping Canada's natural landscape (Stocks et al., 2003). Forest fire activity is influenced by the climate (Ali et al., 2009; Flannigan et al., 2000; Krawchuk et al., 2006; etc.), watershed size and connectivity of landscape (Ali et al., 2009), forest makeup, including the age and type of trees (Dale et al., 2001), soil and biomass characteristics (Beverly et al., 2009; Shakesby and Doerr, 2006), terrain attributes (Schoennagel et al., 2004; Shakesby and Doerr, 2006), and ignition regime (Ali et al., 2006; Beverly et al., 2009).

Fire activity is partially dependent on the phenology of the plant life (Flannigan et al., 2000). In west central Alberta, fuel type and distribution can greatly influence the susceptibility of a forest to fire. For example, larger and more intense fires occur in

coniferous than deciduous stands (Hély et al., 2001). Fire susceptibility is higher in contiguous forest stands (Beverly et al., 2009) and large crown fires are more likely to occur in high density forest stands, through canopy to canopy spread (Schoennagel et al., 2004). Variation in the type of available fuels can affect fire initiation. The probability of ignition is greater in spruce dominated forests than in stands dominated by aspen and other deciduous species (Krawchuk et al., 2006). Some studies suggest that forests consisting of older coniferous species are much more susceptible to fire (Kang et al., 2006).

The type of previous forest disturbance and time since a forest disturbance can greatly affect the fire regime (Flannigan et al., 2000). Wild and prescribed fires can decrease the vulnerability of a stand to further fires (Beverly et al., 2009) because immediately following a fire, deciduous trees grow faster and become the dominant species and are generally less prone to fires than coniferous stands (Krawchuk et al., 2006) except under extreme fire weather conditions (Hély et al., 2001). Forests in subalpine regions generally experience more stand-replacing crown fires than surface fires due to the lack of fine fuels at the ground level, and instead have smaller trees mixed in a mature stand that can act as a “ladder” for fires to reach the canopies (Schoennagel et al., 2004). In the Rocky Mountains specifically, the large but infrequent stand-replacing forest fires dominate (Schoennagel et al., 2004), thus creating a large region where forest fires cannot occur temporarily following a fire due to the lack of available fuels.

2.4.2 Forest Fire Activity

The months included in a fire season vary geographically. The forest fire season across Canada typically occurs from April through mid-October, with the majority of

fires initiating from late April to late August (Stocks et al., 2003). However, the most area burned in western Canadian boreal forests from 1831 to 1995 occurred from fires in the months of April through June (Johnson et al., 1999). The greatest incidence of fires in the subalpine areas of the Rocky Mountains is during July and August (Johnson and Larsen, 1991) with the entire fire season in this area ranging from May through August (Nash and Johnson, 1996). As global warming advances, the length of a fire season may be extended. Observed increases in forest fire activity in western North America can be attributed to the rise of spring and summer temperatures (Running, 2006; Westerling et al., 2006). Earlier warm temperatures in spring months cause mountain snowpacks to melt between one and four weeks earlier (Westerling et al., 2006) which creates a longer warm, dry season in which forest fires can occur (Nitschke and Innes, 2008; Running, 2006). These years with earlier snowmelt have had as many as five times the number of forest fires as years that experienced late snowmelt in the western United States (Westerling et al., 2006). Future fire season length is expected to increase in the coming century (Westerling et al., 2006) by as much as 27% by the year 2100 (Nitschke and Innes, 2008). The change in fire season length is greatest in spring, as global warming causes warmer temperatures and earlier snowmelt, thus creating a longer dry period (Nitschke and Innes, 2008).

The severity of a forest fire is determined by the amount of fuel consumed and the burn depth of the organic matter on the forest floor (Flannigan et al., 2000; Stocks et al., 2003). It is directly related to the intensity at which a fire burns and greatly impacts the landscape composition post-fire (Flannigan et al., 2000). Forest fire severity and fire weather severity are predicted to increase as temperatures rise in the near future (Dale et al., 2001; Flannigan et al., 2000; Flannigan et al., 2009; Nitschke and Innes, 2008;

Westerling et al., 2006). The fire weather severity in south-central British Columbia may increase by as much as 95% by the year 2070 (Nitschke and Innes, 2008). Throughout the rest of North America, the severity of fire weather may increase by 10-50% by the year 2060 (Flannigan et al., 2000), with an average increase of 46% across Canada (Flannigan and Wagner, 1991).

Return intervals between fires are strongly influenced by climate (Shakesby and Doerr, 2006). However, human factors have influenced the number of fires occurring and the return intervals between fires, by adding more ignition sources as well as additional fuel types and amounts (Shakesby and Doerr, 2006). Over the past 250 years in subalpine Rocky Mountain areas, the fire cycle has been approximately 100 years (Johnson and Larsen, 1991). In the southern Canadian Rocky Mountains, all forest stands will burn in time and less than five percent of a region will experience 200 years without a fire (Johnson and Wowchuk, 1993). The frequency of fire disturbance can greatly interrupt or halt the life cycles of forest stands (Stocks et al., 2003). Anthropogenic global warming has already increased the frequency of fires in forests across Canada, by effectively warming fire susceptible areas (Gillett et al., 2004). Forest fire frequencies will likely increase, due to climate changes in the future (Flannigan and Wagner, 1991; Flannigan et al., 2005b; Flannigan et al., 2009; Girardin, 2007; Nitschke and Innes, 2008; Soja et al., 2007). Increases in the frequency of forest fires could alter species composition and lower tree density (Westerling et al., 2006).

The area burned by fire is determined by a number of factors, including the size and topography of the forest stand as well as obstructions such as water bodies and man-made infrastructure that could stop a fire from growing (Stocks et al., 2003). Local weather, fuel availability, time of year, and fire management techniques can influence fire

sizes (Stocks et al., 2003). More than half of the area burned by fire in Canada is sparked by lightning (Krawchuk et al., 2009). The size of a fire determines irregularities in the age and evenness of landscapes (Flannigan et al., 2000; Johnson et al., 2001). Regeneration is more challenging in large burned areas, because seeds will have a greater distance to travel (Flannigan et al., 2000). In North American forests, large fires account for less than five percent of the number of total fires. However, large fires can account for more than eighty-five percent of area burned (Fauria and Johnson, 2008). Recent decades have shown a pronounced increase in the area burned by forest fires in Canada (Flannigan et al., 2005b; Gillett et al., 2004), with the months of June and July experiencing the greatest area burned (Stocks et al., 2003). Projections indicate that the area burned by fires will continue to increase with global warming into the next century (Flannigan and Wagner, 1991; Flannigan et al., 2000; Girardin, 2007; Krawchuk et al., 2009; Running, 2006; Soja et al., 2007). Although some future years may experience few forest fires, the area burned could double by the year 2069 in the Yukon Territory (McCoy and Burn, 2005). In conditions favourable to fire, the area burned across Canada could increase by as much as 118% under a tripled CO₂ climate (Flannigan et al., 2005b; Gillett et al., 2004). The area burned in response to lightning initiation alone could increase by 2.6 times by the 2080-2089 period (Krawchuk et al., 2009).

2.5 The Canadian Forest Fire Weather Index System

The Canadian Forest Fire Weather Index System (CFFWIS) is a system built to determine the fire danger of forests in Canada. The CFFWIS has proven to be useful and, as such, is used in many other countries around the world, including Mexico, New

Zealand, and Portugal, as well as countries in Southeast Asia and parts of the United States (Amiro et al., 2004).

2.5.1 Structure of the Canadian Forest Fire Weather Index System

The following information regarding the structure of the CFFWIS was summarized from the Development and Structure of the Canadian Forest Fire Weather Index System (Van Wagner, 1987) and from the Weather Guide for the Canadian Forest Fire Danger Rating System (Lawson and Armitage, 2008). The system commonly used to calculate forest fire danger in Canada is the CFFWIS, as depicted in Figure 1.1. Estimates for fire hazard are made using multiple calculations with meteorological variables as input. The CFFWIS uses the noon-time weather variables of air temperature, relative humidity, and wind speed along with 24 hour total precipitation accumulation to calculate fire hazard. Three different moisture codes, namely the Fine Fuel Moisture Code (FFMC), the Duff Moisture Code (DMC), and the Drought Code (DC) are computed to determine moisture levels in different depths of the soils. The fuel moisture codes are then used to determine the three fire behaviour indices: the Initial Spread Index (ISI), the Buildup Index (BUI), and the Fire Weather Index (FWI). Noon-time weather variables are used for these calculations, in order to estimate the fire danger level during the peak burning period that typically occurs mid-afternoon. Given that the only values necessary for computation are meteorological variables and the time of year, the CFFWIS can be easily used to forecast future fire danger. All values calculated in the CFFWIS are unit-less.

Each of the three moisture codes has a unique soil depth for which dryness is calculated. The FFMC approximates the moisture content of the litter layer and other

fine fuels on the uppermost part of the forest floor, with a depth of up to 1.2 centimetres. The FFMC requires all four weather variables and the previous day's FFMC to indicate the likelihood of fire ignition. The DMC represents the moisture content of the duff layer, or the decomposing, lightly packed, organic matter present up to seven centimetres deep in a forest stand. Temperature, relative humidity, precipitation, and the previous day's DMC are required to determine the possibility of fire occurrence. The DC represents the deepest and heaviest layer of organic matter with a depth of up to eighteen centimetres. Air temperature and precipitation amount are the only meteorological variables required for the DC calculation. The quick-drying fuels represented by the FFMC are less reliant on the daylength than the DMC and DC, which are much slower-reacting with respect to moisture and respond to changing daylength as the season progresses.

The various fire weather indices examined in this study are determined separately. The ISI combines the wind speed at noon with the FFMC, to determine how quickly the fire will be able to spread without the influence of fuel. While FFMC is the best indicator of forest fire incidence, the ISI is most closely associated with area burned. The BUI uses the DMC and the DC to determine fuel characteristics for fire spread. Combining the ISI and the BUI through a series of proportions and logarithmic equations creates the FWI, to determine the intensity of a fire. The FWI can be used as an indicator for fire danger. An optional component of the CFFWIS is the Daily Severity Rating (DSR) which reflects the difficulty of fire management and control, as the FWI was not seen to be in direct proportion to the amount of effort necessary for fire suppression. It was not originally part of the CFFWIS, but was added because the FWI alone does not clearly reflect the difficulty of control of the fire (the DSR reduces disproportionately

high values of the FWI). The DSR can be averaged over the entire fire season, to create the Seasonal Severity Rating (SSR) which is used to compare fire weather from one season to another or across regions.

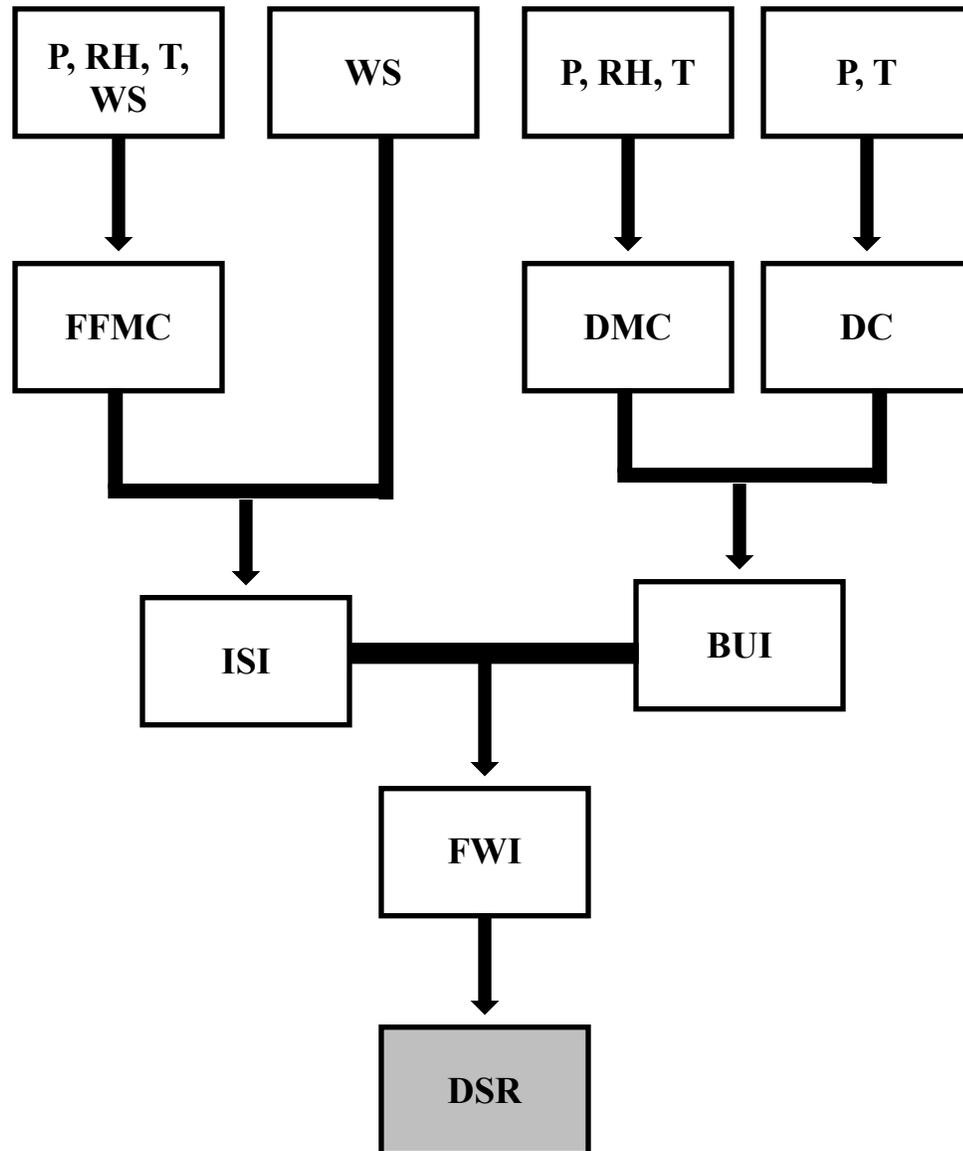


Figure 2.1: Structure of the Canadian Forest Fire Weather Index System (CFFWIS) (adapted from Van Wagner, 1987); where P is 24-hour precipitation; RH is noon-time relative humidity; T is noon-time air temperature; WS is noon-time wind

speed; FFMC is the Fine Fuel Moisture Code; DMC is the Duff Moisture Code; DC is the Drought Code; ISI is the Initial Spread Index, BUI is the Buildup Index, FWI is the Fire Weather Index, and DSR is the Daily Severity Rating.

There are five fire danger classes in the CFFWIS, as outlined in Table 2.1, along with the corresponding FWI and approximate DSR minima for each classification (adapted from Williams, 1959). A rating of zero means that the conditions are too wet for fires to start or spread. DSR values of 12.0 units or greater are indicative of extreme forest fire hazard.

Table 2.1: Fire danger classes along with corresponding FWI and DSR values. Adapted from Williams (1959).

Fire Danger Class	Fire Weather Index Range	Daily Severity Rating Range
Extreme	≥ 31.7	≥ 12.0
High	16.5 - 31.6	4.0 - 11.9
Moderate	7.8 - 16.4	1.0 - 3.9
Low	3.1 - 7.7	0.2 - 0.9
Nil	0 - 3.0	0 - 0.1

2.6 The GENGRID Model

The GENGRID model (also called SIMGRID) is a fine-scale, physically based meteorological model developed at the University of Lethbridge (Sheppard, 1996). The GENGRID model combines a series of equations and subroutines with a geographic information system (GIS), to simulate meteorological states on a daily time-step throughout mountainous watersheds (MacDonald et al., 2012). The model uses recorded point temperature and precipitation values to estimate maximum and

minimum temperature, daily total precipitation, and relative humidity at the different elevations across the watershed. Solar radiation is estimated for the area, using a GIS. Terrain categories (TCs) were developed using a GIS with a total of 997 TCs in the upper NSW (MacDonald et al., 2012) and 82 TCs in the upper St. Mary watershed (SMW; MacDonald, 2009). TCs were categorized into 100 metre elevation bands and land cover types. Average slope and aspect values for these TCs were calculated to assign a general value for the area (MacDonald, 2009). All of the hydrometeorological variables were calculated for each of the unique TCs. For this study, meteorological output from the GENGRID model was used as input for the CFFWIS, to predict fire hazard across the basin.

2.7 Climate Change Scenarios

General Circulation Models (GCMs) are presently considered the most refined approach for simulating large-scale physical processes (Laprise et al., 2003). A variety of emission scenarios are put into GCMs, to predict future climate patterns. Confidence in climate models comes from the ability of the models to reproduce past and current observed climates (Branković et al., 2010; Randall et al., 2007). In recent years, the confidence in climate model accuracy has increased, but still remains prone to error (Branković et al., 2010; Houghton et al., 2001). Furthermore, climate change studies often require data at a finer scale than what GCMs provide, as GCMs operate at a scale of hundreds of kilometres (Laprise et al., 2003). This results in considerable simulation error, especially at small-scale areas (Randall et al., 2007). This error is attributable to inaccuracies in downscaling, because of the resulting coarseness of local weather patterns (Randall et al., 2007). Overall, climate models have been found to simulate

temperature considerably better than they can simulate precipitation (Branković et al., 2010; Randall et al., 2007).

Emission scenarios are based on postulations made about future population, economic growth, energy production, and energy utilization, as these all affect atmospheric GHG concentrations (Branković et al., 2010). Four distinct GHG emission scenarios have been defined by the IPCC in its Special Report on Emissions Scenarios (IPCC, 2000), to represent expected changes in population, economies, and environmental technologies: A1, A2, B1, and B2. The A1 scenario outlines a future with increasing economic expansion, a population peak and then a decline starting near 2050, combined with the use of more efficient technologies. The A1 scenario can be further broken down into three sub- categories: A1FI, A1T, and A1B. The A1FI scenario focuses on fossil fuels as the main energy source, the A1T scenario looks at non-fossil fuel sources for energy, and the A1B is a balance across the different energy sources. The A2 scenario is similar to the A1 scenario but with slower growth and expansion in most areas and is regionally dependent. The A2 scenario assumes a steadily increasing population, with society continuing to use fossil fuels as the main energy source. The B1 scenario is based on solutions at a global scale toward greener technologies and a more sustainable environment. The B1 scenario assumes rapid changes in economic and technological structures, but with the same population peak as seen in the A1 scenario. The B1 scenario assumes less GHG use. The B2 scenario has similar goals to the B1 scenario with respect to environmental targets, but the emphasis is on local as opposed to global solutions, so that slower technological change occurs. The population in this scenario would be steadily increasing, but not to the degree seen in the A2 scenario. The A1 and A2 scenarios generally predict greater CO₂ emissions and concentrations over

the next century and, therefore, greater temperature increases than do the B1 and B2 scenarios (Houghton et al., 2001). The IPCC recommends three future time periods for climate impact studies: the 2020s (2010-2039), the 2050s (2040-2069), and the 2080s (2070-2099).

2.8 Summary

An improved understanding of the physical and meteorological processes involved in forest fire ignition and spread is essential to predict future wildfire hazard and elucidate the potential impacts on natural ecosystems and human society. As forest fire activity continues to rise, better predictions for future fire hazard are fundamental for fire management preparation. As this literature review has outlined, it is generally accepted that as temperature rises in the coming decades, forest fire activity will increase throughout North America. This includes an increase in the length of the forest fire season, the frequency of fire occurrence, the severity of fire weather, and the size of future fires.

CHAPTER 3:

Historical Fire Hazard in the Northern Rocky Mountains

3.1 Introduction

Fire is one of the major disturbances that impact forests (Dale et al., 2001). Forest fire characteristics such as its frequency, extent, and severity are all influenced by weather (Dale et al., 2001). Weather plays a more important role in the intensity of surface fires and crown fire initiation in subalpine environments than available fuels (Bessie and Johnson, 1995). Specifically, weather conditions affect the moisture content of fuels, thereby affecting fire occurrence. Warm temperatures are among the most important driving factors with respect to forest fires due to the increased likelihood of drier fuels as a result of increased evapotranspiration (Hély et al., 2001; Flannigan et al., 2005; Westerling et al., 2006). In the Canadian Rocky Mountains, the local climate has been shown to affect both fuel moisture and ignition incidence, which are the main determinants of forest fire frequency (Johnson and Larsen, 1991; Schoennagel et al., 2004) and severity (Schoennagel et al., 2004). Forest fires in western North America are highly correlated with the prevalence of drought during the summer months (Westerling et al., 2006).

Anthropogenic global warming has already greatly affected forest fire occurrence and area burned in Canada (Gillett et al., 2004). Based on studies in the western United States, higher spring temperatures can cause mountain snowpacks to melt between one

and four weeks earlier (Westerling et al., 2006), resulting in a longer warm, dry season in which forest fires can occur (Running, 2006; Nitschke and Innes, 2008). Years with earlier snowmelts have had as many as five times the number of forest fires in the western United States relative to years with late snowmelt (Westerling et al., 2006).

The purpose of this study was to examine, quantify, and compare historical (1960 to 2010) fire weather regimes for two sub-watersheds within the Rocky Mountains of western North America. Fine-scale fire weather calculations have been made to determine variation in daily fire weather patterns both altitudinally and spatially. The GENGRID meteorology model (Sheppard, 1996) was used to calculate daily meteorological values at 100 m resolution. The Canadian Forest Fire Weather Index System (CFFWIS) (Van Wagner, 1987) was used to calculate daily fire weather index values using the GENGRID output values.

3.2 Study Area

Two sub-watersheds along the eastern slopes of the northern Rocky Mountains were selected as the regions of study: the North Saskatchewan watershed (NSW) and the St. Mary watershed (SMW; Figure 3.1).

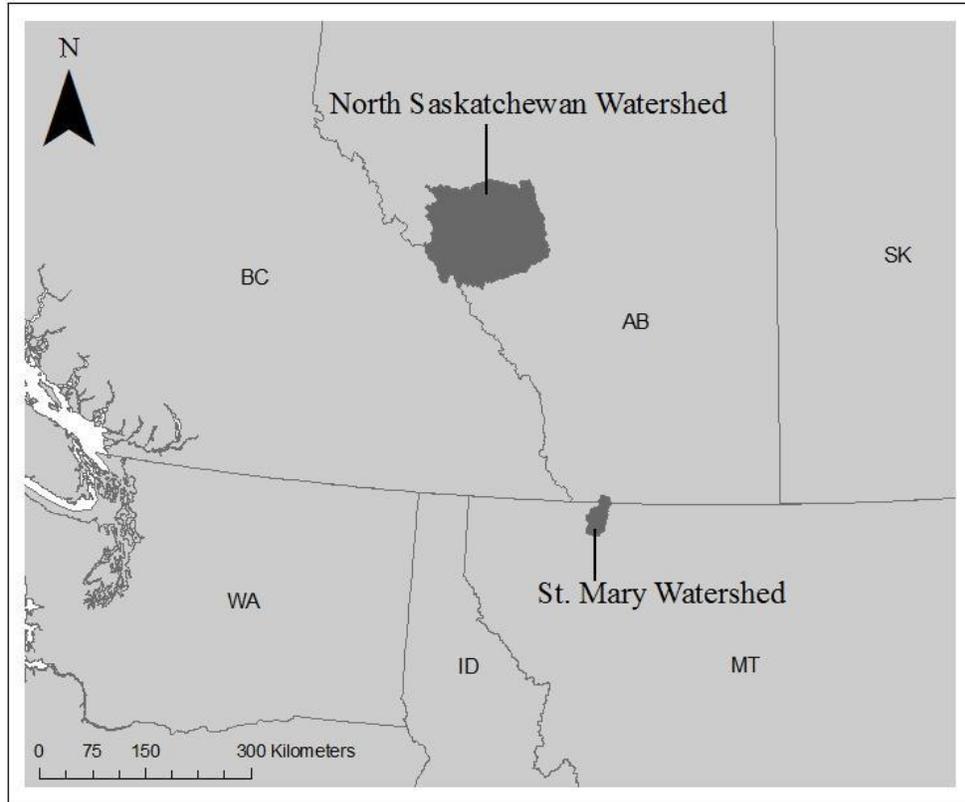


Figure 3.1: Study area map showing the relative locations in western North America of the North Saskatchewan and St. Mary watersheds.

The NSW is located at the headwaters of the North Saskatchewan River in Alberta. The upper NSW covers an area of 20,527 km², from the continental divide, east to the outlet near Rocky Mountain House, Alberta. The northern extent of the basin is in the southern portion of Jasper National Park. Most of the watershed is classified as alpine and subalpine, with elevations of up to 3484 m with lower elevations in the eastern foothills regions as low as 752 m. The watershed consists of glaciated areas in high elevations, densely forested regions, shrublands, and grasslands at the lowest elevations to the east. Overall, forested areas make up 62% of the basin with the treeline in the watershed ranging up to 2800 m. Tree species include coniferous and mixedwood forests, but mainly consist of lodgepole pine

(*Pinus contorta Douglas ex Loudon*), Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco), Engelmann spruce (*Picea engelmannii Parry ex Engelm*), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), trembling aspen (*Populus tremuloides Michx.*), balsam poplar (*Abies balsamea* (L.) Mill.), and white spruce (*Picea glauca* (Moench) Voss; NSW, 2005).

Due to the large size of the NSW, three climate stations were used to drive the model in this basin for better spatial representation. The climate stations are located at Bighorn Dam, Clearwater, and Nordegg (Figure 3.2), located at 1341, 1280, and 1320 metres above sea level, respectively. Each climate station was responsible for driving the model for a subsection of the NSW. The centrally located Bighorn Dam climate station reported a normal (1961-1990) annual air temperature of 2.7 °C and mean annual total precipitation of 493.0 mm (Table 3.1; Environment Canada, 2011). Monthly average air temperature is the coldest in January (-9.1 °C) and warmest in July (14.0 °C). Monthly precipitation totals range from 15.0 mm in February to 76.9 mm in July.

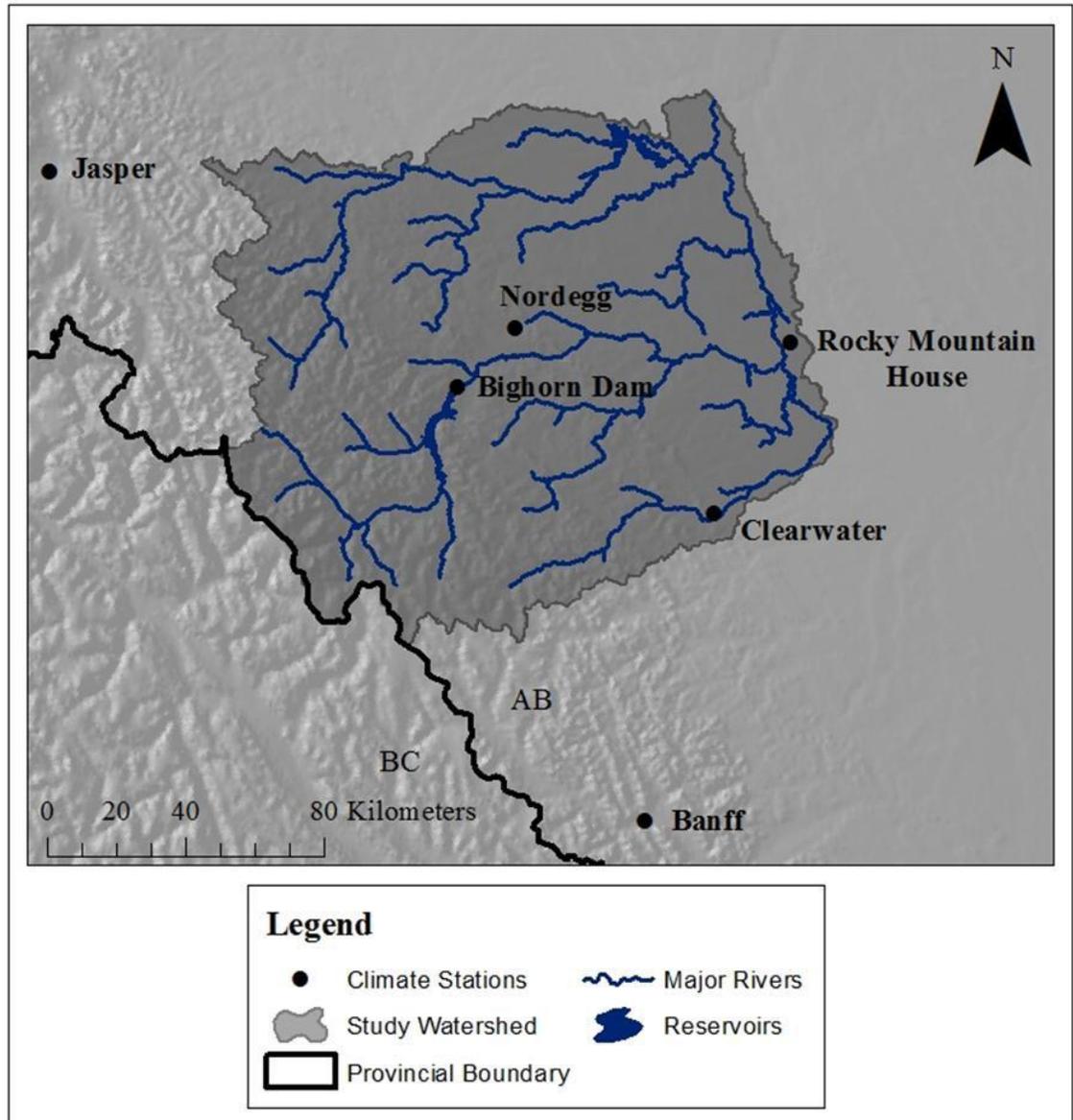


Figure 3.2: Study area map of the NSW depicting locations of climate stations used in this study.

The SMW comprises the headwaters of the St. Mary River in northern Montana and southern Alberta, along the eastern slopes of the Rocky Mountains. The SMW covers 1195 km² of diverse terrain. It ranges in elevation from 1249 m to 3031 m. A large portion of the watershed is within Glacier National Park, and as a result, is relatively undisturbed. The watershed is composed of 74% vegetation; the remaining 26% of the watershed is barren rock, soil, and water (USGS, 2006). Lodgepole pine and Douglas fir are among the most prevalent tree species in the region (NPS, 2011). The treeline is roughly 2700 m in this basin. The St. Mary climate station, at 1359 metres above sea level was used as the sole driver station within the model (Figure 3.3). The St. Mary climate station reported a mean (1961-1990) annual air temperature precipitation of 5.1 °C and 705.1 mm (Table 3.1; NCDC, 2006). Monthly air temperature is coldest in January (-6.4 °C) and warmest in July and August (16.5 °C). July has the least precipitation on average (41.1 mm) and January has the most (74.4 mm).

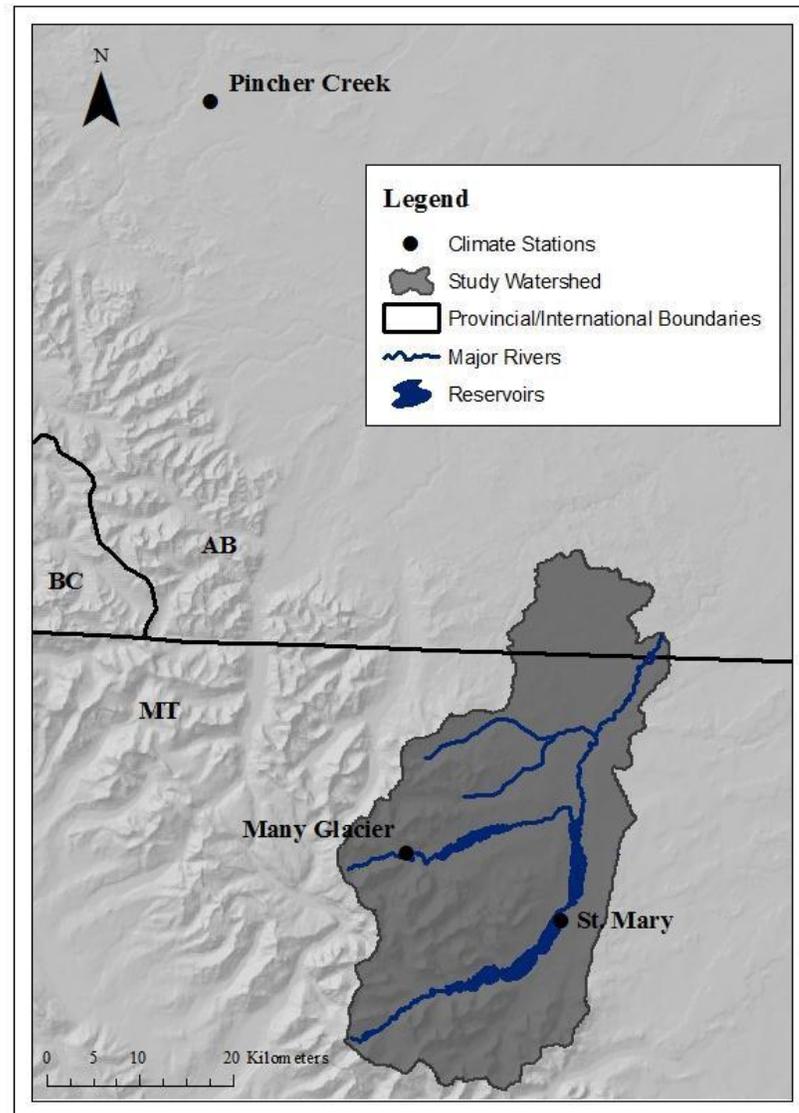


Figure 3.3: Study area map of the SMW depicting locations of the climate stations used in this study.

Table 3.1: Normal (1961-2000) monthly and annual air temperatures (°C) and precipitation volumes (mm) for the Bighorn Dam and St. Mary climate stations. Bighorn Dam station data from Environment Canada (2011). St. Mary station data from NCDC (2006).

	Bighorn Dam		St. Mary	
	Mean Air Temperature (°C)	Mean Total Precipitation (mm)	Mean Air Temperature (°C)	Mean Total Precipitation (mm)
January	-9.1	24.1	-6.4	74.4
February	-6.3	15.0	-3.8	59.8
March	-2.7	19.4	-0.8	48.6
April	2.8	27.1	4.2	56.8
May	7.5	62.6	9.1	71.2
June	11.5	76.6	13.4	73.1
July	14.0	76.9	16.5	41.1
August	13.3	70.4	16.5	49.4
September	8.7	53.1	11.2	50.8
October	3.8	30.0	6.8	49.6
November	-3.7	18.3	-0.8	68.3
December	-7.3	19.8	-5.5	61.9
Annual	2.7	493.3	5.1	705.1

3.3 Methods

To analyze forest fire hazard in the two study watersheds, the GENGRID meteorology model (Sheppard, 1996) was first used to spatially simulate climatic conditions. The daily GENGRID output was then used as input into the CFFWIS model (Van Wagner, 1987) to calculate daily values for forest vulnerability to fire (Figure 3.4). Descriptions of both models along with modifications and additions to the GENGRID model follow.

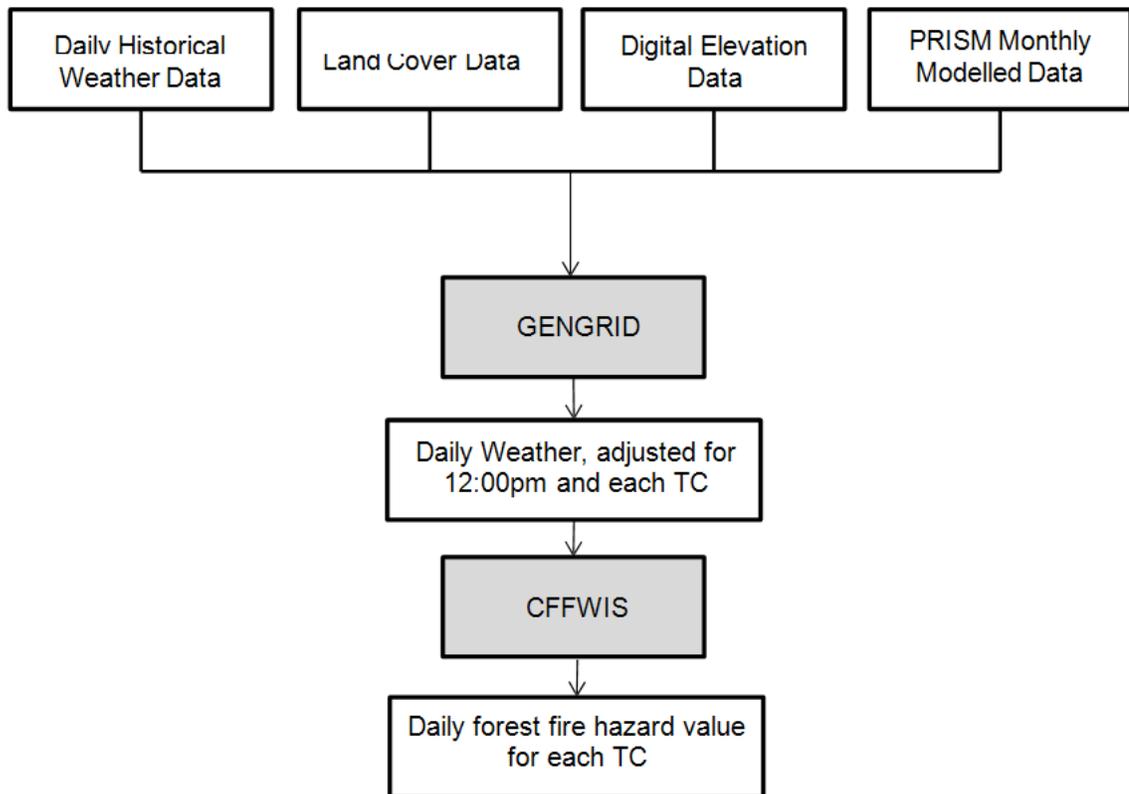


Figure 3.4: Flowchart outlining the basic processes used in this study to determine fire hazard, where LST is local standard time and TC is terrain category.

3.3.1 GENGRID Model

The GENGRID fine-scale meteorology model (Sheppard, 1996) is based on the MTCLIM Microclimate Simulator (Hungerford et al., 1989), but has been incorporated into a Geographic Information System (GIS) to simulate daily meteorological conditions throughout variegated alpine watersheds (Sheppard, 1996). GENGRID provides realistic estimates of temperature and precipitation, more specifically snow-water equivalence, across the physically diverse North Saskatchewan (MacDonald et al., 2012) and St. Mary (MacDonald et al., 2009) watersheds. Due to a lack of available meteorological data, it was not possible to verify the model for other variables. For further discussion of

developments and applications of GENGRID, refer to Sheppard (1996), Lapp et al., (2005), MacDonald et al., (2009), Larson et al., (2011), and MacDonald et al., (2012).

Due to the heterogeneity of the watersheds, the basins were divided into regions of similar topography, elevation, and land cover type, called terrain categories (TCs). Elevation bands were created at 100 m increments. The average slope and aspect values for these TCs were calculated to assign a general value for the area (MacDonald, 2009). The NSW was divided into 997 unique TCs: 368 TCs in the Bighorn subwatershed, 265 TCs in the Clearwater subwatershed, and 364 TCs in the Nordegg subwatershed (MacDonald et al.,2012). The SMW was divided into 82 unique TCs (MacDonald, 2009).

Maximum air temperature, minimum air temperature, daily precipitation accumulation, and daily noon-time wind speeds were used as input into the GENGRID model. Additions and refinements were made to the GENGRID model to produce the necessary variables for fire weather predictions. Recent alterations to the GENGRID model are described in sections to follow, along with brief discussion of the routines already in place.

3.3.2 Air Temperature

Estimations of maximum and minimum surface air temperatures have been calculated for every TC in both study regions. Monthly maximum and minimum air temperature lapse rates were derived using Parameter-elevation Regression on Independent Slopes Model (PRISM) output (Daly et al., 2008) and then calibrated to accurately estimate air temperature values for each elevation band throughout the study

watersheds. Daily maximum and minimum air temperatures have been calibrated and verified at three Alberta Environment air temperature sites in the North Saskatchewan study region ranging in elevation from 1070 m to 2120 m (MacDonald et al., 2012) and one air temperature site (Many Glacier SNOTEL site at 1493 m) in the SMW (Figure 3.5). The accuracy of the air temperature estimations in the NSW were found to decrease with elevation. This could be due to the distance from the less elevated driver stations, the high variability of meteorological conditions in mountainous regions, and the low density of meteorological stations at high elevation sites (MacDonald et al., 2012).

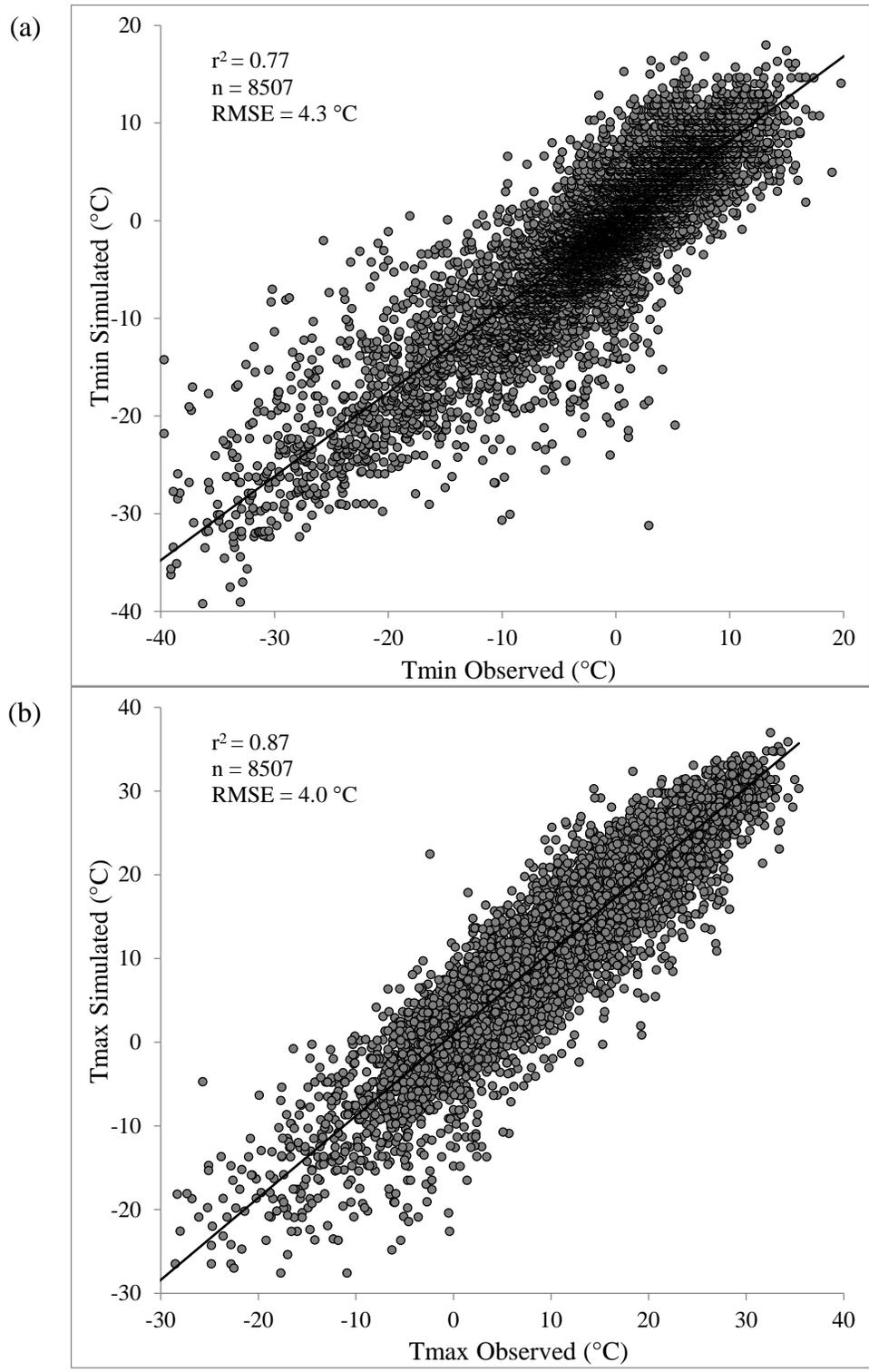


Figure 3.5: Air temperature lapse rate verification at Many Glacier in the SMW for (a) minimum air temperature, and (b) maximum air temperature.

Air temperature values for 12:00 p.m. local standard time were needed for this study. Noon-time air temperature (T_{NOON}) values were calculated from maximum and minimum air temperatures, using the method developed by Parton and Logan (1981) for estimating diurnal variations in air temperature with a limited number of parameters. This model uses an abbreviated sinusoidal curve for daytime temperatures along with maximum and minimum air temperatures at the site, site latitude, and day length factors to estimate the temperature at any time throughout the day. This method assumes that daytime air temperature always follows a truncated sinusoidal curve, maximum air temperature occurs during daytime hours, and minimum air temperature occurs in early morning hours. Day lengths were determined from the Julian date and the site latitude [see Parton and Logan (1981)]. The diurnal curve for air temperature was given by (Parton and Logan, 1981), as:

$$T_i = (T_x - T_N) * \sin\left(\frac{\pi * m}{Y + 2a}\right) + T_N \quad (\text{Equation 3.1})$$

Where,

T_i = air temperature at i^{th} hour

Y = day length (hours)

T_x = maximum air temperature

T_N = minimum air temperature

m = number of hours after T_N occurs until sunset

a = lag coefficient for T_x .

The value for m was calculated as a function of day length. The value used for the lag coefficient, $a = 1.86$, was the same average value for a used by Parton and Logan (1981).

Nordegg and Rocky Mountain House meteorological data (Environment Canada, 2011) were used for T_{NOON} model verification and calibration in the NSW (Figures 3.6 and 3.7). Although this method resulted in a high r-squared value (0.93 at Nordegg and 0.89 at Rocky Mountain House) between simulated and observed T_{NOON} values, it overestimated noon-time temperature data for the NSW. The T_{NOON} values were, thus, adjusted using linear regression to better fit the observed data. The same method of simulating T_{NOON} resulted in a slightly weaker fit of simulated versus observed data for the SMW ($r^2 = 0.80$) than it did for the NSW (Figure 3.8). T_{NOON} values in the SMW were calibrated using observed data at Many Glacier (NRCS, 2011).

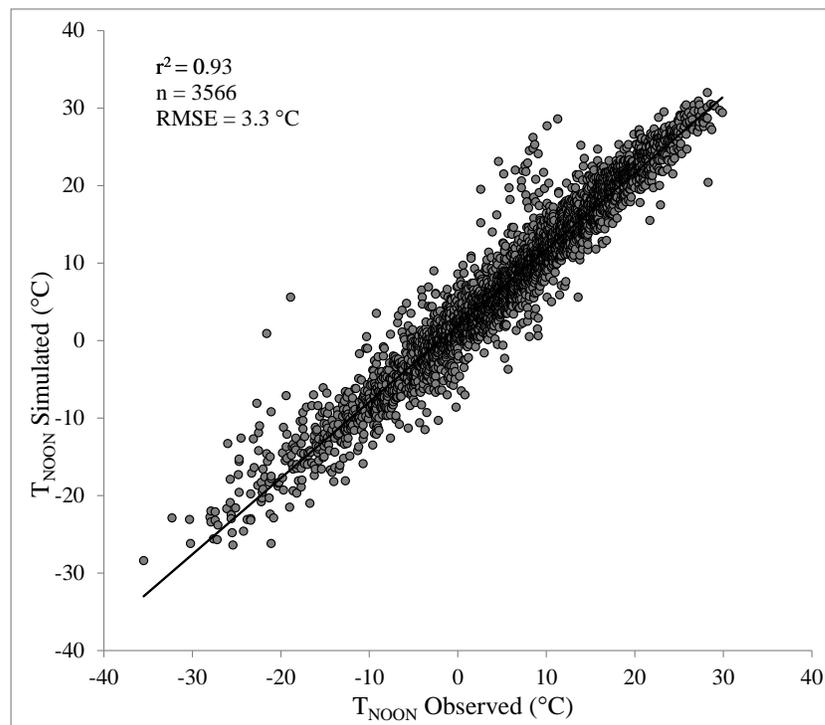


Figure 3.6: Simulated versus observed air temperature at 12:00pm at Nordegg, Alberta.

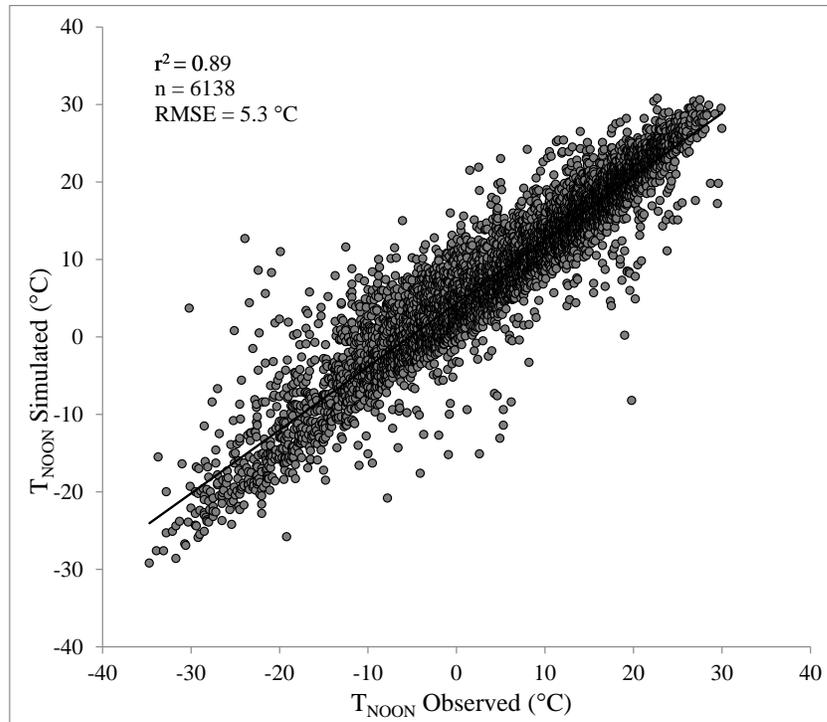


Figure 3.7: Simulated versus observed air temperature at 12:00pm at Rocky Mountain House, Alberta.

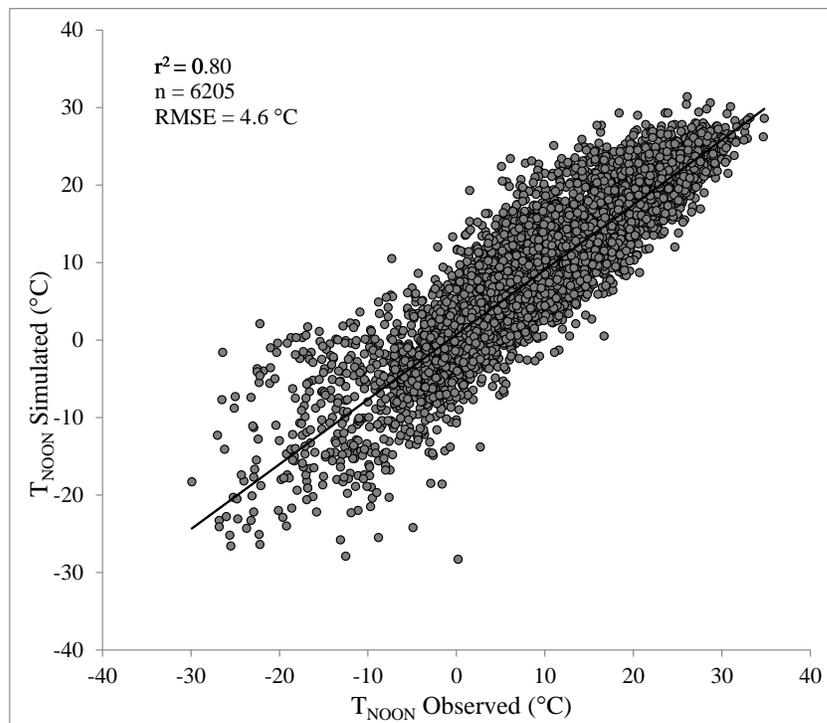


Figure 3.8: Simulated versus observed air temperature at 12:00pm at Many Glacier, Montana.

3.3.3 Precipitation

Precipitation values were estimated in GENGRID by using monthly precipitation-elevation relationships. Monthly spatial correction factors were developed using PRISM output. Daily precipitation accumulations have been verified using snow-water equivalent (SWE) values found at snow pillows in the upper NSW (see MacDonald, 2012) and in the SMW (see MacDonald, 2009). No changes in the precipitation modelling were made for this study.

3.3.4 Relative Humidity

In previous versions of GENGRID, daylight average relative humidity was calculated using

$$RH = \frac{e_s}{e_{sd}} * 100\% \quad (\text{Equation 3.2})$$

Where,

$$e_s = 6.1078 * e^{\frac{17.269 * T_d}{273.3 + T_d}}$$

$$e_{sd} = 6.1078 * e^{\frac{17.269 * T}{273.3 + T}}$$

and where, RH is the daytime relative humidity in percent; e_s is the saturation vapour pressure (in kPa) at dewpoint temperature, T_d ; and e_{sd} is the saturation vapour pressure (in kPa) at the average daytime temperature, T (Sheppard, 1996). As T_d values were not available for that study, minimum temperature was used as a substitute for T_d (Sheppard, 1996). Minimum temperature is often not a suitable surrogate for T_d in arid climates where the dewpoint temperature is often lower than the minimum temperature (Kimball et al., 1997). Due to the model's tendency to overestimate low temperatures and underestimate high temperatures, relative humidity was over simulated at high ends of the

temperature scale and under simulated at low ends of the scale (Hungerford et al., 1989).

For this current study, it was necessary to know the relative humidity daily at 12:00pm LST. Midday T_d s were needed in order to calculate noon-time RH. Surrogating T_N as the T_d resulted in recurring over-simulations of T_d . Unpublished noon-time dewpoint and minimum temperature data from April 2010 to August 2011 for three meteorological stations within the Star Creek watershed in the Alberta Rocky Mountains were provided (MacDonald, 2011). Separate monthly linear relationships were found between the minimum and midday dewpoint temperatures. These same relationships were then used to calculate estimates for midday T_d based on recorded T_N data, a method recommended by Howell and Dusek (1995).

After estimating midday T and T_d , it was then possible to calculate RH at noon using equation 3.3 for diurnal RH, from Beck and Trevitt (1989):

$$RH(t) = \frac{e_s(t)}{e_{sd}(t)} * 100\% \quad (\text{equation 3.3})$$

Where t is the hour in study, in this case 12:00pm.

Dewpoint temperature values, and thus RH, were difficult to accurately simulate based on the limited available parameters. Simulated versus observed midday T_d data were evaluated for Nordegg (Figure 3.9) and Rocky Mountain House (Figure 3.10). Both climate stations resulted in similar accuracy of T_d simulations. Midday T_d values were not available for model verification within the St. Mary watershed.

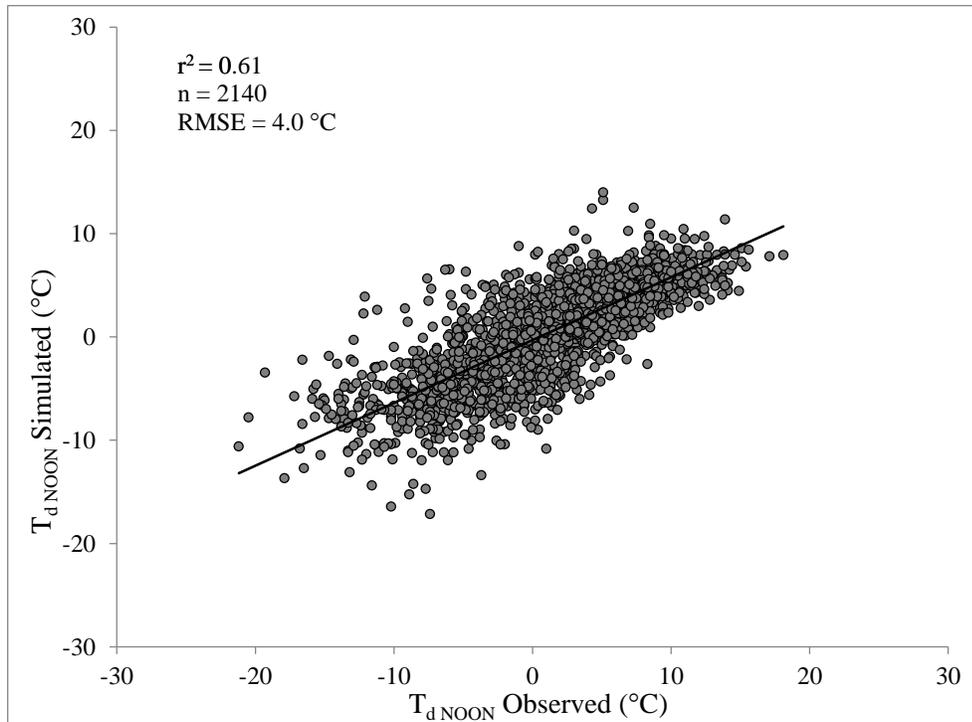


Figure 3.9: Simulated versus observed dewpoint temperature at 12:00 p.m. at Nordegg, AB.

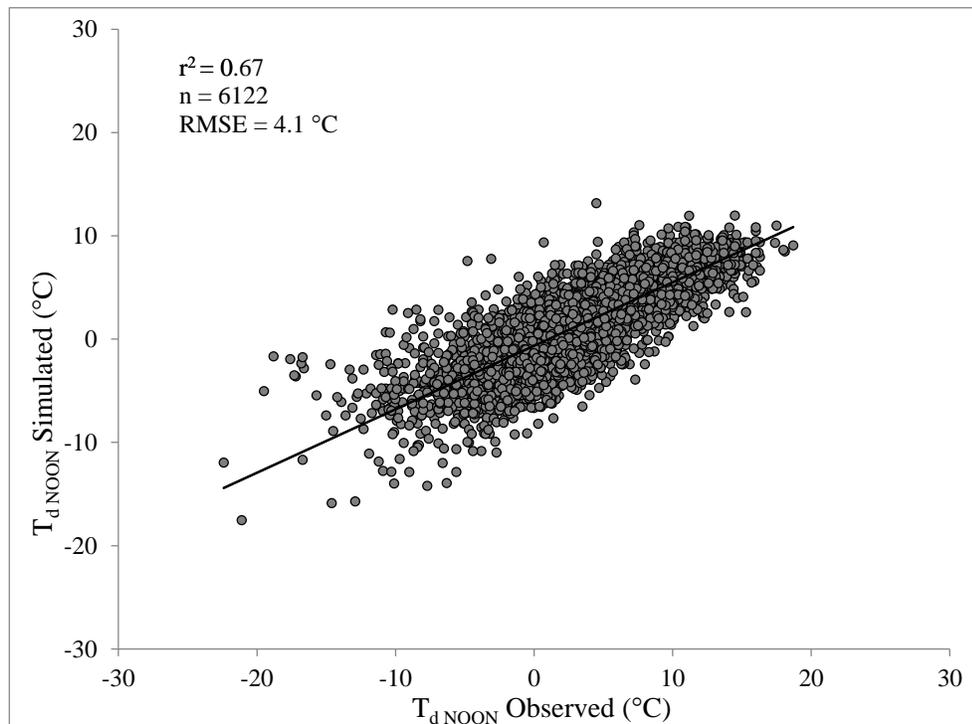


Figure 3.10: Simulated versus observed dewpoint temperature at 12:00 p.m. at Rocky Mountain House, AB.

3.3.5 Wind Speed

The estimation of wind flow in complex alpine environments is a difficult task (Landberg et al., 2003; Weber, 1999). Orographic flow is affected by topographic features (Landberg et al., 2003). Wind characteristics are especially challenging to simulate when wind flow is parallel to the landforms, as opposed to orthogonal (Weber, 1999). Due to the complexity of achieving high accuracy in wind speed estimation at high spatial resolution, it was decided to model regional wind climates (see Landberg et al., 2003).

Available wind speed data were limited for the two study watersheds. For the NSW, hourly wind speed records spanning the entire time series (1960 – 2010) were only available at Rocky Mountain House, though data were available for the nearby stations of Jasper and Banff. Average wind speed normals at Bighorn Dam were available for the period 1971 - 2000 and were used in this study given the central location of this site within the study region. Available wind speed data for the SMW only consisted of hourly data for 2006 to 2010 at the Many Glacier SNOTEL site. The closest climate station to the SMW with available hourly wind speed data was at Pincher Creek, AB.

Wind speed normals (1971 - 2000) for five climate stations were analyzed (Bighorn Dam, Jasper, Banff, Rocky Mountain House, and Pincher Creek; Figure 3.10). Wind speeds at Pincher Creek were often twice as fast as the stations surrounding the NSW. Since Pincher Creek is in a similar elevation range as the other four stations, but the wind speed was so much higher at the surface and upper levels at Pincher Creek (Figure 3.11), it was decided that separate wind speed lapse rates would be needed for each of the two study watersheds.

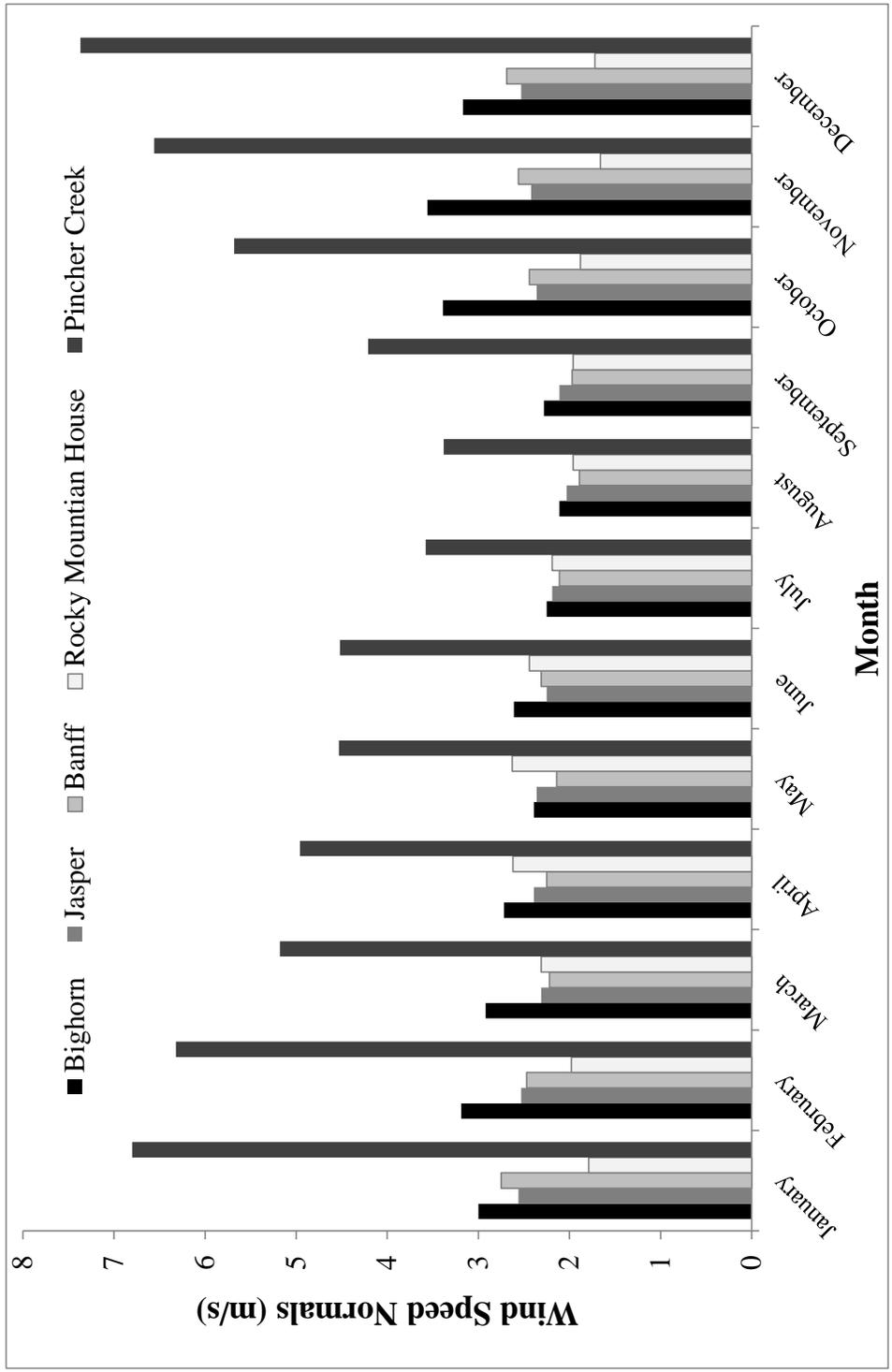


Figure 3.11: Comparison of monthly wind speed ($\text{m}\cdot\text{s}^{-1}$) normals (1971-2000) for five climate stations in the Rocky Mountains and surrounding foothills regions.

A new method for modelling wind speed was developed, to estimate altitudinal variation at high elevations when little data are available. This method involved using only wind speed data at the driver stations and estimating wind speeds at other elevations through the use of a logarithmic wind speed profile. Monthly wind speed normals for the 1971 – 2000 period were used to develop lapse rates for each of the study regions. Logarithmic curves were fit to three data points: surface wind speed, wind speed at 1500m above sea level, and wind speed at 3000m above sea level. From here, monthly logarithmic lapse rates were established for the North Saskatchewan (Figure 3.12) and St. Mary watersheds (Figure 3.13). Daily wind speeds at noon for 1960-2010 were adjusted for elevation, using the ratio between the wind speed at the driver station and the other elevations.

The Bighorn Dam climate station, which is centrally located in the basin, provided wind speed normals for 1971-2000 that were used as the surface wind speed component for the NSW lapse rates. Monthly normal wind speeds were not available within the SMW, so data for Pincher Creek were used as the surface wind speed component. The wind speed data at Many Glacier (2006 to 2010) were compared to wind data from Pincher Creek. It was found that the Many Glacier wind speeds were consistently lower than Pincher Creek. The Pincher Creek data were adjusted using linear regression to better represent the SMW using the wind speed data from Many Glacier.

NCEP/NCAR reanalysis data (NOAA, 2011) were used to determine wind speeds at two different pressure levels above the surface for each watershed. Wind speeds at pressure levels of 850 mb and 700 mb were used to represent wind speeds at 1500 m and 3000 m, respectively. The use of NCEP/NCAR reanalysis data was beneficial to the model, because these data are available for the entire Earth. NCEP/NCAR data were

gathered in the free atmosphere to avoid local effects on wind speed. The shortcomings of using NCEP/NCAR reanalysis data are that they are represented at a low resolution (2.5° grid cell size) and that wind speeds high above ground are not always determinant of surface wind speeds (Landberg et al., 2003).

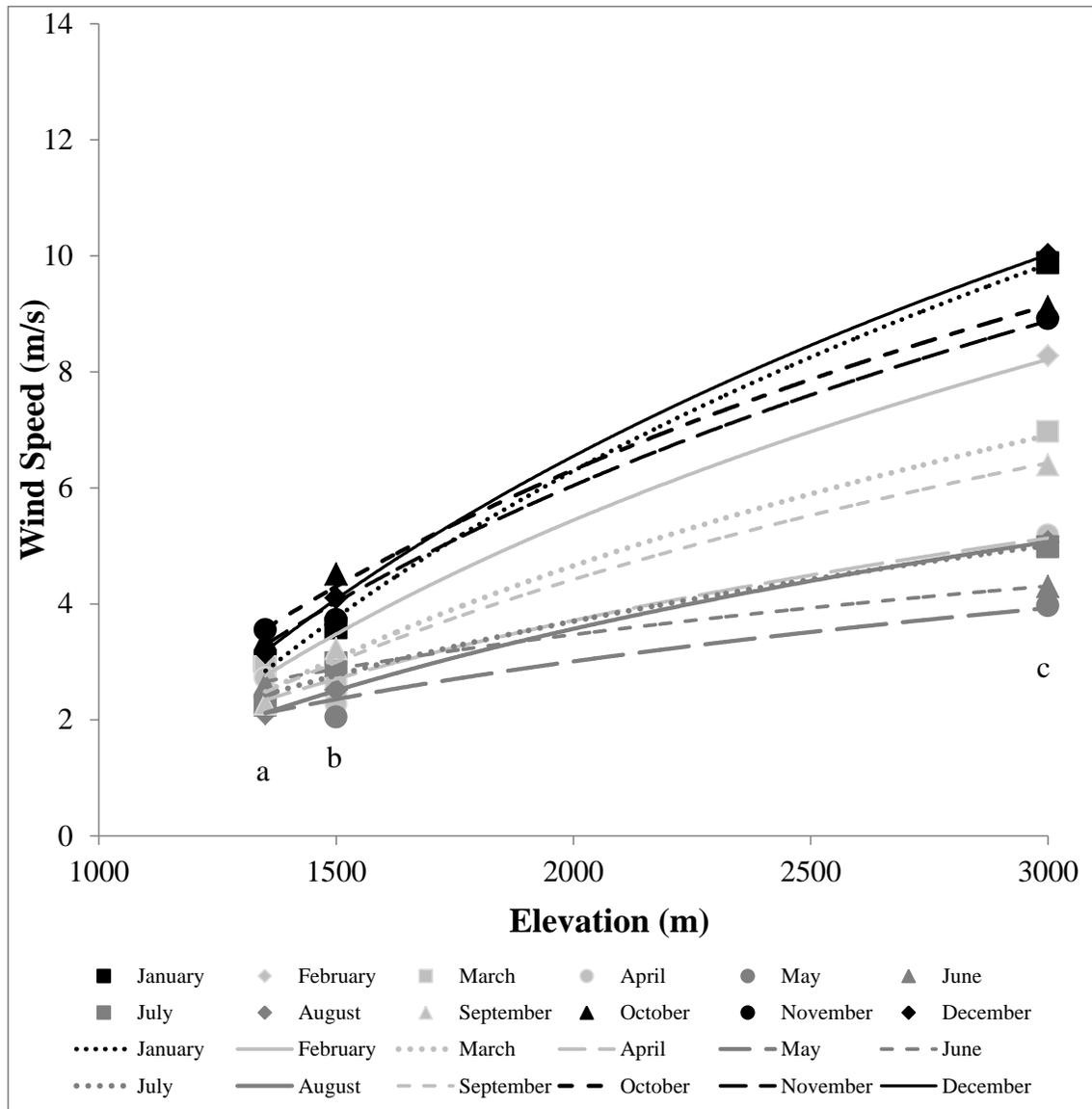


Figure 3.12: Monthly logarithmic curves used for calculating wind speed in the NSW. Data points at *a* represent surface wind speed values at Bighorn Dam, points at *b* represent wind speeds at 850 mb (1500 m) above the surface, and points at *c* represent wind speeds at 700 mb (3000 m) above the surface.

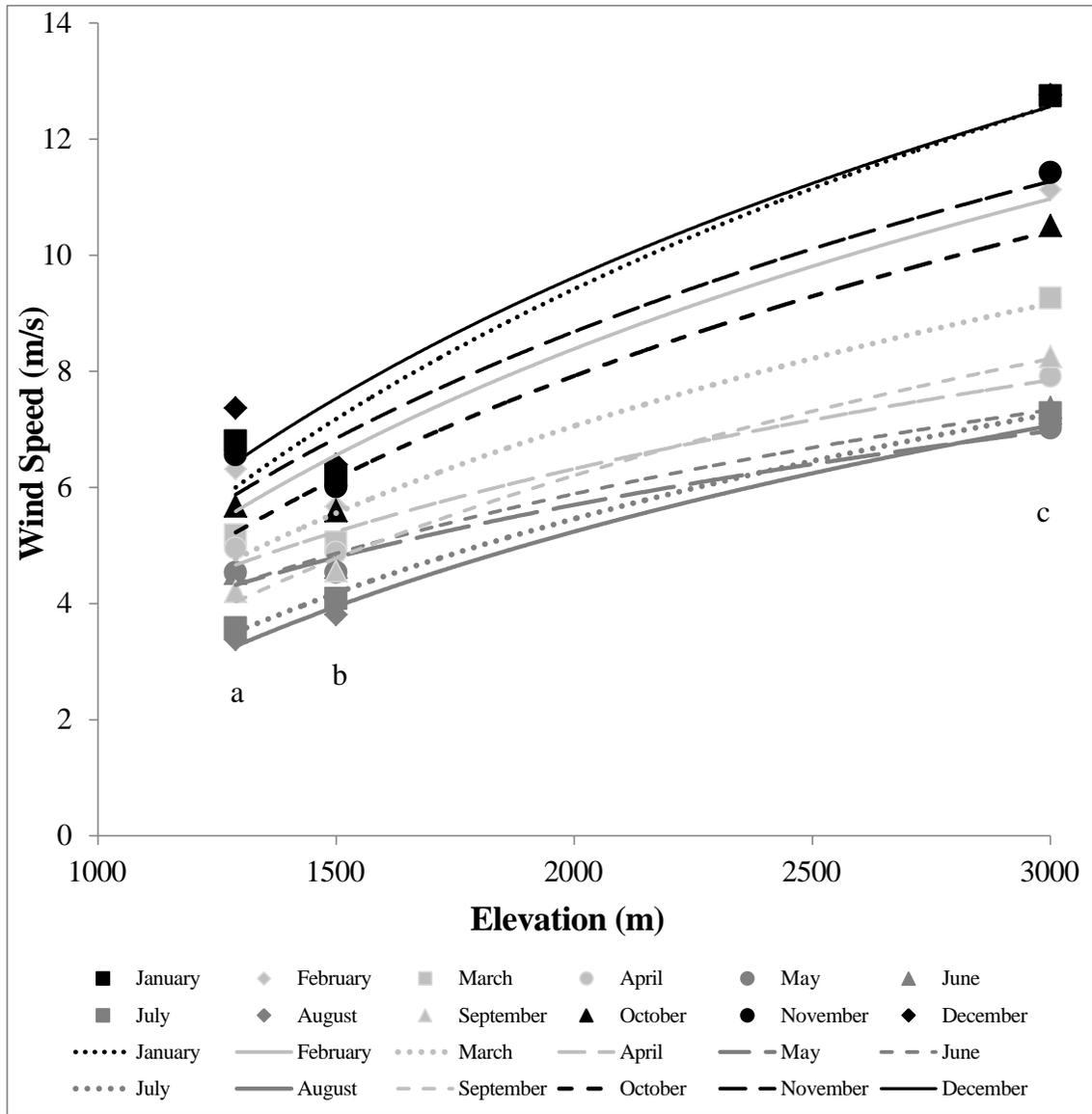


Figure 3.13: Monthly logarithmic curves used for calculating wind speed in the SMW. Data points at *a* represent adjusted surface wind speed values at Pincher Creek, points at *b* represent wind speeds at 850 mb (1500 m) above the surface, and points at *c* represent wind speeds at 700 mb (3000 m) above the surface.

Daily midday wind speed values from Banff, Rocky Mountain House, and Jasper were used in the NSW in place of the Bighorn Dam, Clearwater, and Nordegg driver stations, respectively, due to unavailable wind speed data at those locations for the required time series. Although Banff and Jasper are located outside of the study

watershed, the wind speed normals were comparable with those at Bighorn Dam, so daily wind speeds from these sites were used in basin simulations. Daily midday wind speeds at Pincher Creek, using the Many Glacier adjustment, were used to drive the wind speed model for the SMW. Hourly data for Nordegg (2001 – 2010) were used for model verification in the NSW (Table 3.2). This method found relatively weak similarities between the simulated and observed wind speeds at Nordegg (r-squared values between 0.2 and 0.5). The root mean square error (RMSE) ranged from 0.6 to 1.6 $\text{m}\cdot\text{s}^{-1}$. Greater error occurred in winter months, when wind speeds were slightly higher. A two-tailed test of simulated versus observed wind speeds using the Pearson correlation coefficient indicated all wind speeds were significant when $\alpha = 0.05$. This method was found to over simulate low wind speeds and under simulate high wind speeds. It was assumed that error of the magnitude found in this study would have a marginal effect on overall fire weather predictions, because it would take an increase of 5.3 $\text{m}\cdot\text{s}^{-1}$ to double the FWI (Van Wagner, 1987).

Table 3.2: Verification statistics comparing simulated v. observed wind speed at Nordegg, AB.

	n	r²	RMSE ($\text{m}\cdot\text{s}^{-1}$)
January	266	0.19	1.6
February	246	0.34	1.0
March	250	0.38	0.8
April	261	0.41	0.7
May	250	0.37	0.6
June	226	0.33	0.7
July	236	0.30	0.8
August	263	0.24	0.7
September	259	0.41	1.0
October	266	0.50	1.2
November	258	0.22	1.4
December	276	0.26	1.6

3.3.6 Canadian Forest Fire Weather Index System

The Canadian Forest Fire Weather Index System (CFFWIS), developed by Van Wagner (1987), was adapted to calculate forest fire hazard in the upper North Saskatchewan and upper St. Mary watersheds. Estimates for fire hazard were made using a series of calculations with daily meteorological variables as input. The CFFWIS uses midday air temperature, relative humidity, wind speed, and daily precipitation accumulation, to calculate fire hazard (Figure 3.14). Midday weather variables were used for these calculations, because the CFFWIS model was originally designed and calibrated to forecast afternoon fire hazard using the meteorological recordings at noon of the same day. The CFFWIS model was designed in this manner, as the peak burning period typically occurs mid-afternoon (Van Wagner, 1987).

The Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), and Drought Code (DC) were computed, to determine moisture levels at multiple depths within the soils. These three fuel moisture codes were then used to determine the following three fire behavior indices: Initial Spread Index (ISI), Buildup Index (BUI), and Fire Weather Index (FWI). All CFFWIS indices are dimensionless. The FWI can be used as a marker for fire danger. An optional component of the CFFWIS that was used in this study was the Daily Severity Rating (DSR), which reflects the difficulty of fire management and control given that FWI is not directly proportional to the amount of effort required for fire suppression (Lawson and Armitage, 2008). The FWI is not a direct reflection of the difficulty of fire control. The DSR is useful, as it minimizes disproportionately high FWI values. The DSR can be averaged over the entire fire season to create the Seasonal Severity Rating (SSR) which can be used to compare fire weather from one season to another or across regions. For this study, fire seasons were defined as the period from May 1st to September 30th.

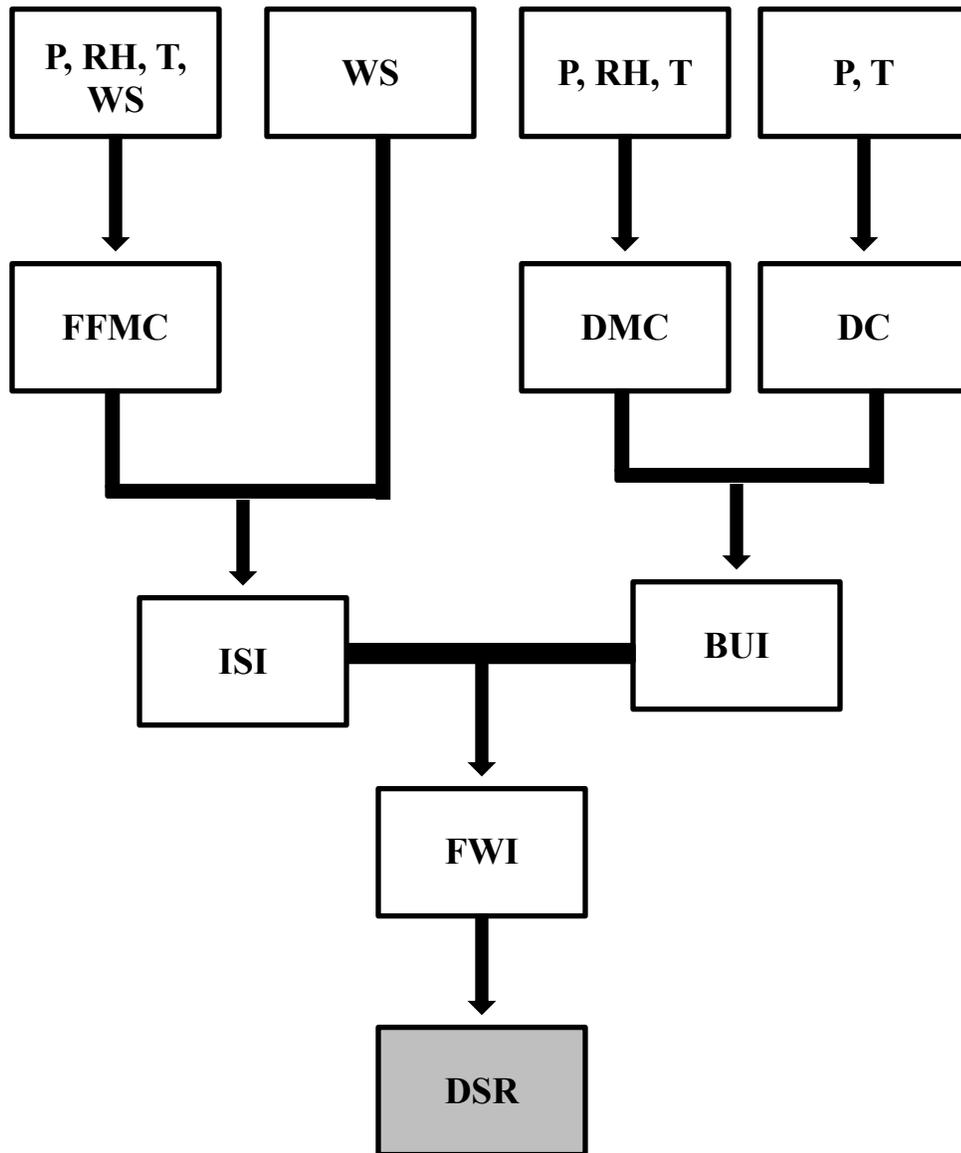


Figure 3.14: Structure of the CFFWIS, where, P is daily 24 hour precipitation (mm), RH is relative humidity at noon (%), WS is wind speed at noon ($\text{km}\cdot\text{h}^{-1}$), T is air temperature at noon ($^{\circ}\text{C}$), FFMC is the Fine Fuel Moisture Code, DMC is the Duff Moisture Code, DC is the Drought Code, ISI is the Initial Spread Index, BUI is the Buildup Index, FWI is the Fire Weather Index, and DSR is the Daily Severity Rating.

There are five fire danger classes in the CFFWIS, as outlined in Table 3.3, along with the corresponding FWI and approximate DSR minimum values for each classification (adapted from Williams, 1959). A rating of zero indicates that the wet conditions preclude fires from starting or spreading, even if highly flammable fuels are present. Nil danger represents DSR values between 0 and 0.1, low danger has a DSR range of 0.2 to 0.9, moderate is between 1.0 and 3.9, high DSR values are between 4.0 and 11.9, and the extreme danger class represents all DSRs greater than 12.

Table 3.3: Fire danger classes along with corresponding FWI and DSR values. Adapted from Williams (1959).

Fire Danger Class	Fire Weather Index Range	Daily Severity Rating Range
Extreme	≥ 31.7	≥ 12.0
High	16.5 - 31.6	4.0 - 11.9
Moderate	7.8 - 16.4	1.0 - 3.9
Low	3.1 - 7.7	0.2 - 0.9
Nil	0 - 3.0	0 - 0.1

3.4 Results

Calculations to determine fire hazard were solely dependent on current weather conditions; fuel availability was not taken into account. The daily and seasonal severity ratings of fire weather were analyzed in two ways:

1. The number of days per fire season in which the DSR was in the high or extreme hazard range ($DSR \geq 4$) were examined. For simplicity, these days were termed *fire days*. This does not mean that fires occurred on each of the *fire days*, but simply that the climatic conditions were favourable for forest fire initiation and spread.

2. The average SSR was examined. This value was determined by summing the DSR values for the entire fire season, then dividing by the number of days in said fire season (153 days for the fire season of May 1st through September 30th).

3.4.1 Fire Days

Time series of fire day values were examined for possible inter-annual lag-correlations at three elevation bands (centered on 1500 m, 2000 m, and 2500 m) for both watersheds. No significant correlation ($P > 0.1$) was found between the number of fire days in a given year with the previous year's fire day count for the same location and elevation, nor was there any significant correlation for longer lags. Therefore, the number of fire days in any given year was not significantly dependent on, or predictable from, previous year's values. Annual data for the six groups (two locations and three elevation bands) were compared (Table 3.4). ANOVA indicated that mean fire hazard (as represented by the number of fire days) was significantly greater in the St. Mary watershed than in the North Saskatchewan watershed ($P < 0.001$). Mean fire hazard at different elevation bands differed ($P < 0.001$; Table 3.5), and the effect of elevation was the same at the two locations (location by elevation interaction was not significant, $P = 0.13$).

Table 3.4 - Summary statistics for the mean number of fire days during 1960-2010 in the North Saskatchewan and St. Mary watersheds.

Watershed	Elevation	N	Mean	Standard Deviation	Standard Error of the Mean
North Saskatchewan	1500 m	51	29.73	15.28	2.14
North Saskatchewan	2000 m	51	22.10	13.26	1.86
North Saskatchewan	2500 m	51	15.28	10.85	1.52
St. Mary	1500 m	51	82.43	19.75	2.77
St. Mary	2000 m	51	67.15	22.04	3.09
St. Mary	2500 m	51	58.39	23.21	3.25

Means were calculated for the number of fire days between 1960 and 2010 in both study watersheds (Figure 3.24). Results of Tukey’s HSD mean comparisons indicated significant differences in fire hazard with elevation (Table 3.5). In both watersheds, fire hazard was greater at lower elevations. In the St. Mary watershed, the number of seasonal fire days at 1500 m differed significantly from the number of seasonal fire days at higher elevations. In the North Saskatchewan watershed, the fire days index at 1500 m elevation differed significantly from the fire days index at 2500 m.

Table 3.5 - Results of Tukey's HSD mean comparisons showing the effect of elevation on fire days. Means with the same letter are not significantly different ($\alpha = 0.05$).

Watershed, Elevation	Least Square Mean				
St. Mary, 1500 m	82.43	A	B	C	D
St. Mary, 2000 m	67.15				
St. Mary, 2500 m	58.39				
North Saskatchewan, 1500 m	29.73		C	D	
North Saskatchewan, 2000 m	22.10				
North Saskatchewan, 2500 m	15.28				

The number of fire days per fire season was calculated for each TC. The NSW (Figure 3.15), which is the more northern basin of the two, experienced fewer fire days on average per fire season than the SMW (Figure 3.16). Both of the watersheds had more fire days in the regions with lower elevations that are generally in the eastern portions of the basins than in the higher, western regions. However, higher incidences of fire days also occurred in river valleys throughout. The reason for the higher number of average fire days in the SMW over the NSW can be attributed to the higher air temperatures, lower summer precipitation volumes, and greater wind speeds in the SMW. Although annually St. Mary received more precipitation than Bighorn Dam, the hottest months of June, July, and August saw less precipitation at St. Mary than Bighorn Dam (refer to Table 3.1 for actual values).

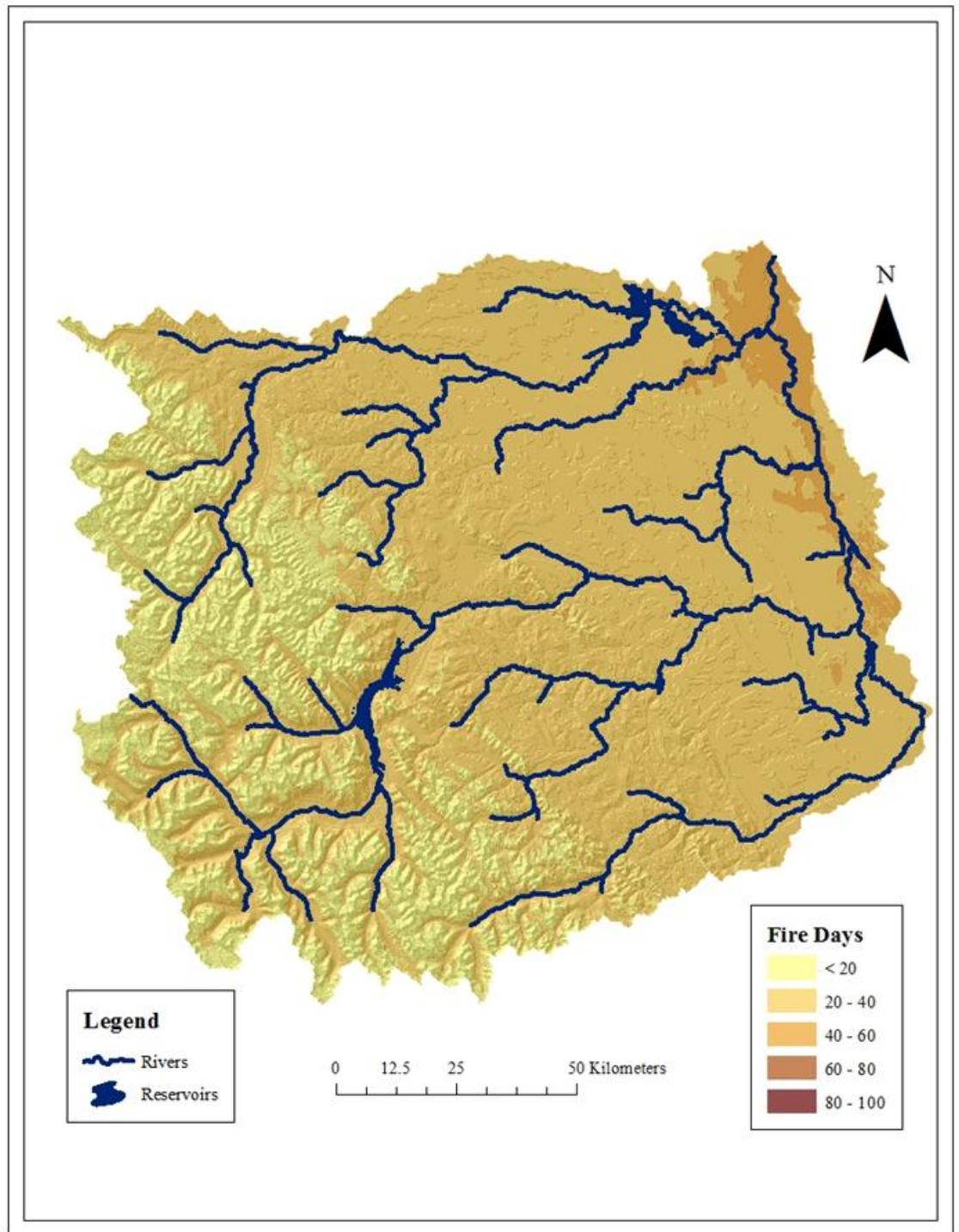


Figure 3.15: The mean number of fire days per fire season between 1960 and 2010 in the NSW.

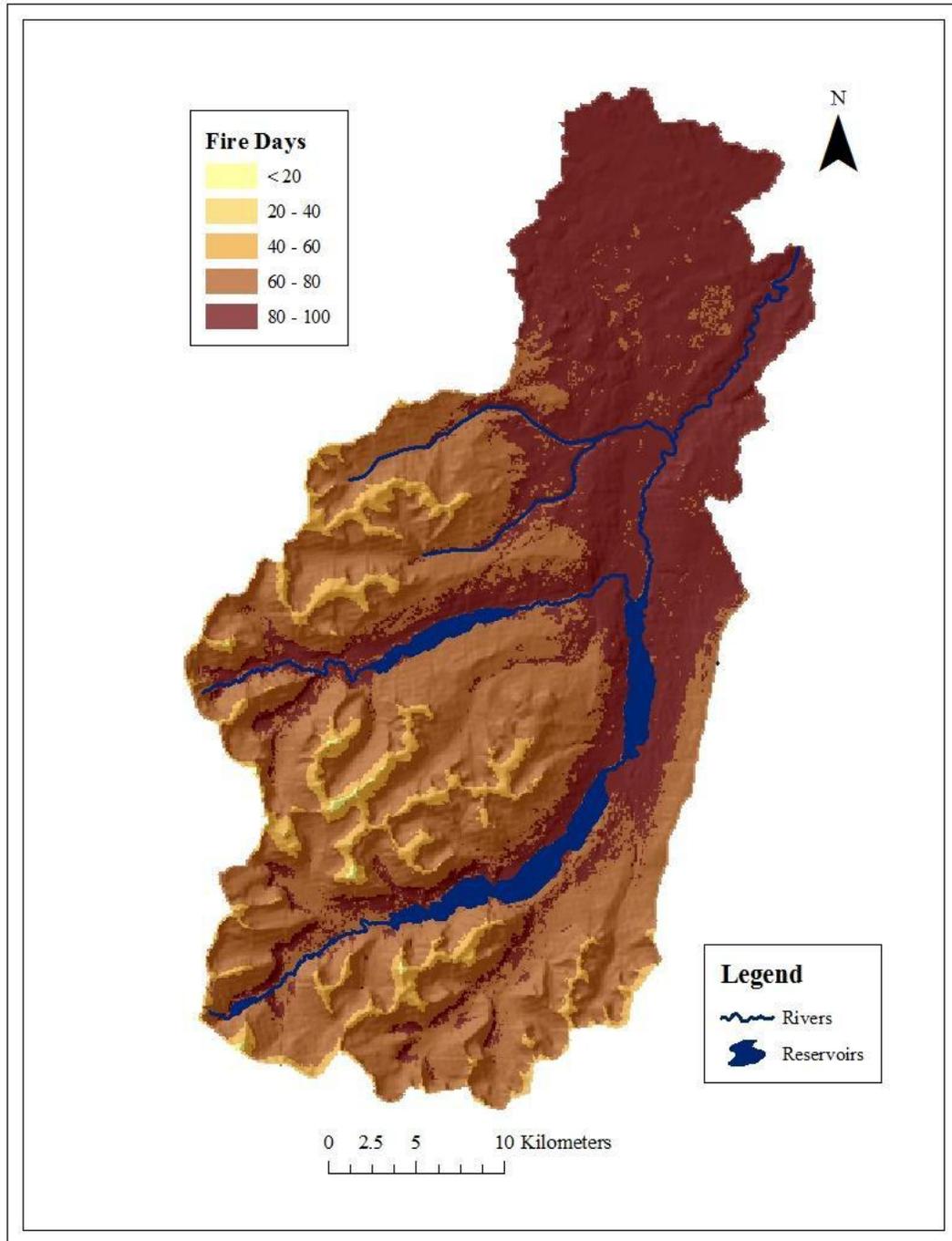


Figure 3.16: The mean number of fire days per fire season between 1960 and 2010 in the SMW.

Analyses of the number of fire days in each fire season at elevations of 1500 m, 2000 m, and 2500 m were performed annually for the North Saskatchewan and St. Mary watersheds (Figure 3.17). Each year, the SMW aggregated more days with high or extreme hazard than the NSW. For both watersheds, areas at elevations of 1500 m had the greatest number of fire days and areas at elevations of 2500 m had the fewest number of days per fire season. This is attributed to the greater air temperatures and lower precipitation amounts at lower elevations. So although wind speeds are greater at higher elevations, the fire hazard has been shown to be strongly influenced by warm temperatures and less precipitation in lower regions. Throughout the time series, variability was present from year to year because of the natural variance in weather patterns.

There were no significant trends or major changes in average air temperature (Figure 3.18; $P=0.78$), and only a slight increase in precipitation trend (Figure 3.19; $P=0.0014$), within the NSW over the study period, although average air temperature and precipitation increased slightly. Wind speed in the NSW decreased slightly ($P<0.0001$) during this time period. These changes in weather variables were attributed as a possible cause of the general reduction in fire days over time in the NSW. In the SMW, no major changes were found in air temperature (Figure 3.18; $P=0.008$) and precipitation (Figure 3.19; $P=0.0014$) variables over time, although the slight declines were statistically discernible. Wind speed increased slightly though significantly ($P<0.001$) from 1960 to 2010. These changes in weather variables may explain the slightly increasing trend in fire days over 1960 to 2010 in the SMW. In the NSW, the trend in fire days indicated a slight decline over the study period ($P=0.007$; Figure 3.20). In the SMW, there was no significant change in fire days ($P>0.5$; Figure 3.20).

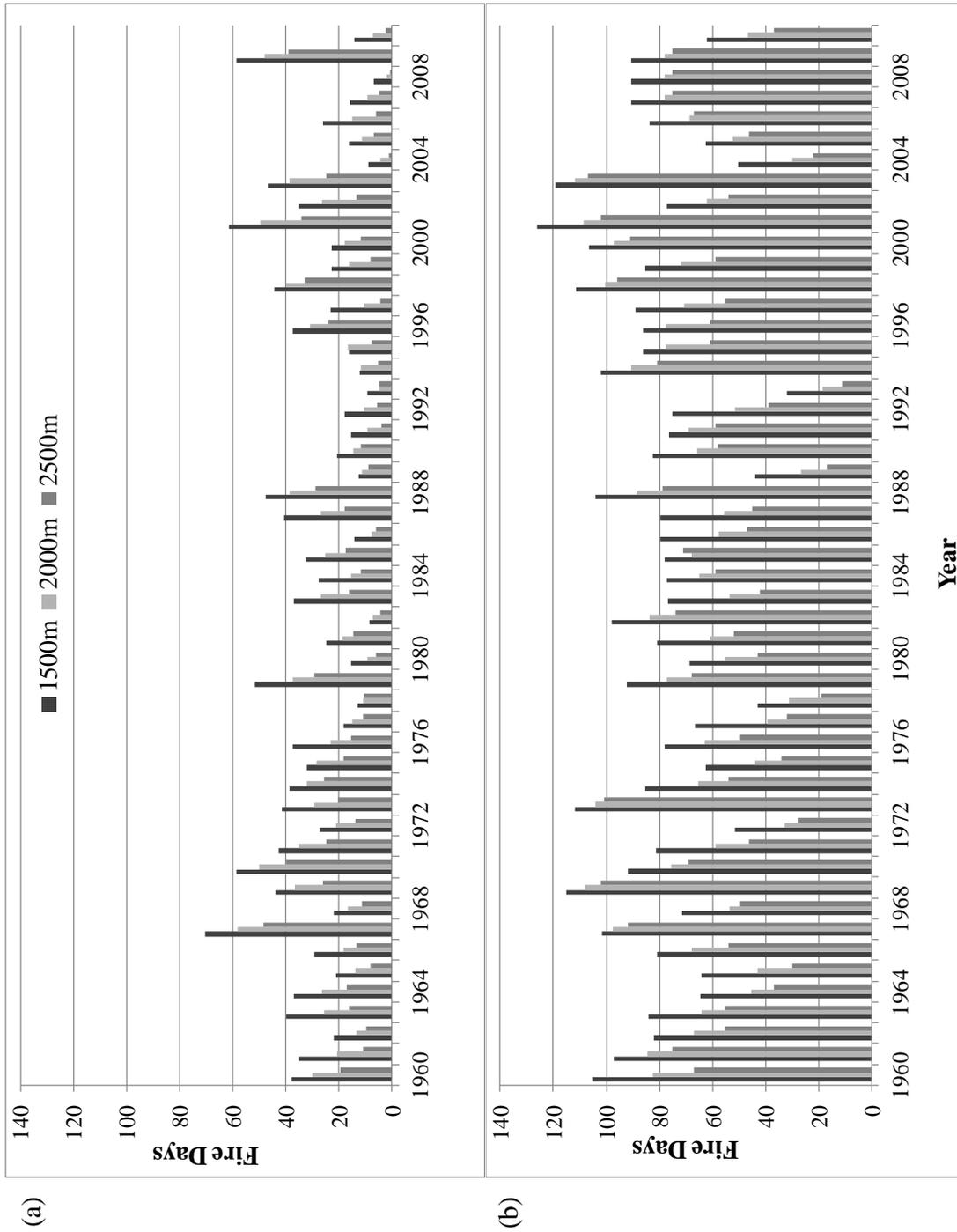


Figure 3.17: Annual number of fire days between 1960 and 2010 in the (a) NSW and (b) SMW.

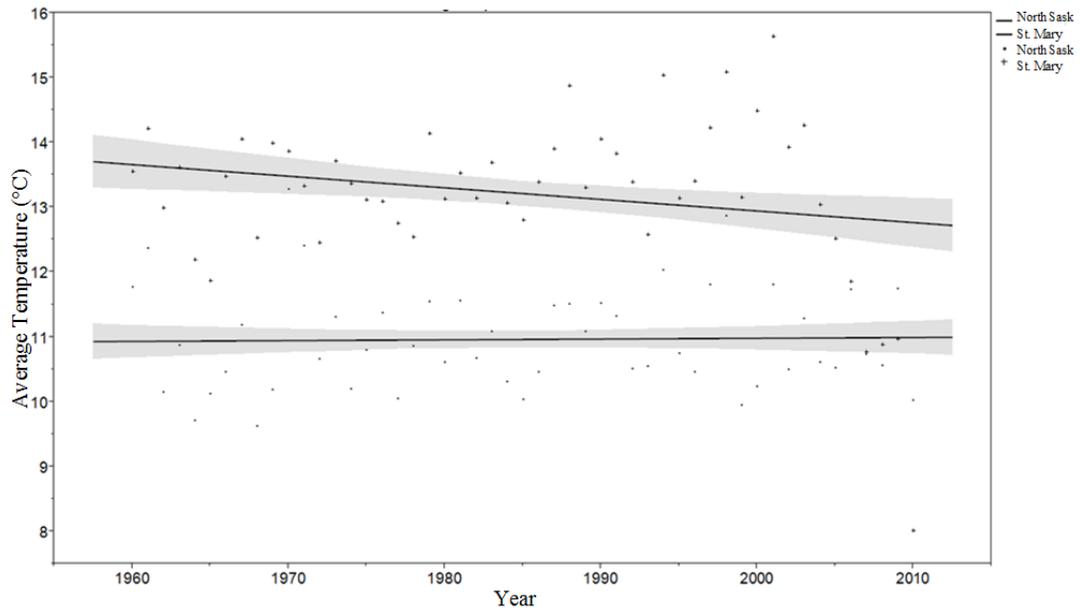


Figure 3.18 - Trend in average temperature over time in the North Saskatchewan (slope=0.0012, P=0.78) and St. Mary (slope=-0.0179, P=0.008) watersheds. 95% Confidence Bands for the predicated mean value are shown.

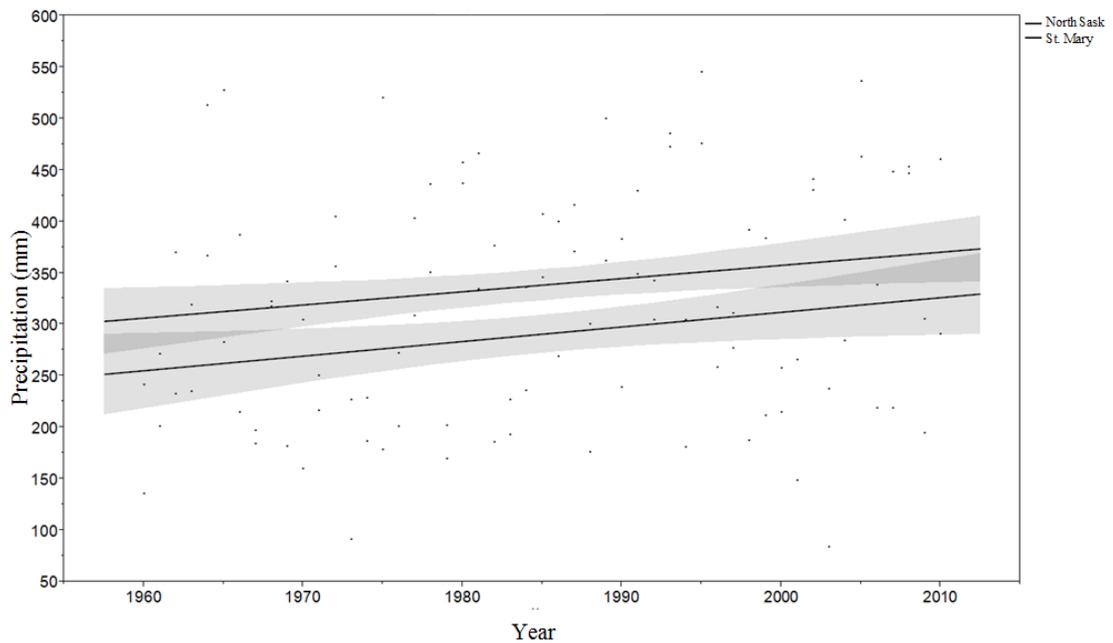


Figure 3.19 - Trend in precipitation over time in the North Saskatchewan and St. Mary watersheds (slope=1.350, P=0.0014). 95 % Confidence Bands for the predicated mean value are shown.

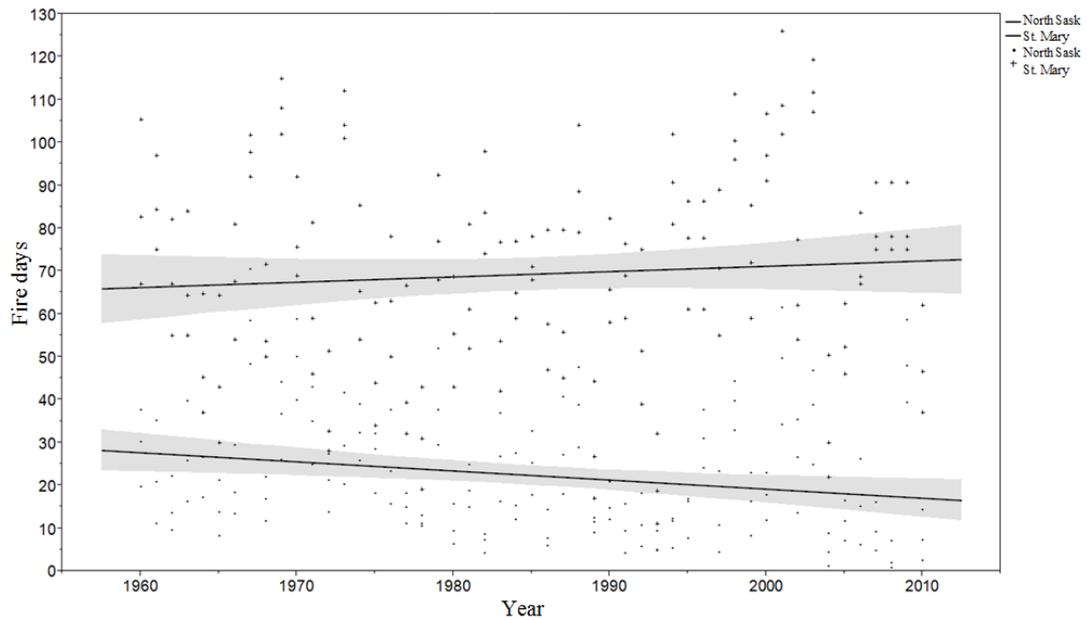


Figure 3.20 - Trend in fire days over time in the North Saskatchewan (slope=-0.212, P=0.007) and St. Mary (slope=0.124, insignificant) watersheds. 95% Confidence Bands for the predicated mean value are shown.

The mean number of annual fire days was calculated per decade for three elevation bands within the two study areas (Figure 3.21). In the NSW, the 1970s (1970-1979) saw the greatest number of high or extreme fire hazard days followed by the 1960s (1960-1969), the 2000s (2000-2009), the 1980s (1980-1989), then lastly the 1990s (1990-1999). In the SMW, the 2000s experienced the most number of days at high or extreme fire hazard followed by the 1960s, then the 1990s, the 1980s, and the 1970s. For both watersheds, these patterns stayed consistent throughout the three elevation bands of 1500 m, 2000 m, and 2500 m. Again, the fewest number of fire days occurred in areas at higher elevations. Overall, the NSW saw an average decline of 2.6 fire days per decade at 1500 m, 2.0 fire days per decade at 2000 m, and 1.7 fire days per decade at 2500 m. The SMW saw an increase in the number of fire days per decade with 0.5 days at 1500 m, 1.3 days at 2000 m, and 2.0 days at 2500 m. Due to the high

variability of the fire weather variables, these values are given only as generalizations of trends.

From 1960 to 2010, the number of annual fire days in the NSW declined by a factor of 0.64 to 4.8 days throughout various regions of the basin (Figure 3.22). Greater negative change was seen in lower elevations of the NSW where, on average, more days of high or extreme fire hazard occurred. At higher elevations, less declination was seen, however, these were areas that had fewer fire days on average and were above the tree-line. The Mann-Kendall trend test showed that the number fire days had a negative trend significant when $\alpha = 0.05$ at 1500 m and 2000 m, and significant when $\alpha = 0.01$ at 2500 m.

Unlike the NSW, the number of fire days within the SMW increased by factors of 0.096 to 2.4 days annually between 1960 and 2010 (Figure 3.23). In the SMW, regions that increased the most in number of fire days per fire season were at the highest elevations. This indicates that the areas that experienced an increase in the severity of fire weather variables the most were at the highest elevations, however, like the NSW, these areas were above the tree-line. The Mann-Kendall showed positive association between the year and the number of fire days, however, the trend was not significant at the 90% or 95% confidence levels.

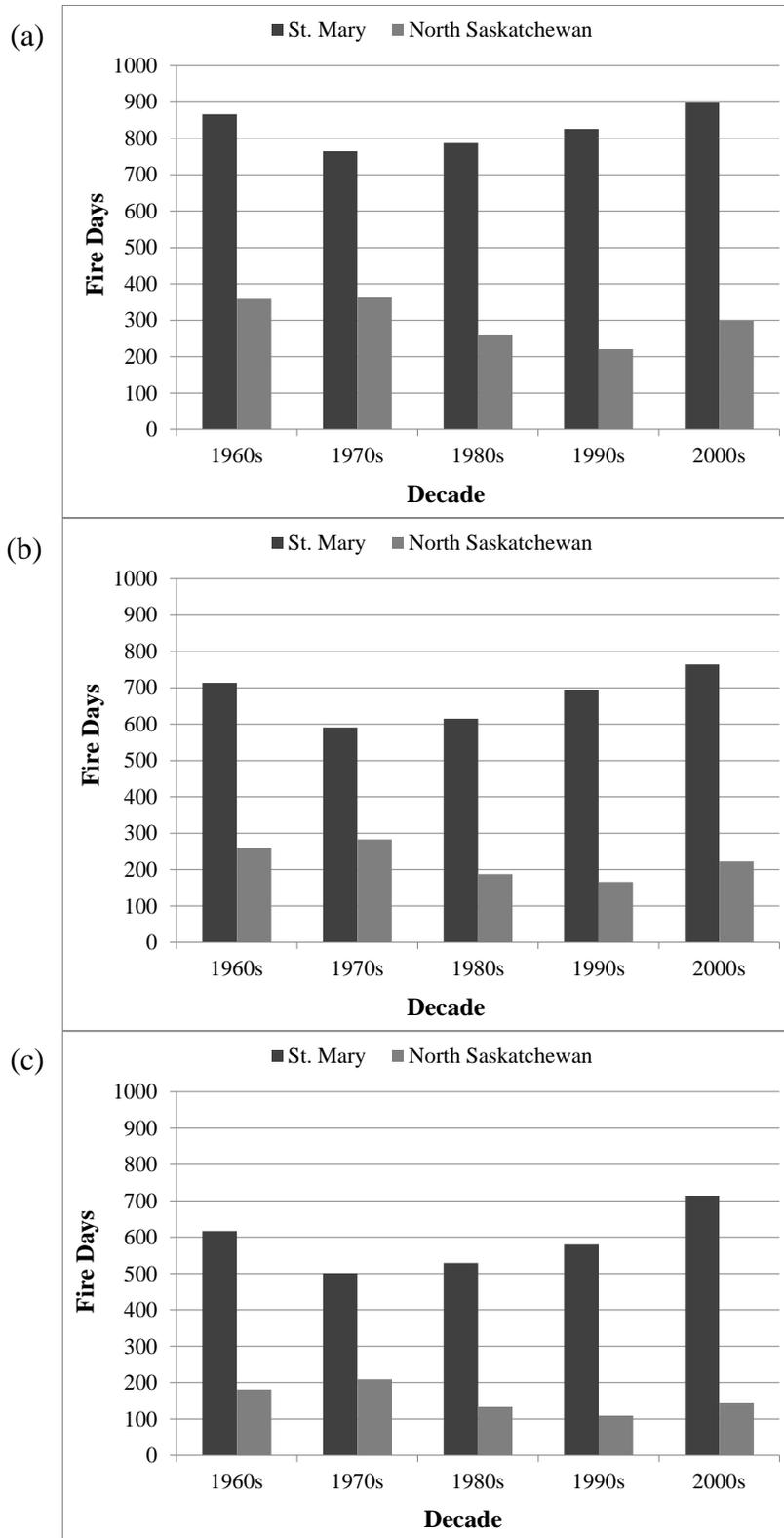


Figure 3.21: A comparison of the total number of fire days per decade at elevations of (a) 1500 m; (b) 2000 m; and (c) 2500 m.

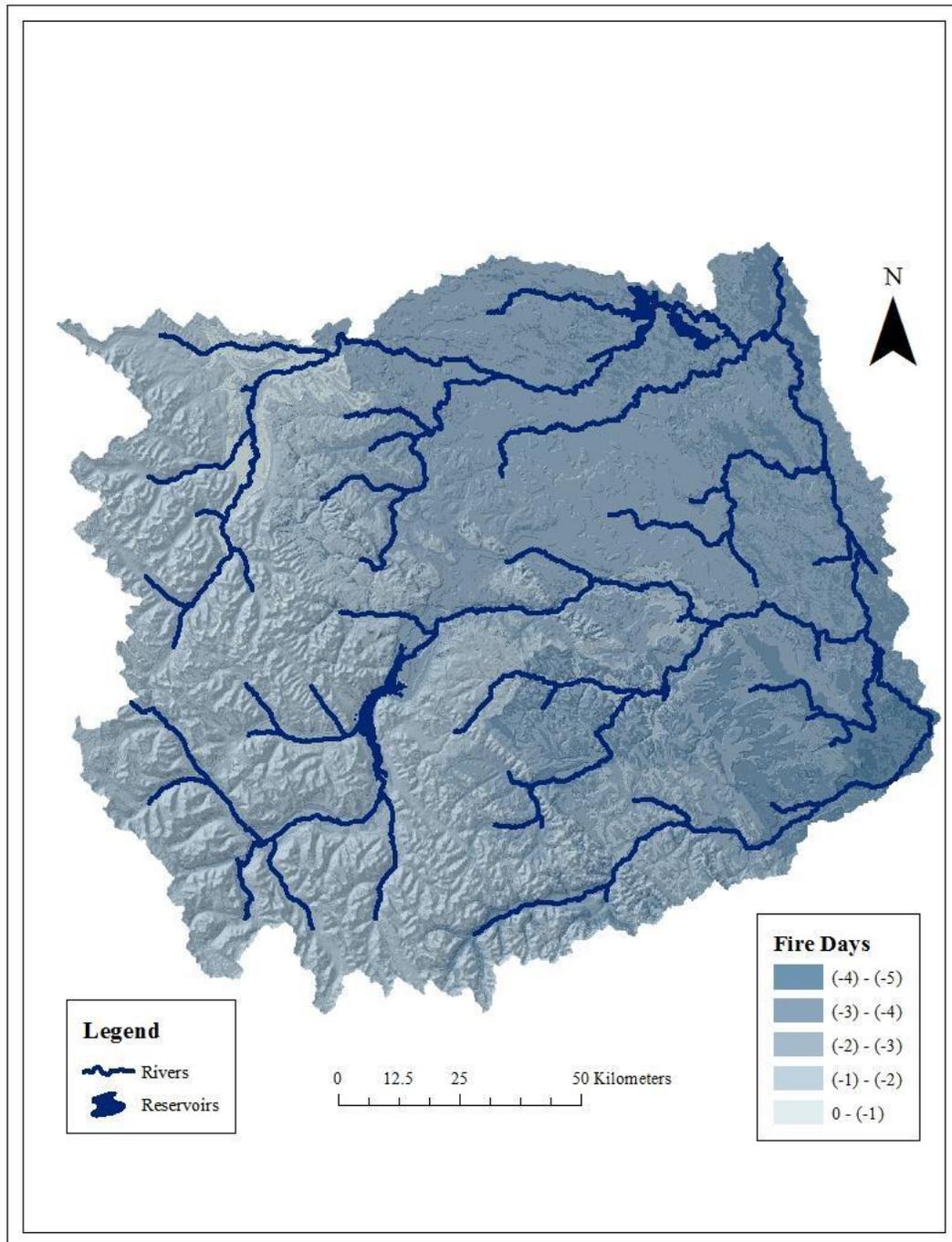


Figure 3.22: Spatial representation of the NSW showcasing the change in the number of fire days. The figure represents the degree of change in the number of fire days per decade for the period of 1960 to 2009.

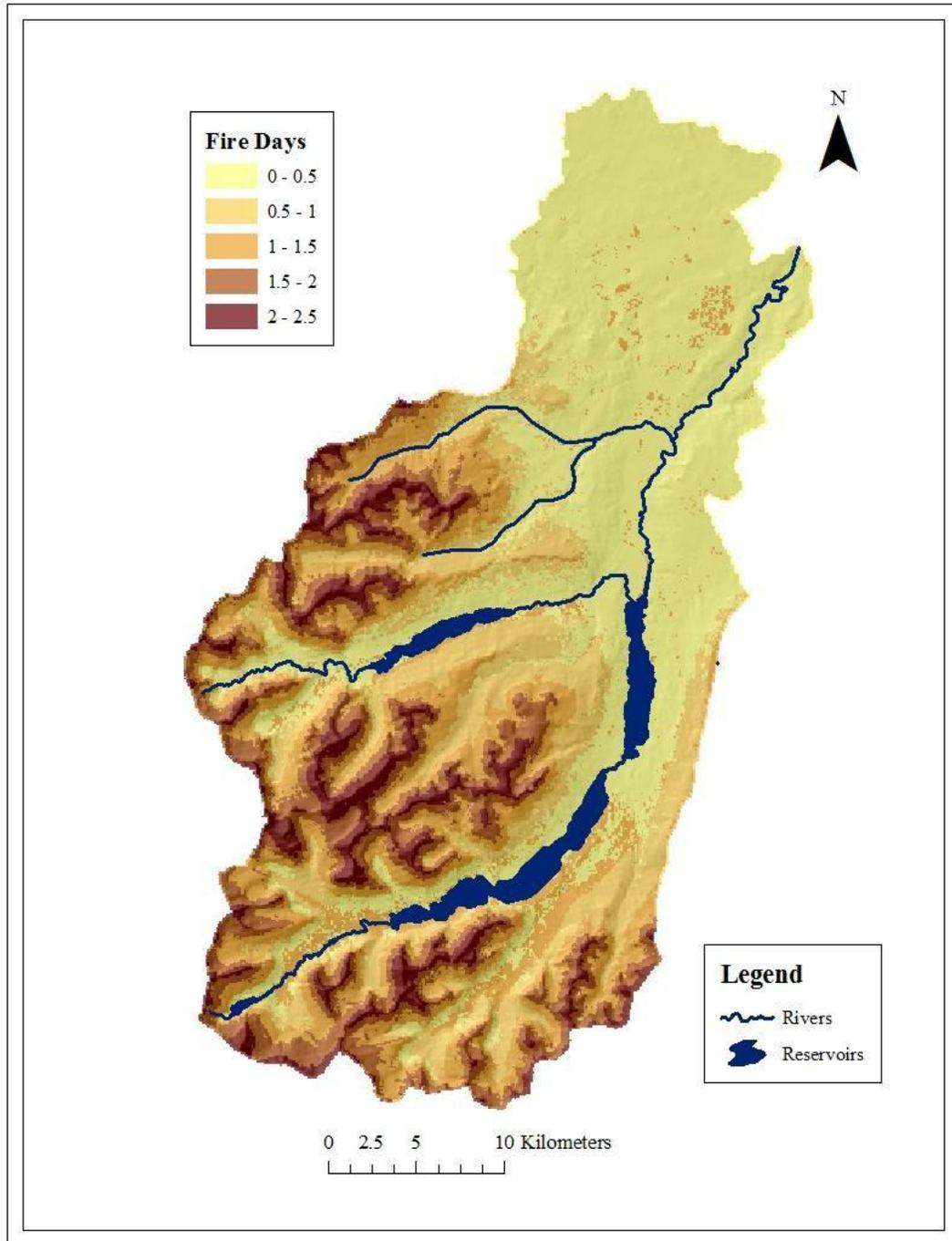


Figure 3.23 - Spatial representation of the SMW showcasing the change in the number of fire days. The figure represents the degree of change in the number of fire days per decade for the period of 1960 to 2009.

There was a positive correlation between number of fire days and average seasonal air temperature in both watersheds (Figure 3.24). This means that as air temperatures rise, so does the fire hazard. The correlation was negative between precipitation and fire days in both regions (Figure 3.25), because as precipitation increases, the risk for fire decreases. The relationships of elevation, average air temperature, and precipitation on fire days within both watersheds are illustrated graphically in Appendix A.

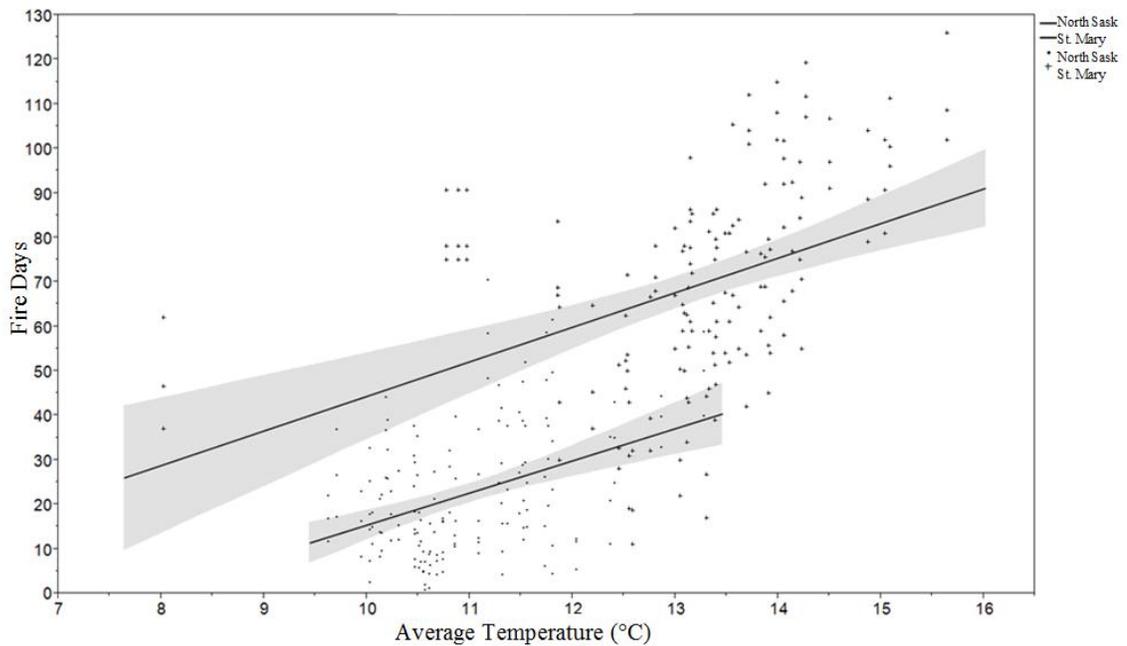


Figure 3.24 - Fire days versus average seasonal air temperature in the North Saskatchewan (slope=7.225, $P<0.0001$, $r^2=0.16$) and St. Mary (slope=7.768, $P<0.0001$, $r^2=0.16$) watersheds. 95% Confidence Bands for the predicated mean are shown.

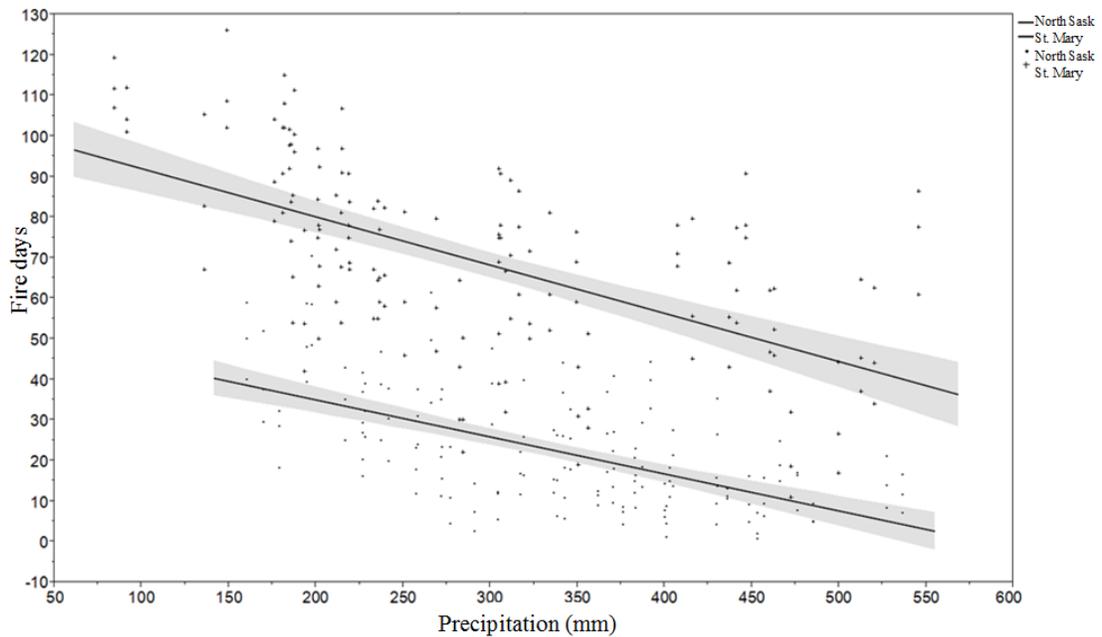


Figure 3.25 - Fire days versus seasonal precipitation in the North Saskatchewan (slope=-0.0912, $P<0.0001$, $r^2=0.36$) and St. Mary (slope=-0.1189, $P<0.0001$, $r^2=0.34$) watersheds. 95% Confidence Bands for the predicated mean value are shown.

3.4.2 Seasonal Severity Rating

Average SSRs were calculated from 1960 to 2010 for every TC in the study regions. Higher mean SSR were found to occur in lower elevations in both the North Saskatchewan (Figure 3.26) and St. Mary (Figure 3.27) watersheds. Mean SSRs were much lower across the NSW compared with the SMW. Again, this can be attributed to the warmer surface air temperatures, less summer precipitation, and greater wind speeds in the St. Mary basin. The SMW was found to be almost encompassed by high severity areas. However, this was somewhat misleading because a few days with high enough DSR values can significantly increase the SSR even if the majority of days did not experience high fire hazard values. Similarly, multiple days with low fire weather severity in a year can create a relatively low SSR, even though there may have been many days with high or extreme DSR values, as is the case with the NSW.

Mean SSR values were consistently higher in the SMW than in the NSW each year from 1960 to 2010 (Figure 3.28). In many of the fire seasons, the SSR values for the SMW were more than four times the SSR values in the NSW. Although most years exhibited greater SSR values at 1500 m in comparison to SSR values at 2000 m or 2500 m, both watersheds occasionally had fire seasons in which greater fire severity was seen at elevations of 2000 m or 2500 m. This can be credited to the greater wind speeds at higher elevations. In general, this implies that the cooler temperatures and greater precipitation volumes at higher elevations would lessen the severity of fire weather, however, if wind speeds are high enough and the other fire weather variables were favourable, the DSR and thus SSR values can be markedly increased.

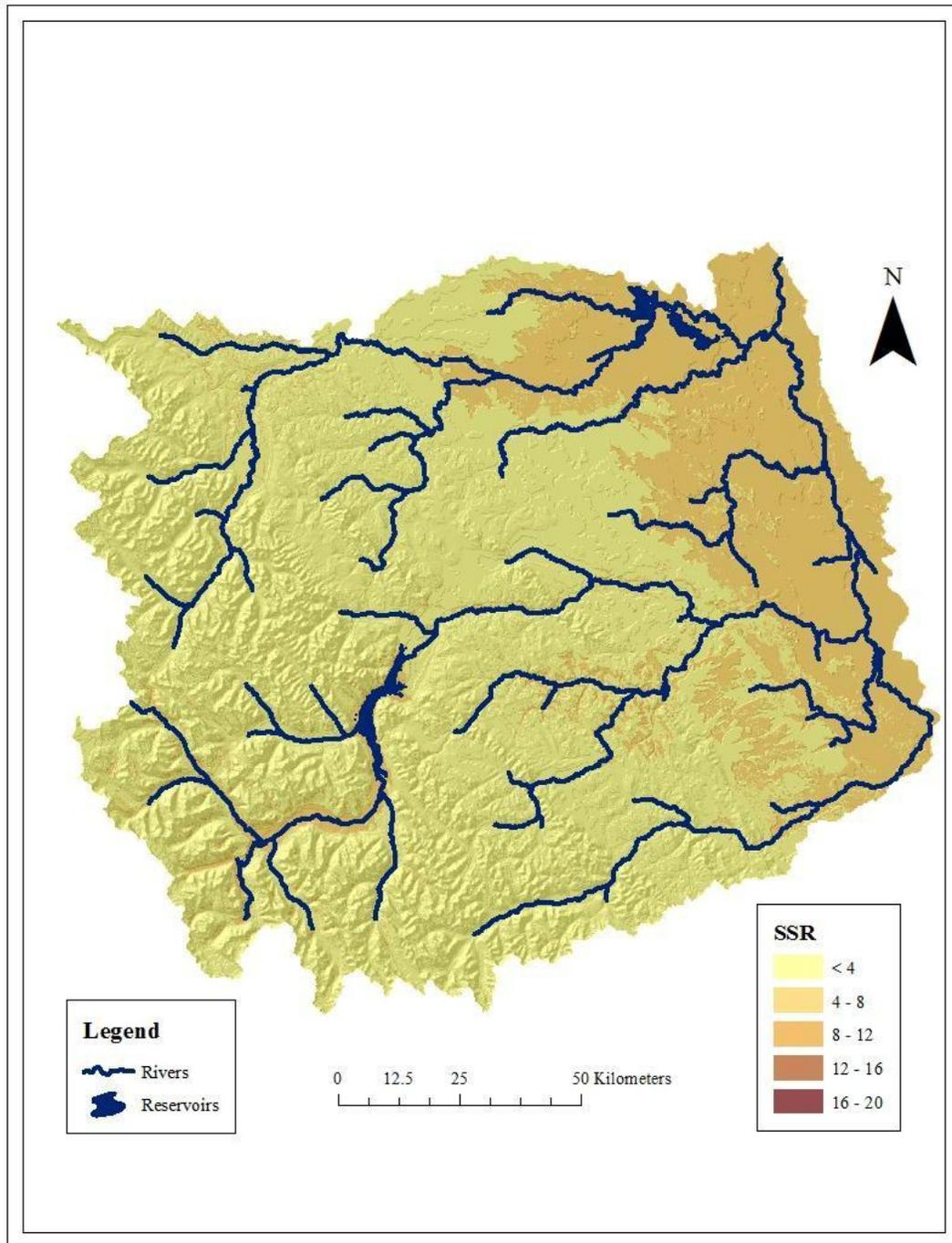


Figure 3.26: Spatial representation of the mean SSR values in the NSW for the period of 1960 to 2010.

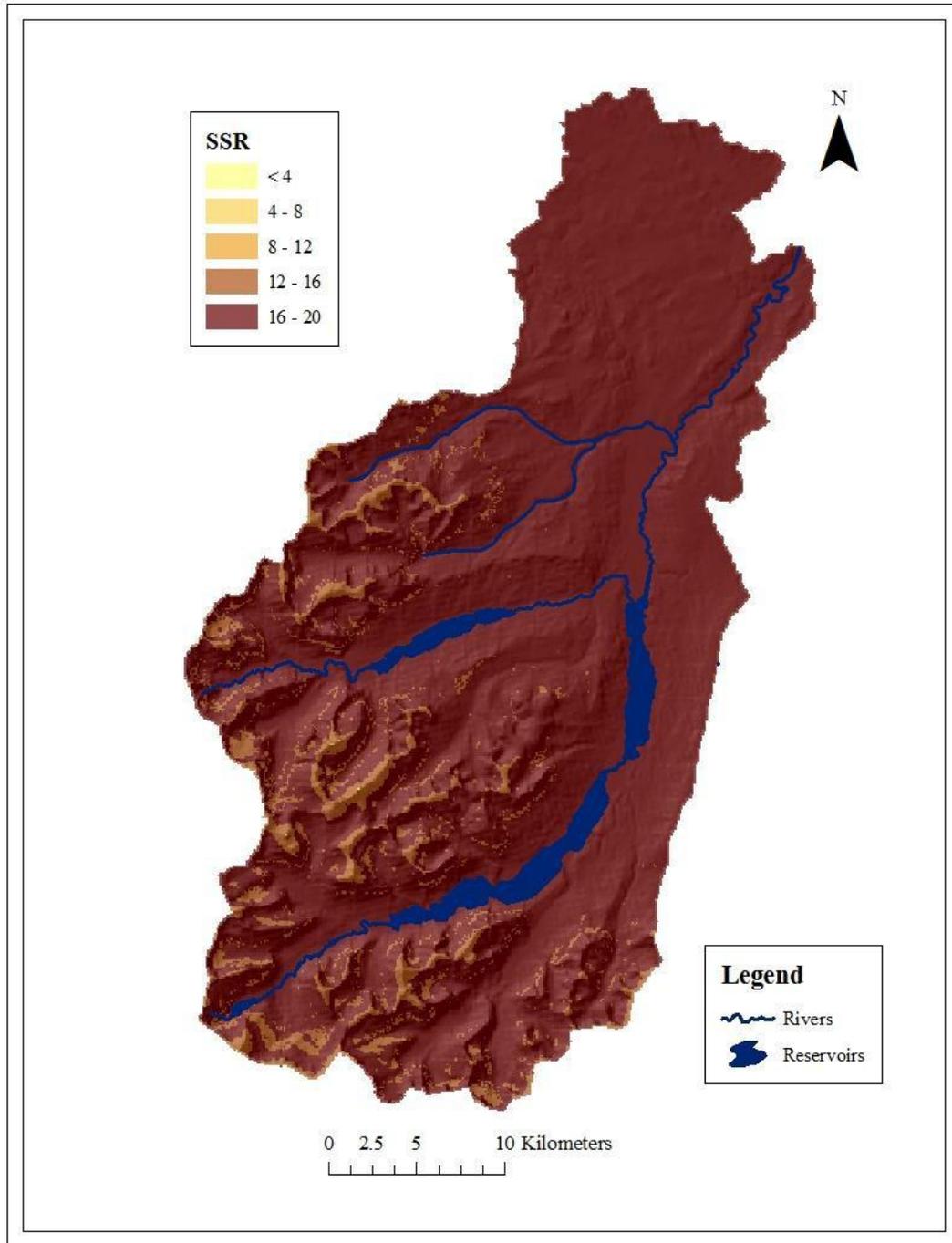


Figure 3.27: Spatial representation of the mean SSR values in the SMW for the period of 1960 to 2010.

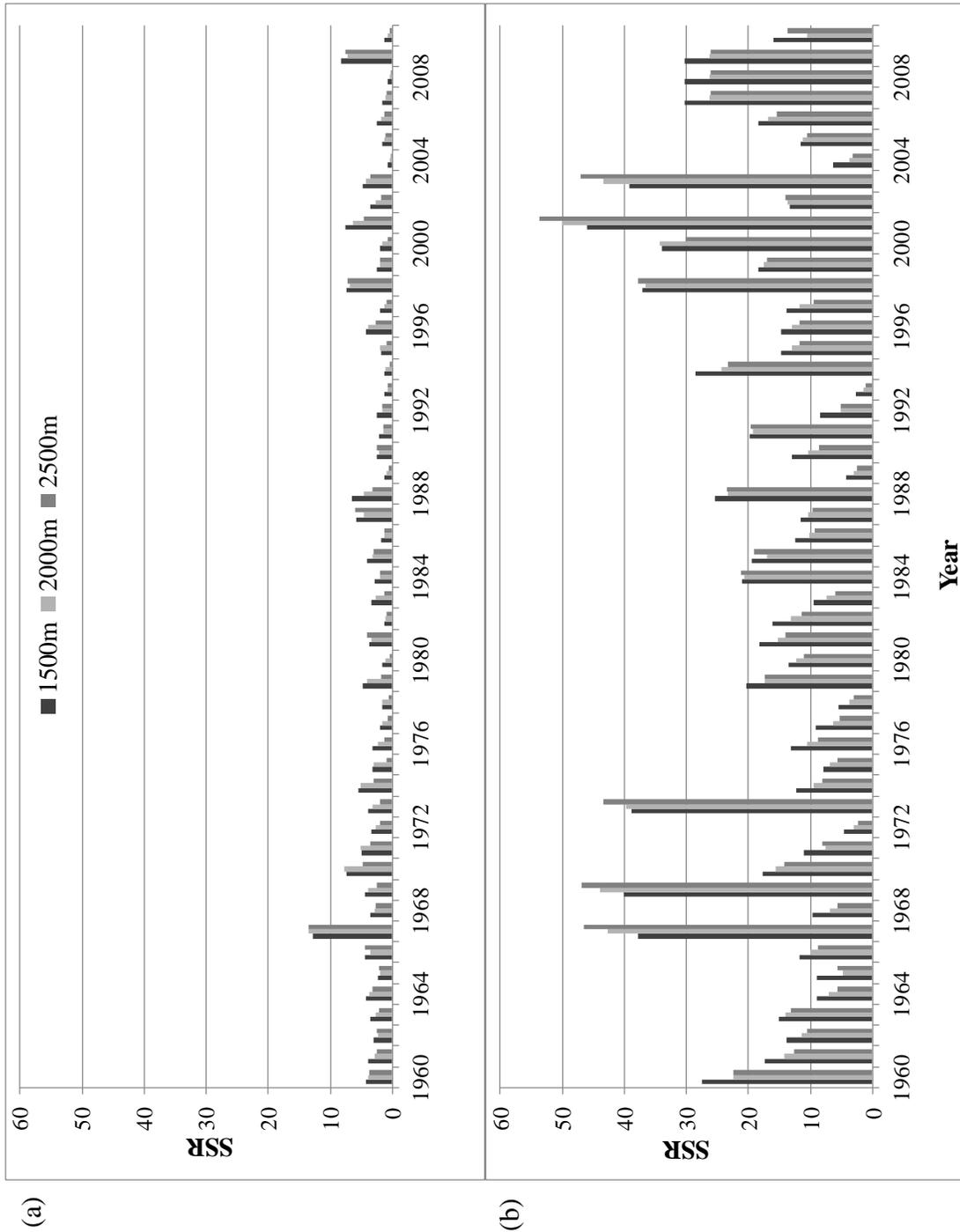


Figure 3.28: Annual SSR for three elevation bands for the period of 1960 to 2010 for the (a) North Saskatchewan, and (b) St. Mary watersheds.

When SSR values were averaged for each decade, it was found that the areas at elevations of 1500 m had greater fire hazard than those areas at 2000 m and 2500 m for both watersheds (Figure 3.29). Once again, this is attributed to the warmer temperatures at lower elevations, and the greater precipitation volumes and wind speeds at higher elevations. The NSW saw highest SSR values in the 1960s, followed by the 1970s, 2000s, 1980s, and the 1990s, which inhibited finding trends throughout the fifty year period. The SMW accumulated the highest SSR values in the 2000s, followed by the 1960s, then an upward trend through the 1970s, 1980s, and 1990s.

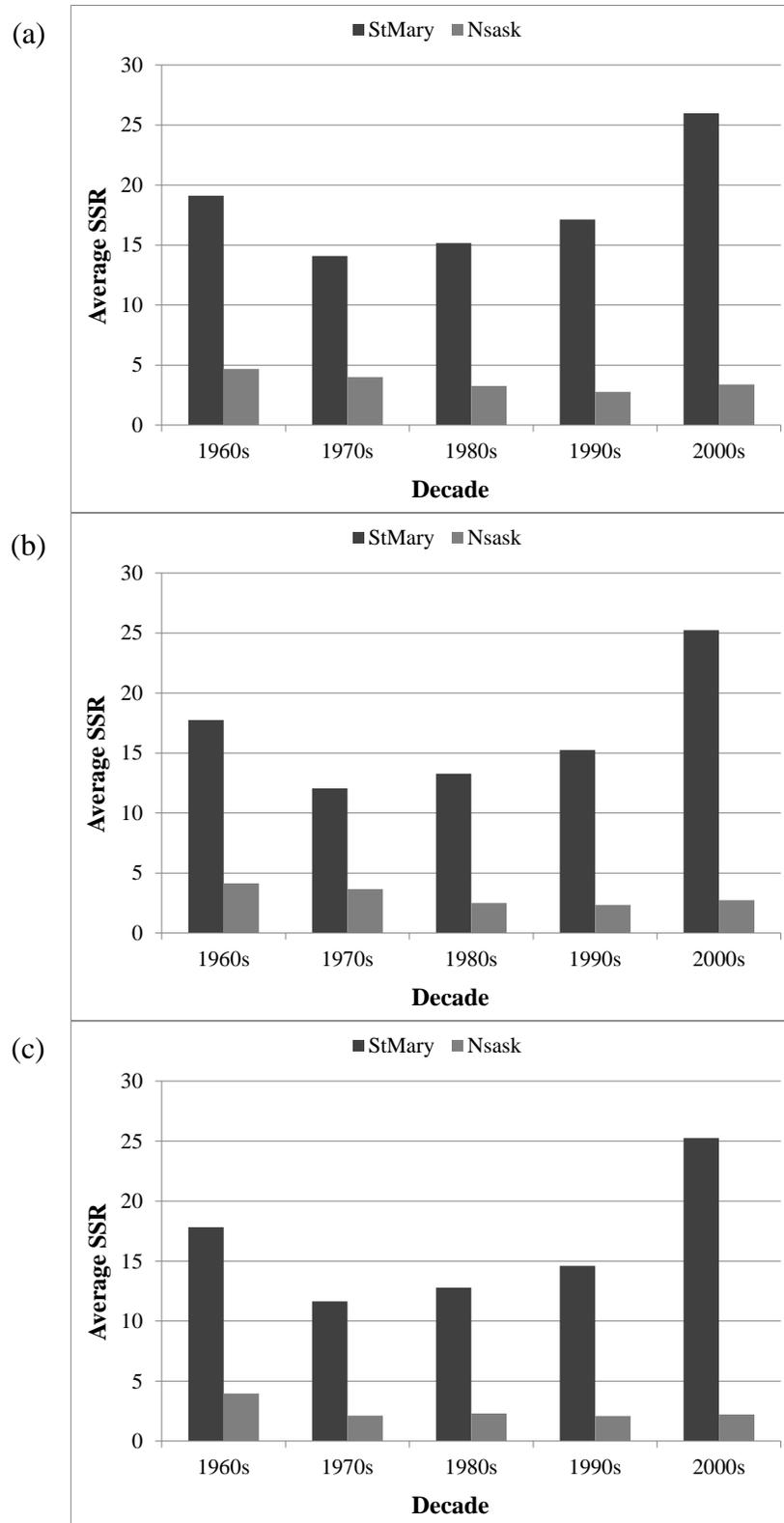


Figure 3.29: SSR values for each fire season averaged per decade for the two study watersheds at elevations of (a) 1500 m; (b) 2000 m; and (c) 2500 m.

Slope analysis was performed to determine the amount of change in SSR values per decade and their respective locations in the North Saskatchewan (Figure 3.30) and St. Mary (Figure 3.31) watersheds. Overall, the NSW saw a decline in SSR values throughout the entire basin from 1960 to 2010. This decreasing trend of SSR with time was significant when $\alpha = 0.05$ at 1500 m, and when $\alpha = 0.01$ at 2000 m and 2500 m elevation. Many of the regions in the NSW that saw the greatest change (a decrease of up to 0.8 SSR units per decade) occurred in the highest elevations with many of the regions with less than 0.2 units of decline in fire hazard occurring at lower elevations. At 1500 m, the NSW saw a decrease of 0.37 SSR units per decade, 0.40 units per decade at 2000 m, and 0.33 units per decade at 2500 m.

The fire weather severity in the SMW increased from 1960 to 2010, however, the Mann-Kendall trend analysis indicated that this trend was not significant at the 90% and 95% confidence levels. Areas at highest elevations saw the greatest change in SSR values. Some regions experienced more than 1.8 units of increase in SSR throughout the time period where the greatest amount of change took place at higher elevations and the least change (less than 0.2 units) generally occurred at lower elevations. The SMW increased by 1.5 SSR units per decade at 1500 m, 1.6 SSR units per decade at 2000 m, and 1.7 SSR units per decade at 2500 m.

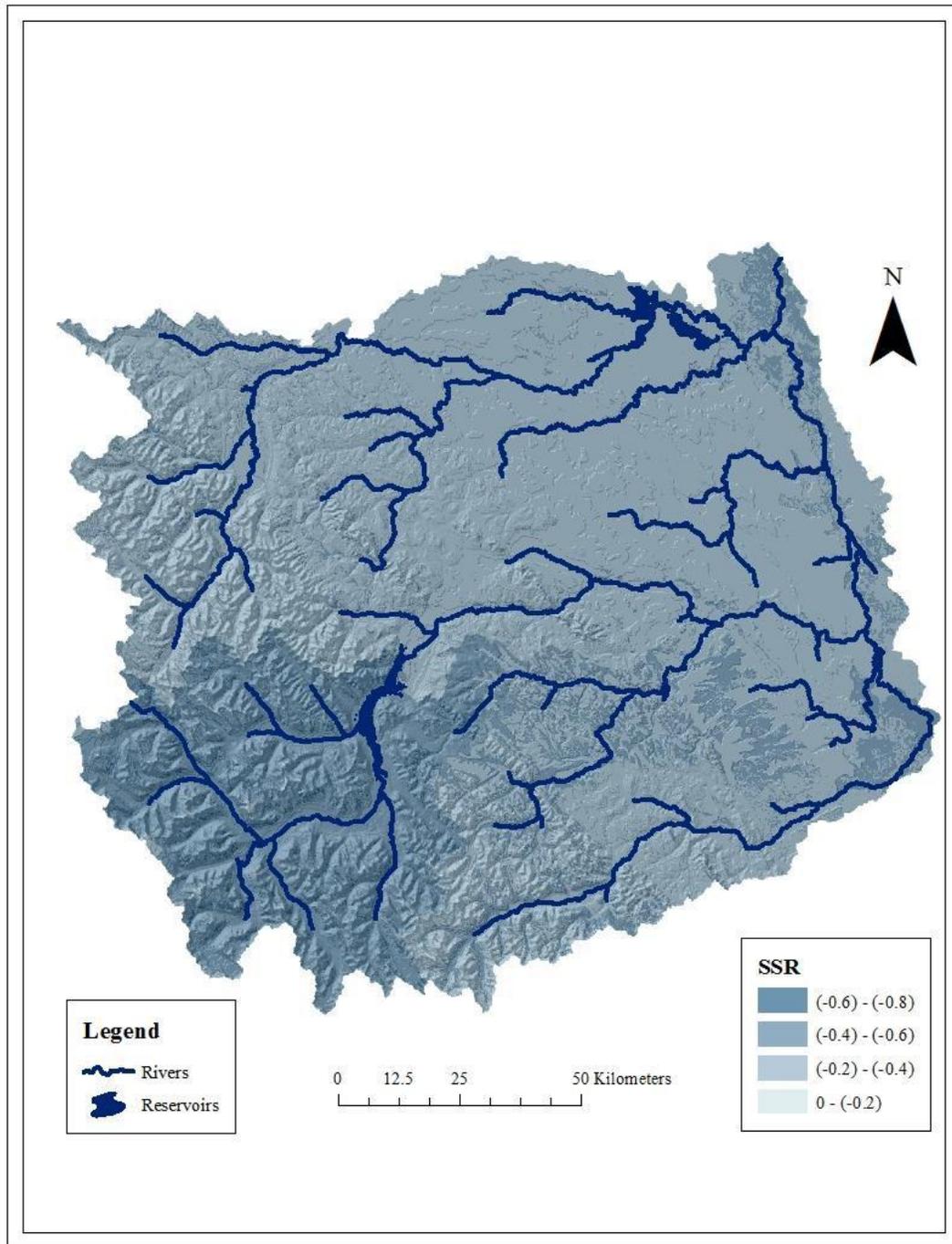


Figure 3.30: Spatial representation of the amount of change in SSR values per decade across the NSW from 1960 to 2010.

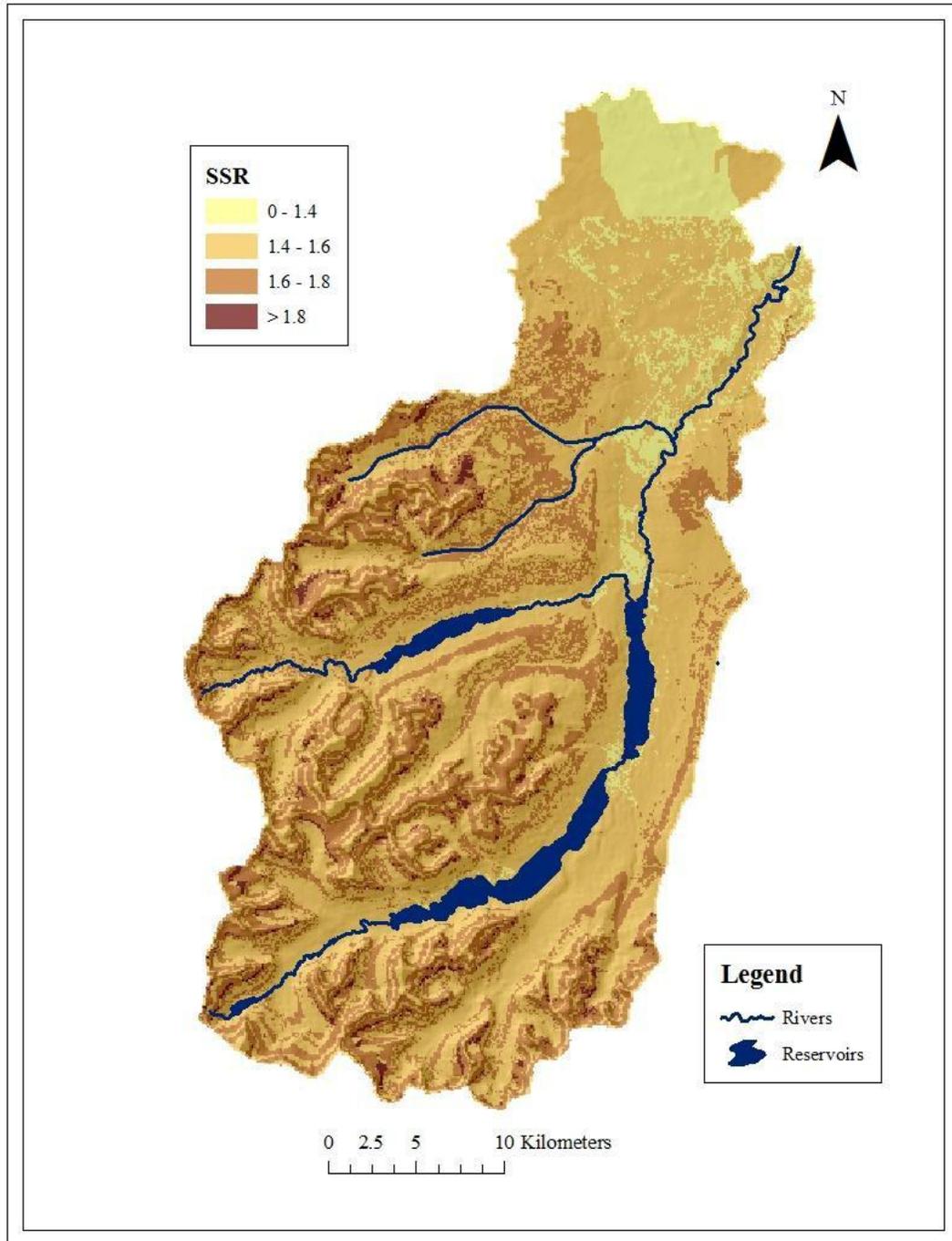


Figure 3.31: Spatial representation of the amount of change in SSR values per decade across the SMW from 1960 to 2010.

3.5 Discussion

This study has demonstrated the ability of the GENGRID model to simulate daily weather variables needed for forest fire prediction in complex mountainous terrain. This model requires relatively few model inputs compared to similar fine-scale meteorological models. This has enabled the GENGRID model to be applicable in multiple watersheds where there are limited available meteorological data.

There are a number of uncertainties when simulating weather conditions across large areas. In the NSW, long-term climate data were only available at three locations, and in the SMW, sufficient data were only available at one. The meteorological input data from the few climate stations are likely not representative of the entire regions due to the size and heterogeneity of the watersheds. However, as there were very few stations with long-term climate data, using few climate stations was appropriate for this study.

It was important to simulate air temperature values at 12:00 p.m., because the CFFWIS had been calibrated to determine fire hazard during the period of greatest fire danger, approximately 4:00 p.m., based on the values provided at noon of the same day (Van Wagner, 1987). The truncated sinusoidal curve given by Parton and Logan (1981) provided a reliable source for simulating diurnal air temperature. This method was used to simulate T_{NOON} and gave realistic values compared to recorded midday air temperature data within both study watersheds. It is plausible that this same method can be applied in other mountainous watersheds where meteorological data are limited. Recorded T_{NOON} data were not available at high elevations for the purpose of model calibration and validation. However, accuracy has been shown in the use of temperature lapse rates for predicting minimum and maximum air temperatures in both the North Saskatchewan (MacDonald et al., 2011) and St. Mary (MacDonald et al., 2009) watersheds.

In Canada and the United States, RH and T_d are often only measured at main climate stations, with even less availability of these variables in mountainous regions. Additionally, T_d sensors are prone to measurement errors, thus, there is a need to estimate RH across large areas for the purpose of ecological modelling (Kimball et al., 1997). Empirical data were combined with methods outlined for simulating T_d (Howell and Dusek, 1995) and diurnal RH (Beck and Trevitt, 1989) to simulate RH at noon in both watersheds using only air temperature values for model inputs. T_d values were used for model verification in the NSW, however, data were not available for verification in the SMW. Although the model did not always accurately simulate midday T_d , this method was deemed appropriate for this study. More meteorological data would be needed to create a method for better estimation of RH across the complex watersheds.

Hourly wind data are very limited in Alberta and Montana, especially at high elevations, leaving mountainous regions highly under-represented orographically. This adds to the difficulty in simulating wind speeds in mountainous environments (Landberg et al., 2003; Weber, 1999). Wind speed profiles were constructed using base station data, and reanalysis data at approximately 1500 m and 3000 m above sea level. Although this method gives a general interpretation of the exponential wind speed increase with elevation, it does not account for wind speed changes caused by the topography of the land. This method also assumes that wind speeds are equal at similar elevations, regardless of the direction the mountain- or hill-slope faces. While this method does present weaknesses and limitations, it was used to provide a simplistic approach to simulating wind speeds based on few parameters. In future studies, a more advanced wind speed model would provide a more realistic method for determining fine-scale fire hazard in mountainous regions.

Historically, the fire days index and the SSR were consistently higher in the SMW than in the NSW. The fire indices were higher in the SMW where annual temperatures are higher, summer precipitation is lower, and wind speeds are greater. From the period of 1960 to 2010, average seasonal air temperatures in the NSW rose slightly, precipitation increased, and wind speed declined. The increased precipitation and the slower winds were not impactful enough to offset the rising temperature, resulting in a decline in the fire hazard indices. This declining trend is not consistent with most studies that present increases in fire activity in the late twentieth century (Gillett et al., 2004; Kang et al., 2006; Soja et al., 2007; Stocks et al., 2003). Contrary to the NSW results, the fire days index and SSR in the SMW increased throughout the fifty year historical period. Wind speeds increased slightly during this time frame, with a decline in annual precipitation. This combination of changes in weather variables increased the fire hazard in the SMW, which is in agreement with most forest fire studies.

3.6 Conclusions

This study consisted of two main parts. First, the GENGRID model was refined in order to simulate the necessary fire weather variables spatially throughout the North Saskatchewan and St. Mary watersheds. This included creating a model to simulate wind speeds at all elevations throughout the alpine basins. General regional wind patterns were simulated using surface wind speed data and reanalysis wind data at 850mb and 700mb pressure levels (retrieved from NOAA, 2011). The CFFWIS model was then adapted for use with the GENGRID output in order to determine fire hazard severity ratings at 100 m resolution.

The main limitation in this study was the lack of available meteorological data at

a fine scale in mountainous regions. This is supported by Daly et al. (2007), in that the lack of data in mountainous regions is a key limitation in alpine model validation. Simulations at high elevations have proven difficult when the only climate stations available as drivers to the model were located at relatively low elevations. In addition, more climate stations with hourly data would have aided in model verification and calibration for daily meteorological variables at noon.

Although the centres of the two watersheds were roughly only 450 km apart, they were substantially different with respect to fire hazard regime. A number of conclusions were made in this study:

- Both study watersheds generally exhibited the greatest number of fire days in lower elevations and eastern regions of the basins.
- In total, the SMW had more fire days each fire season from 1960 through 2010 than the NSW at equivalent elevations.
- Greater numbers of fire days were seen at low elevations and fewer fire days were seen at relatively high elevations.
- The number of fire days in the NSW declined across the entire watershed from 1960-2010 by a factor of 0.64 to 4.8 days per fire season. The greatest change was seen at low elevations, however, greater certainty occurred at higher elevations.
- The number of fire days in the SMW increased all through the watershed by a factor of 0.10 to 2.4 days per fire season from 1960 to 2010. The greatest changes in fire days were at high elevations.
- Average SSR values for the period of 1960-2010 were greatest at low elevations for both watersheds.

- Overall, the SMW experienced higher SSRs than the NSW.
- Typically, highest SSR values occurred at low elevations (1500 m) and the lowest SSR values occurred at relatively high elevations (2500 m), however, some years exhibited highest SSR values at elevations of 2000 m or 2500 m.
- The NSW experienced a decline in the SSR from 1960 to 2010 by a factor of 0.18 to 0.79 units. Most change in the SSR occurred at high elevations.
- The SSR values in the SMW increased by a range of 1.3 to 1.9 units per fire season from 1960 to 2010.
- The greatest amount of change from 1960 to 2010 for both study basins occurred at high elevations, however, the NSW experienced negative change while the SMW experienced positive change.

The increase in fire weather severity that occurred in the SMW over the past five decades was consistent with the findings of multiple studies on fire activity regimes in western North America including the occurrence, extent, or vulnerability of forests to fire (Flannigan et al., 2005; Gillett et al., 2004; Running, 2006; Westerling et al., 2006; and Nitschke and Innes, 2008). The decline that was seen in the NSW does not agree with most studies on historical fire hazard. However, Wallenius et al., (2011) have found evidence of decreased area burned in the boreal forests of north western Canada since the middle of the nineteenth century to present, but, were not able to determine a trend in common fire climate indices and area burned. Further studies will investigate the possible impacts of climate change on fire weather severity in the North Saskatchewan and St. Mary watersheds.

CHAPTER 4:

Future Fire Hazard in the Northern Rocky Mountains

4.1 Introduction

Forest fires are principal forces in transforming landscapes across Canada (Flannigan et al., 2005b). Greenhouse Gas (GHG) emissions have already contributed to warmed fire-susceptible areas in Canada during the fire season months (Gillett et al., 2004). As global warming continues to advance, forest fire hazard in west-central Alberta is expected to increase (Li et al., 2000). Projections of fire related variables are expected to rise as climates warm, including area burned by fire (Flannigan and Van Wagner, 1991; Flannigan et al., 2000; Flannigan et al., 2005b; Gillett et al., 2004; Running, 2006; Girardin, 2007; Soja et al., 2007, Krawchuk et al., 2009), forest fire frequency (Flannigan and Wagner, 1991; Flannigan et al., 2005b; Girardin, 2007; Soja et al., 2007; Nitschke and Innes, 2008; Flannigan et al., 2009), fire weather severity (Flannigan et al., 2000; Dale et al., 2001; Westerling et al., 2006; Nitschke and Innes, 2008; Flannigan et al. 2009) and fire season length (Westerling et al., 2006; Nitschke and Innes, 2008).

In Chapter 3, the methods for determining the fire weather variables spatially across the North Saskatchewan watershed (NSW) and the St. Mary watershed (SMW) using the GENGRID meteorological model (Sheppard, 1996) were explained. From there, daily fire hazard values were calculated for each year from 1960 to 2010 using the Canadian Forest Fire Weather Index System (CFFWIS; Van Wagner, 1987). In Chapter 3, it was shown that a decline in fire weather variables including SSR and number of fire days per fire season in the NSW occurred over the last five decades. In the SMW an

increase was observed for the same two fire weather variables between 1960 and 2010. It was determined that in both watersheds, highest fire weather severity occurred at lower elevations, where air temperatures were generally warmer and precipitation accumulation was lower.

The purpose of this portion of the study was to assess possible changes in fire hazard throughout the study watersheds as climate change progresses. A range of climate change scenarios were selected to outline the possible changes to fire hazard that may occur. As in Chapter 3, fire hazard values were calculated at 100 m resolution in the North Saskatchewan and St. Mary watersheds.

4.2 Methods

4.2.1 Fire Weather Predictions

The GENGRID meteorological model uses climate station input data of daily precipitation, maximum air temperature, minimum air temperature, and noon-time wind speeds. The GENGRID model was used to spatially represent daily precipitation accumulation volumes, as well as values for air temperature, relative humidity, and wind speed at 12:00 p. m. local standard time (see Sheppard 1996 for further details of GENGRID and Chapter 3 for additions and refinements used in this study). The daily output from the GENGRID model was then used as input into the CFFWIS model to calculate daily values of fire weather severity, namely the daily severity rating (DSR). The fire season for this study was defined as May 1st to September 30th, when weather patterns are generally most conducive to fire ignition. For both watersheds, the seasonal severity rating (SSR) was determined by summing the DSR values for the fire season, and dividing by the total number of days within the defined fire season. The number of days

per fire season with high or extreme fire hazard were also calculated and termed *fire days*.

4.2.2 Future Climate Change: General Circulation Models

General Circulation Models (GCMs) have been selected to represent a range of possible future climates, as they are considered the most refined approach for simulating large-scale physical processes (Laprise et al., 2003). GCMs, combined with different emission scenarios, predict changes in air temperature and precipitation patterns through the year 2100. Gridded monthly and seasonal future climate projections for western North America were made available through the Pacific Climate Impacts Consortium (PCIC, 2011). The Intergovernmental Panel on Climate Change (IPCC 2007), recommends using three future normal periods for climate impact studies: the 2020s (2010-2039), the 2050s (2040-2069), and the 2080s (2070-2099). Since meteorological data were available for 2010, the future periods were adjusted by one year so that the 2020s represents 2011-2040, the 2050s represents 2041-2070, and the 2080s represents 2071-2100.

The IPCC recommends choosing a minimum of two GCM-driven climate change scenarios in order to best represent a range of possible future climates (IPCC-TGCI 1999). For this study, five GCMs were selected for each basin. The climate scenarios for this study were chosen using the method established by Barrow and Yu (2005), where scenarios are selected based on the season most important to the study. The 2050s were used as the selection period because there is too much uncertainty in climate change for the 2080s period (Barrow and Yu, 2005; Cubasch et al., 2001). Summer was deemed the season in which fire weather is most severe, thus, future scenarios were selected based on the climate changes predicted to take place in June, July, and August of the 2050s.

A scatter plot of forty-one climate scenario changes in air temperature and precipitation for the summer of the 2050s period were plotted from the data provided by PCIC for both the North Saskatchewan (Figure 4.1) and St. Mary (Figure 4.2) watersheds. The changes in air temperature and precipitation values are relative to the base period (1961 - 1990). The range in projected data represented in these scatter plots is indicative of the uncertainty of changes in future climate. The variability and uncertainties of future air temperature and precipitation changes results in part from the uncertainty of future GHG emissions and the impacts that the emissions would have on climate (Cubasch et al., 2001). From these scatter plots, five scenarios were selected using the Barrow and Yu (2005) method, where the scenario with median change in air temperature and precipitation is selected, along with four other scenarios to represent climate change extremes.

The future climate predictions presented by PCIC varied between the North Saskatchewan and St. Mary basins, so different GCMs were selected in most cases to represent the different regions. The median scenario selected for both watersheds was the CCCMA-CGCM3 A2 scenario; along with a scenario predicting conditions warmer and wetter than the median, MIROC32-MEDRES A1B for the North Saskatchewan and MIROC32-MEDRES B1 for the St. Mary; warmer and drier conditions, MIROC32-HIRES B1 (North Saskatchewan) and MIROC32-MEDRES B1 (St. Mary); cooler and wetter conditions, CSIRO-MK30 B1 (both watersheds); and cooler and drier conditions, BCCR-BCM20 A2 (North Saskatchewan) and INMCM30-B1 (St. Mary). This method allows for a range of possible air temperature and precipitation changes to be used when predicting future fire hazard. For the purpose of simplicity, the climate change models used in this study were named NS 1-5 and SM 1-5, as outlined in Table 4.1.

Table 4.1: Climate change scenarios selected for this study, including the future climate description with respect to the median scenario, the name of the corresponding GCM, and the abbreviated name given to each of the climate change scenarios.

Climate Description	NSW GCM	NSW GCM (shorthand notation)	SMW GCM	SMW GCM (shorthand notation)
Cool, wetter	CSIRO MK30 (B1)	NS1	CSIRO MK30 (B1)	SM1
Cool, dryer	BCCR BCM20 (A2)	NS2	INMCM30 (B1)	SM2
Median	CCCMA CGCM3 (A2)	NS3	CCCMA CGCM3 (A2)	SM3
Warm, wetter	MIROC32 MEDRES (A1B)	NS4	MIROC32 MEDRES (B1)	SM4
Warm, dryer	MIROC32 HIRES (B1)	NS5	MIROC32 MEDRES (A2)	SM5

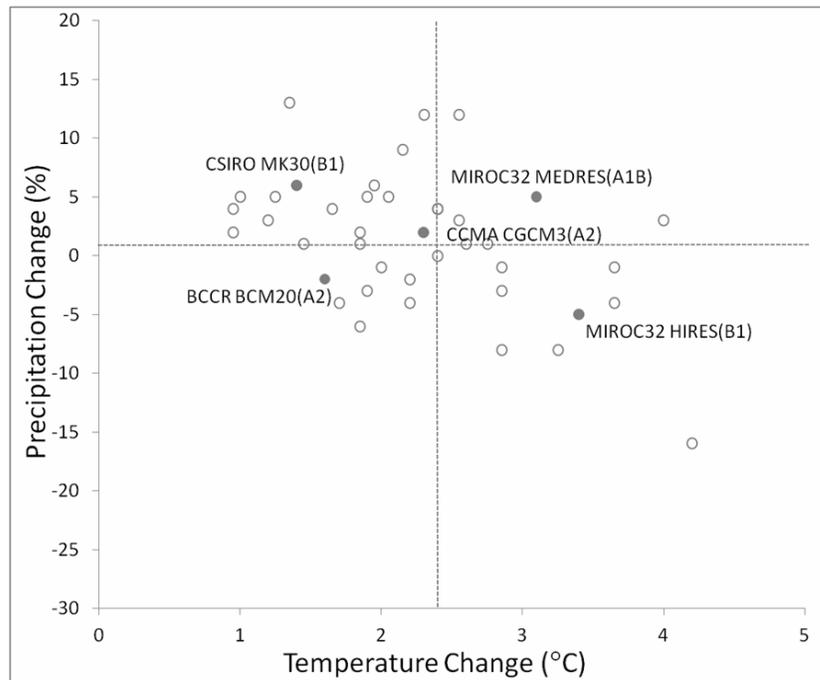


Figure 4.1: GCM projected mean air temperature and precipitation changes for the summer 2050s period for the NSW.

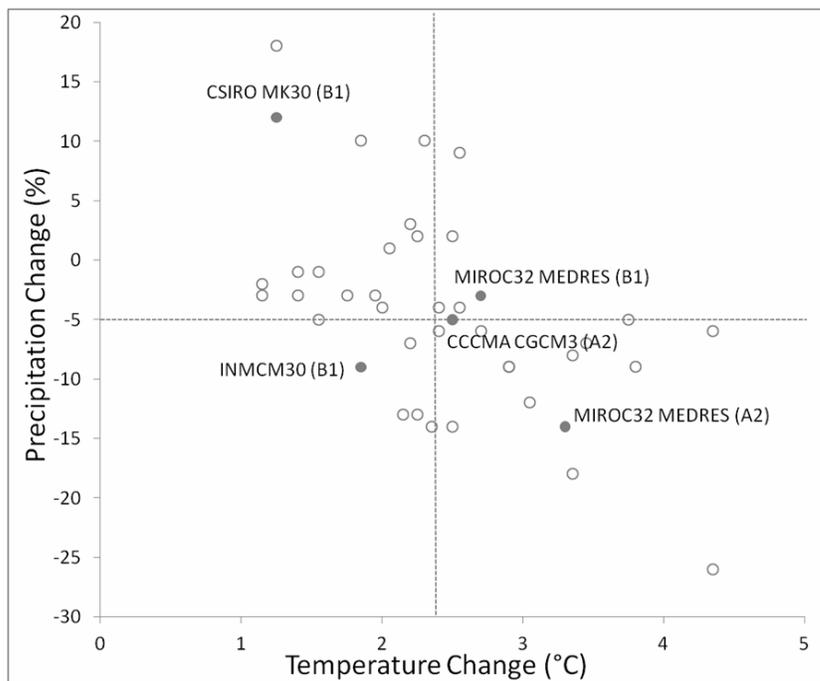


Figure 4.2: GCM projected mean air temperature and precipitation changes for the summer 2050s period for the SMW.

Projections for the monthly changes in maximum and minimum air temperatures, and monthly percent changes for precipitation, were made available by PCIC (2011). The seasonal changes predicted by the selected climate change scenarios are presented in Tables 4.2 (North Saskatchewan) and 4.3 (St. Mary). With minor exceptions for the 2020s period, the climate scenarios predict increases in maximum and minimum air temperature through the year 2100 for both watersheds. By the 2080s, the amount of increase in maximum air temperature for the summer months ranged from 1.5 °C to 5.4 °C in the NSW and 1.5 °C to 5.7 °C in the SMW. The minimum air temperature values ranged from 1.8 °C to 4.6 °C in the NSW and 1.4 °C to 5.0 °C in the SMW. Projected precipitation changes were much more variable throughout the two watersheds. Average summer changes in precipitation ranged from -11% to +8% in the NSW and -14% to +15% in the SMW. A monthly assessment of the GCM projections shows possible precipitation changes from -39% to +25% in certain summer months, however, these values were lessened in extremity when averaged over the entire summer period.

In order to apply the GCM data, monthly temperature and precipitation changes for each time period were applied to the daily base period dataset to represent possible future climates in the 2020s, 2050s, and 2080s. A Fourier transform was performed on the temperature data to smooth the temperature changes before adding them to the base period dataset. The precipitation changes were applied as percentages, so the number of days with precipitation did not change, however, the amount of precipitation received on the reference days were altered. Using the adjusted datasets, the SSR and the number of fire days were estimated for each fire season from 2011 - 2100 for the five GCMs selected in both watersheds.

Table 4.2: Five GCM seasonal projections for the NSW for the 2020s, 2050s, and 2080s. Minimum and maximum air temperature increases and precipitation percent changes are presented.

Climate Change Scenario	Time Period	Climate Index Variable	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)
NS1	2020s	ΔT_x (°C)	0.2	0.1	0.3	0.9
		ΔT_n (°C)	0.2	0.4	0.7	1.0
		ΔP (%)	6	9	6	3
	2050s	ΔT_x (°C)	0.1	0.7	1.3	1.6
		ΔT_n (°C)	1.6	1.1	1.5	1.7
		ΔP (%)	11	11	4	3
	2080s	ΔT_x (°C)	1.3	1.0	1.5	2.0
		ΔT_n (°C)	2.2	1.3	1.8	2.1
		ΔP (%)	15	11	3	5
NS2	2020s	ΔT_x (°C)	0.4	0.4	0.6	0.8
		ΔT_n (°C)	0.7	0.3	0.6	1.1
		ΔP (%)	8	-1	3	6
	2050s	ΔT_x (°C)	1.3	0.5	1.9	1.7
		ΔT_n (°C)	1.8	0.7	1.3	1.5
		ΔP (%)	14	4	-2	0
	2080s	ΔT_x (°C)	2.2	1.6	3.8	3.0
		ΔT_n (°C)	3.0	2.0	3.1	3.1
		ΔP (%)	16	10	0	17
NS3	2020s	ΔT_x (°C)	2.1	1.0	0.8	1.7
		ΔT_n (°C)	2.6	1.6	1.2	2.0
		ΔP (%)	7	8	8	3
	2050s	ΔT_x (°C)	3.0	1.6	2.2	2.3
		ΔT_n (°C)	3.6	2.5	2.4	2.4
		ΔP (%)	18	18	2	12
	2080s	ΔT_x (°C)	4.3	2.9	3.8	3.7
		ΔT_n (°C)	5.3	4.3	3.8	4.2
		ΔP (%)	24	25	1	22
NS4	2020s	ΔT_x (°C)	1.4	2.1	1.9	1.2
		ΔT_n (°C)	1.9	2.3	1.7	1.2
		ΔP (%)	6	3	-1	5
	2050s	ΔT_x (°C)	3.0	2.8	3.1	3.0
		ΔT_n (°C)	4.2	3.2	3.1	2.9
		ΔP (%)	15	10	5	18
	2080s	ΔT_x (°C)	4.4	4.2	5.4	4.3
		ΔT_n (°C)	6.3	4.5	4.6	4.3
		ΔP (%)	26	16	-11	24
NS5	2020s	ΔT_x (°C)	1.9	2.5	2.8	2.0
		ΔT_n (°C)	2.6	2.9	2.3	1.9
		ΔP (%)	10	8	-7	0
	2050s	ΔT_x (°C)	2.8	3.3	3.6	3.0
		ΔT_n (°C)	3.9	4.2	3.2	2.9
		ΔP (%)	13	22	-4	13
	2080s	ΔT_x (°C)	3.8	4.5	4.4	3.8
		ΔT_n (°C)	5.2	5.2	3.9	3.8
		ΔP (%)	7	22	-10	16

Table 4.3: Five GCM seasonal projections for the SMW for the 2020s, 2050s, and 2080s. Minimum and maximum air temperature increases and precipitation percent changes are presented.

Climate Change Scenario	Time Period	Climate Index	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)
SM1	2020s	ΔT_x (°C)	0.3	0.2	0	1.0
		ΔT_n (°C)	0.5	0.4	0.6	0.9
		ΔP (%)	1	4	15	-2
	2050s	ΔT_x (°C)	1.0	0.9	1.1	1.6
		ΔT_n (°C)	2.0	1.0	1.4	1.5
		ΔP (%)	-2	6	11	-1
	2080s	ΔT_x (°C)	1.6	1.2	1.5	2.1
		ΔT_n (°C)	2.8	1.3	1.8	1.9
		ΔP (%)	3	5	8	-9
SM2	2020s	ΔT_x (°C)	1.0	1.0	1.8	1.0
		ΔT_n (°C)	1.3	1.5	0.5	1.0
		ΔP (%)	5	15	-12	10
	2050s	ΔT_x (°C)	2.9	1.4	2.6	2.3
		ΔT_n (°C)	3.6	2.3	1.0	2.1
		ΔP (%)	15	17	-10	10
	2080s	ΔT_x (°C)	3.3	2.0	3.3	2.9
		ΔT_n (°C)	4.3	2.7	1.4	2.6
		ΔP (%)	17	19	-13	9
SM3	2020s	ΔT_x (°C)	1.6	0.6	1.9	1.5
		ΔT_n (°C)	2.1	0.8	1.4	1.7
		ΔP (%)	10	4	-9	1
	2050s	ΔT_x (°C)	3.2	1.3	2.6	2.5
		ΔT_n (°C)	4.1	2.2	2.4	2.5
		ΔP (%)	21	20	-5	5
	2080s	ΔT_x (°C)	4.3	2.8	4.4	3.5
		ΔT_n (°C)	5.7	3.9	4.2	4.0
		ΔP (%)	33	18	-0	21
SM4	2020s	ΔT_x (°C)	0.2	1.4	1.9	1.4
		ΔT_n (°C)	1.8	1.8	1.4	1.2
		ΔP (%)	3	11	-8	3
	2050s	ΔT_x (°C)	2.2	2.6	2.8	2.2
		ΔT_n (°C)	3.3	2.9	2.6	2.2
		ΔP (%)	9	13	-4	19
	2080s	ΔT_x (°C)	2.8	3.4	4.0	3.0
		ΔT_n (°C)	4.3	4.0	3.6	3.0
		ΔP (%)	11	19	-4	16
SM5	2020s	ΔT_x (°C)	1.6	1.2	1.5	0.8
		ΔT_n (°C)	2.0	1.7	1.3	1.0
		ΔP (%)	-0	8	-4	14
	2050s	ΔT_x (°C)	2.6	3.2	3.6	2.8
		ΔT_n (°C)	3.8	3.5	3.0	2.5
		ΔP (%)	9	13	-14	7
	2080s	ΔT_x (°C)	4.3	4.9	5.7	4.2
		ΔT_n (°C)	6.3	5.5	5.0	3.9
		ΔP (%)	17	25	-11	9

4.2.3 Future Climate Change: Sensitivity Analysis

A sensitivity analysis was performed to determine the effects of incremental changes in air temperature and precipitation on SSR. This was done using an array of standard air temperature and precipitation changes that could potentially take place in the study watersheds. Integral air temperature increases between 0 °C and 5 °C, and precipitation changes between -20 % and +20 % were applied to the base period data at the Bighorn Dam (NSW) and St. Mary (SMW) climate stations. The same air temperature increase values were applied to both the minimum and maximum air temperatures for this analysis. From there, the midday air temperatures were calculated. The mean SSR values for the base period, and the mean SSR values assuming the multiple air temperature and precipitation changes, were calculated at both locations. The difference between the possible climate changes and the historical climate data were determined.

4.3 Results

4.3.1 Fire Hazard in the NSW using GCMs

Mean SSR values for forested regions in the NSW were calculated for the 2020s, 2050s, and 2080s for each of the five selected GCM-driven climate change scenarios. The mean SSRs were evaluated at elevations of 1500 m, 2000 m, and 2500 m. The future predicted SSR values were compared to the base period SSR mean (Figure 4.3). Under all five climate change scenarios chosen, the predicted mean SSR values progressively increased throughout the three future time periods. NS1 was consistently the scenario with the lowest SSR, however, future fire weather severity was still predicted to be greater than the base period. These results indicate that future increases in summer

precipitation could be offset by relatively small increases in air temperature and result in greater fire hazard. The NS5 scenario, which projected the warmest and driest climate for the summer 2050s period, was the scenario expected to exhibit the greatest fire hazard. However, this was only true for the 2020s and 2050s. The predictions made for the 2080s period portrayed NS4 as the scenario with the greatest mean SSR. The reason for this shift was due to the greater increase in summer 2080s temperatures for the NS4 scenario relative to the NS5 scenario. The NS2 and NS3 scenarios consistently predicted SSR values greater than the NS1 scenario, but less than the NS4 and NS5 scenarios. At 1500 m elevation, the greatest SSR projection was a value of over seven; this was near double the base period SSR.

The patterns predicted for changes in the future number of fire days were similar to the patterns in future SSR (Figure 4.4). The exception was for the NS1 scenario, where the number of fire days in the 2020s period had a lower count than the base period at elevations of 1500 m and 2000 m. However, assuming NS1 climate conditions, an increase is prospective in the number of fire days at all elevations by the 2050 and 2080 time periods. Once again, the NS4 and NS5 climate scenarios predict the greatest future fire hazard, with projections of more than fifty fire days per season (at 1500 m) by the 2080s. The NS2 and NS3 scenarios predict greater numbers of seasonal fire days than NS1, but fewer than the NS4 and NS5 scenarios.

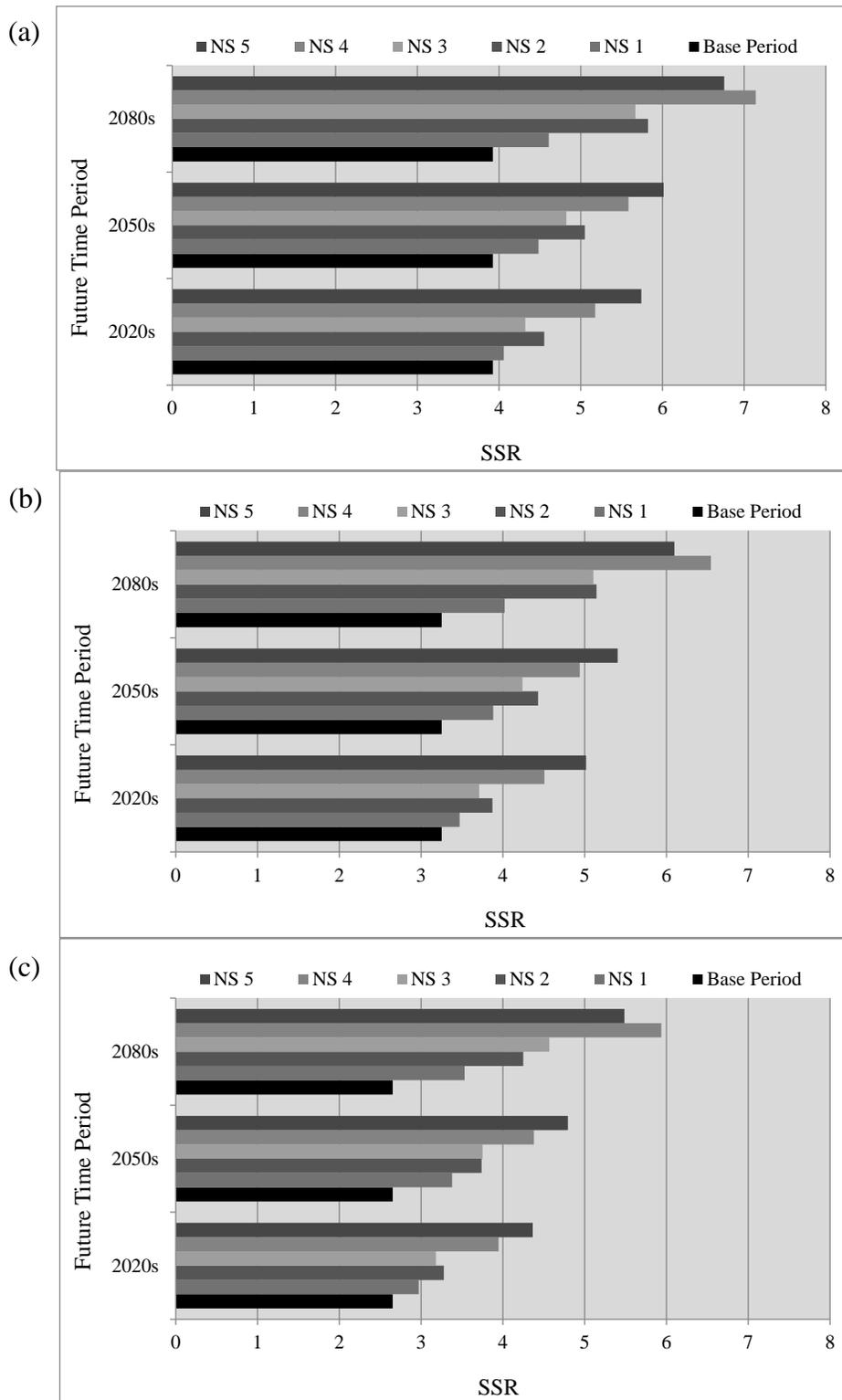


Figure 4.3: Mean SSR values for the base period, and the mean predicted SSR values for three future time periods (2020s, 2050s, and 2080s) using the five selected climate change scenarios in the NSW at elevations of (a) 1500m, (b) 2000m, and (c) 2500m.

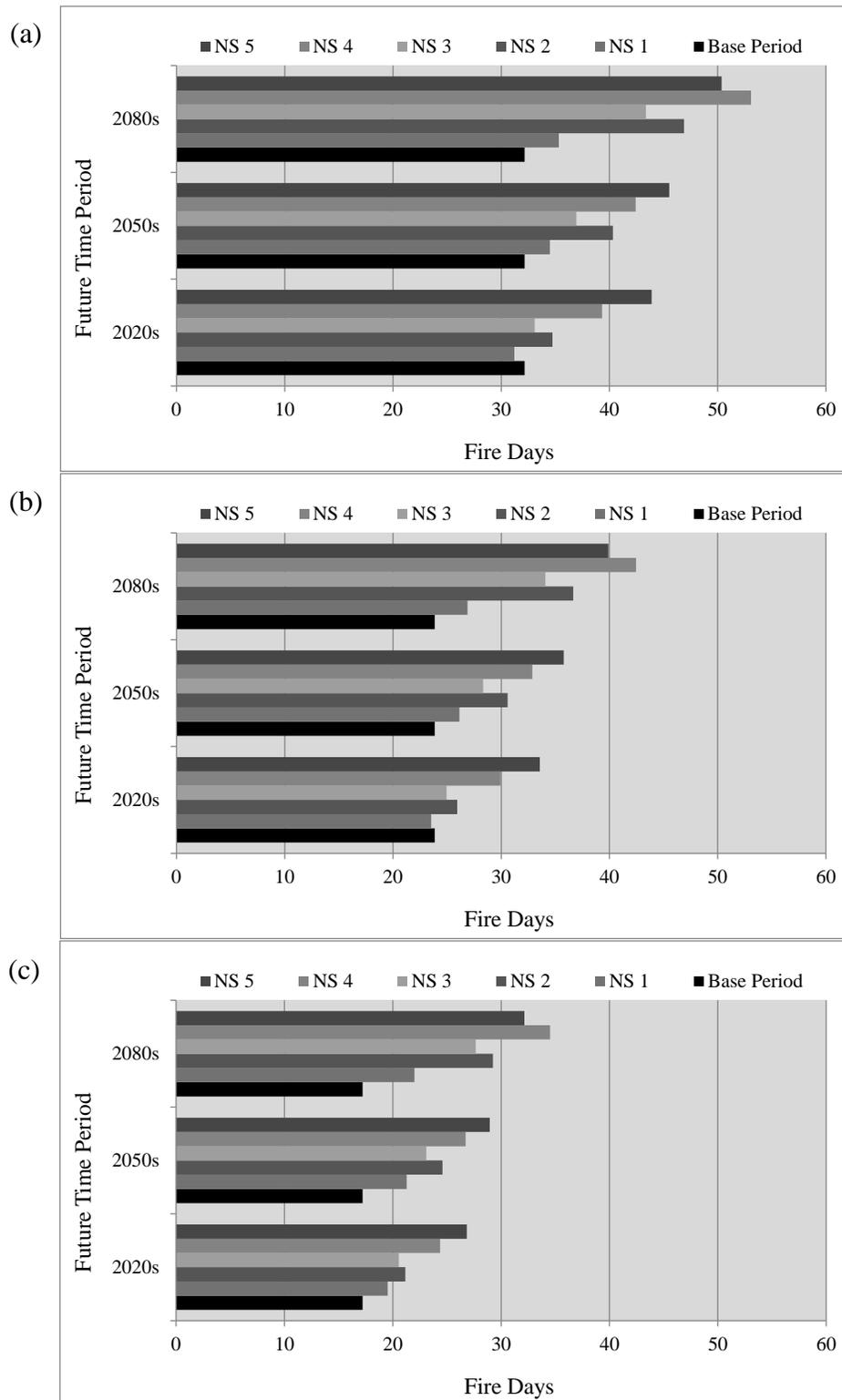


Figure 4.4: Mean number of fire days per fire season for the base period, and the mean predicted number of fire days per fire season for three future time periods (2020s, 2050s, and 2080s) using the five selected climate change scenarios in the NSW at elevations of (a) 1500m, (b) 2000m, and (c) 2500m.

The amount of change in SSR (Figure 4.5) and number of fire days (Figure 4.6) were determined spatially across the watershed from 1960 to 2100, under all five climate change scenarios. The values were expressed in amount of change per decade. In general, the greatest change in fire hazard regime was exhibited at the lower elevations. These were the areas that historically observed greater fire hazard. The NS1 and NS3 scenarios showed the least total change in SSR. These were also the scenarios that showed the smallest increase in number of fire days per decade, although, the NS3 scenario did show a greater increase than the NS1 scenario. The other three scenarios showed more overall change in both SSR and fire days. The NS5 scenario predicted the greatest overall change in both fire hazard indices. Although the fire hazard projections for the NS2 scenario were not as great as the projections for the NS5 scenario, greater overall change was predicted under the NS2 scenario. This can be attributed to the projected climates for the different time periods. While the NS2 scenario had relatively small gains in the SSR and the number of fire days in the 2020s, large gains were projected by the 2080s. By contrast, the NS5 scenario projected relatively high fire hazard for the 2020s, then smaller gains were seen through to the 2080s.

The trends in SSR and number of fire days from 1960 to 2100 were analysed using the Mann-Kendall test at the 1500 m, 2000 m, and 2500 m elevation bands. The statistics indicated that all trends were positive. Significance was tested at the 95% and 99% confidence levels. While all trends were found to be positive, not all trends were significant. Table 4.4 outlines the greatest significance level, α , of the trends under each of the climate change scenarios.

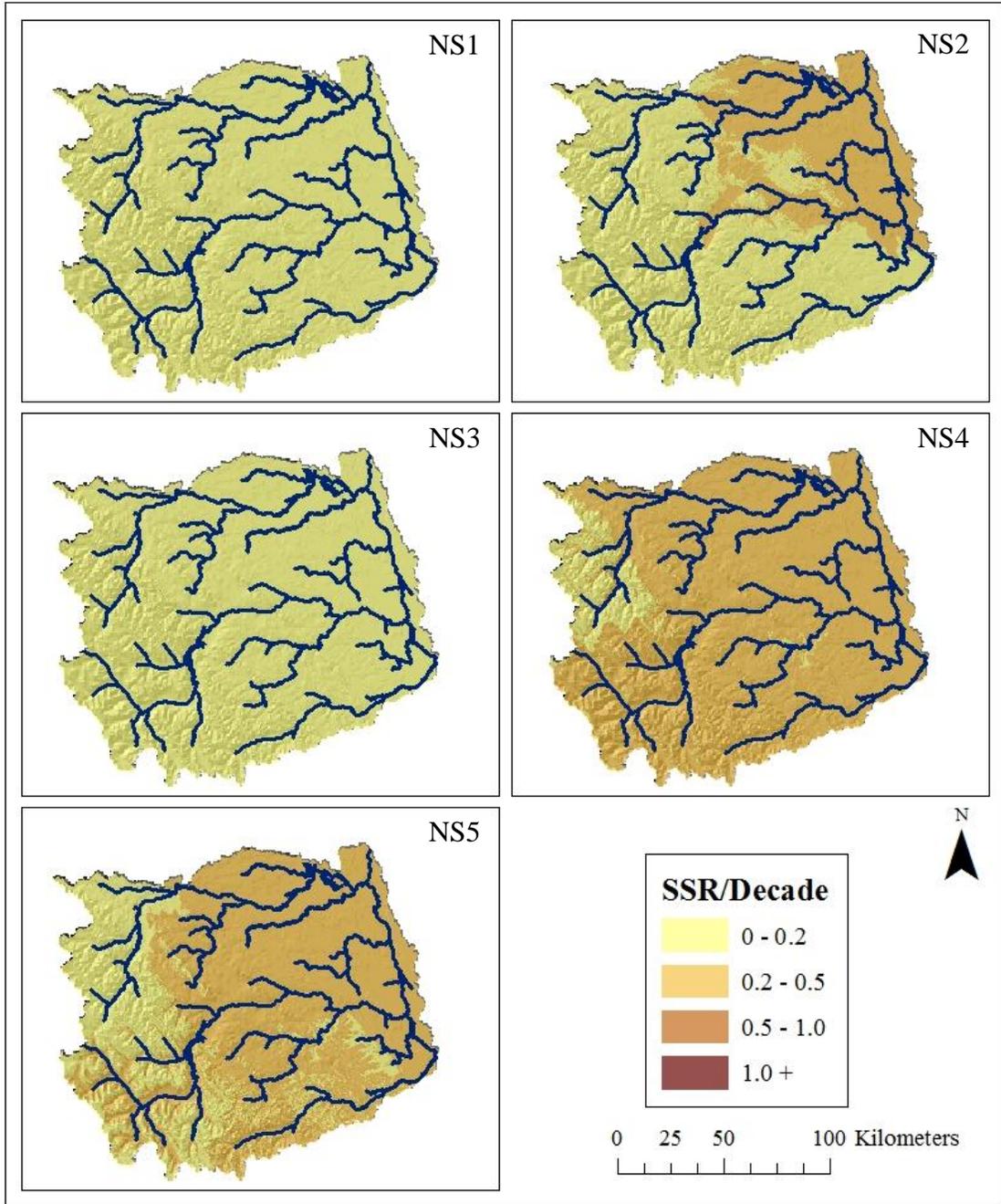


Figure 4.5: Overall projected change in SSR values from 1960-2100 under the five selected climate change scenarios in the NSW. Values are presented in the change in SSR per decade.

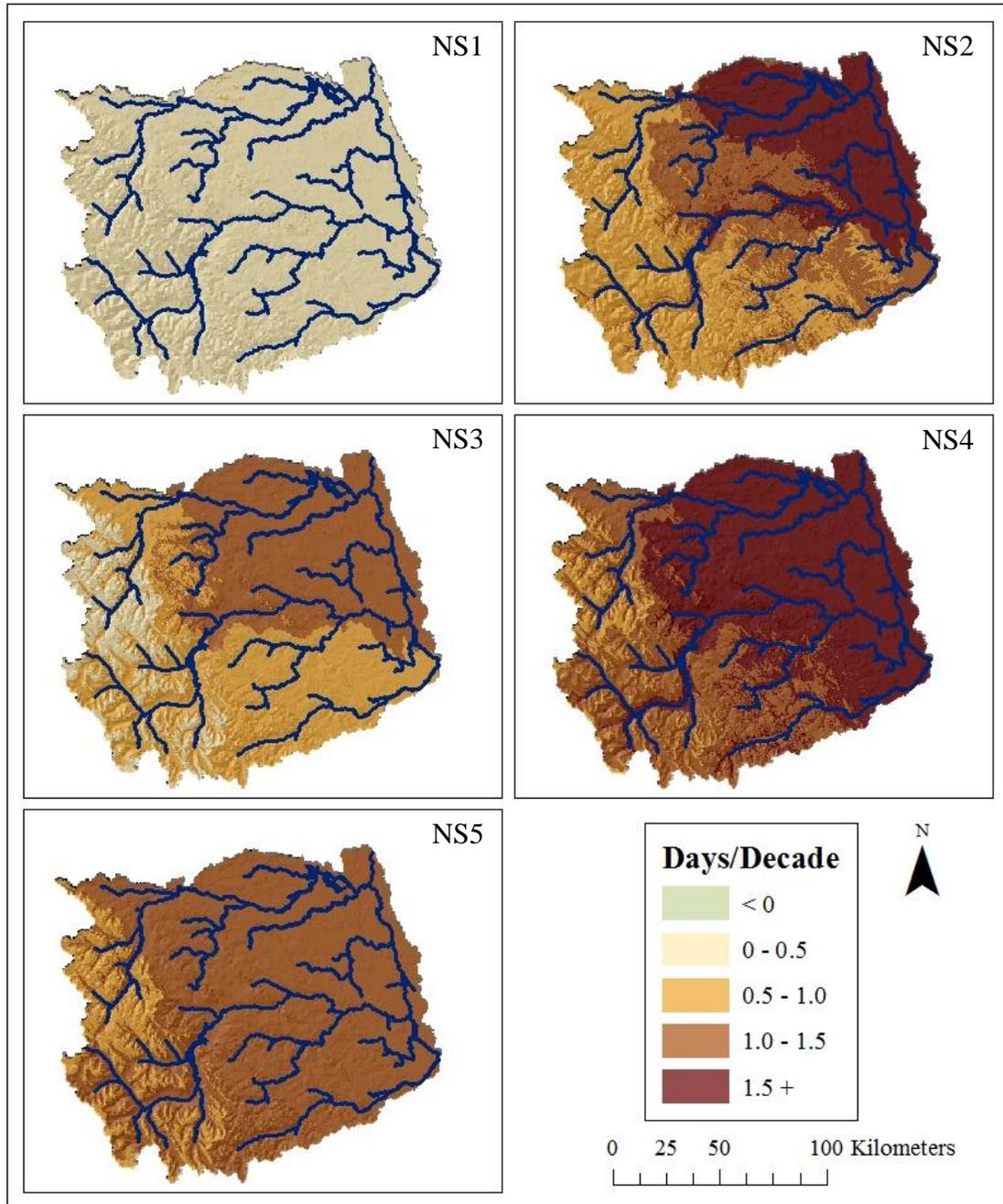


Figure 4.6: Overall projected change in number of fire days per fire season from 1960-2100 under the five selected climate change scenarios in the NSW. Values are presented in the change in number of fire days per decade.

Table 4.4: Trend statistics from 1960-2100 in the NSW using the Mann-Kendall test. The highest significance level, α , is presented. A hyphen indicates the trend was not significant at the 95% or 99% confidence levels.

	Elevation	NS1	NS2	NS3	NS4	NS5
SSR	1500 m	-	0.01	0.01	0.01	0.01
	2000 m	-	0.01	0.01	0.01	0.01
	2500 m	-	0.05	0.01	0.01	0.01
Fire Days	1500 m	-	0.01	-	0.01	0.01
	2000 m	-	0.01	0.05	0.01	0.01
	2500 m	-	0.01	-	0.01	0.01

4.3.2 Fire Hazard using GCMs in the SMW

The same fire hazard variables that were calculated for the NSW were calculated for the SMW. Future projections portrayed the SSR and the number of fire days in the SMW to be greater than the base period average SSR values for all GCM-driven climate change scenarios. Both variables reported greatest fire hazard at lower elevations, and lowest fire hazard at the higher elevations. As with the NSW, the mean SSR values (Figure 4.7) and the mean total fire days (Figure 4.8) were analyzed in the forested regions at elevations of 1500 m, 2000 m, and 2500 m.

The SM1 scenario, which forecasted the coolest and wettest future climate, had the lowest SSR of all five scenarios, yet was still greater than the base mean SSR. The scenario chosen to represent the warmest and driest future climate, SM5, predicted the highest SSR for the 2050s and 2080s. However, the SM3 scenario predicted the greatest SSR for the 2020s. It was only for the 2050s period that the median climate change scenario resulted as the scenario with the median SSR. In the summer of the 2020s, the SM3 scenario had relatively low precipitation estimates, and in the summer 2080s had relatively high air temperature estimates. As a result, there was limited consistency

between the rankings of SSR values throughout the three future time periods. This was due to the varying air temperature and precipitation changes predicted by the GCMs throughout the three future time periods.

The number of fire days followed similar patterns to the future SSR projections. The greatest numbers of fire days were present at lower elevations, where air temperatures were known to be greatest and precipitation accumulations smallest. Once again, SM1 was the scenario with the fewest projected number of seasonal fire days at all elevations, however, this number was still greater than the base period mean. Throughout the three future time periods, the rank of the climate scenarios with respect to the number of fire days did not stay consistent due to the varying climate projections for the 2020s, 2050s, and 2080s.

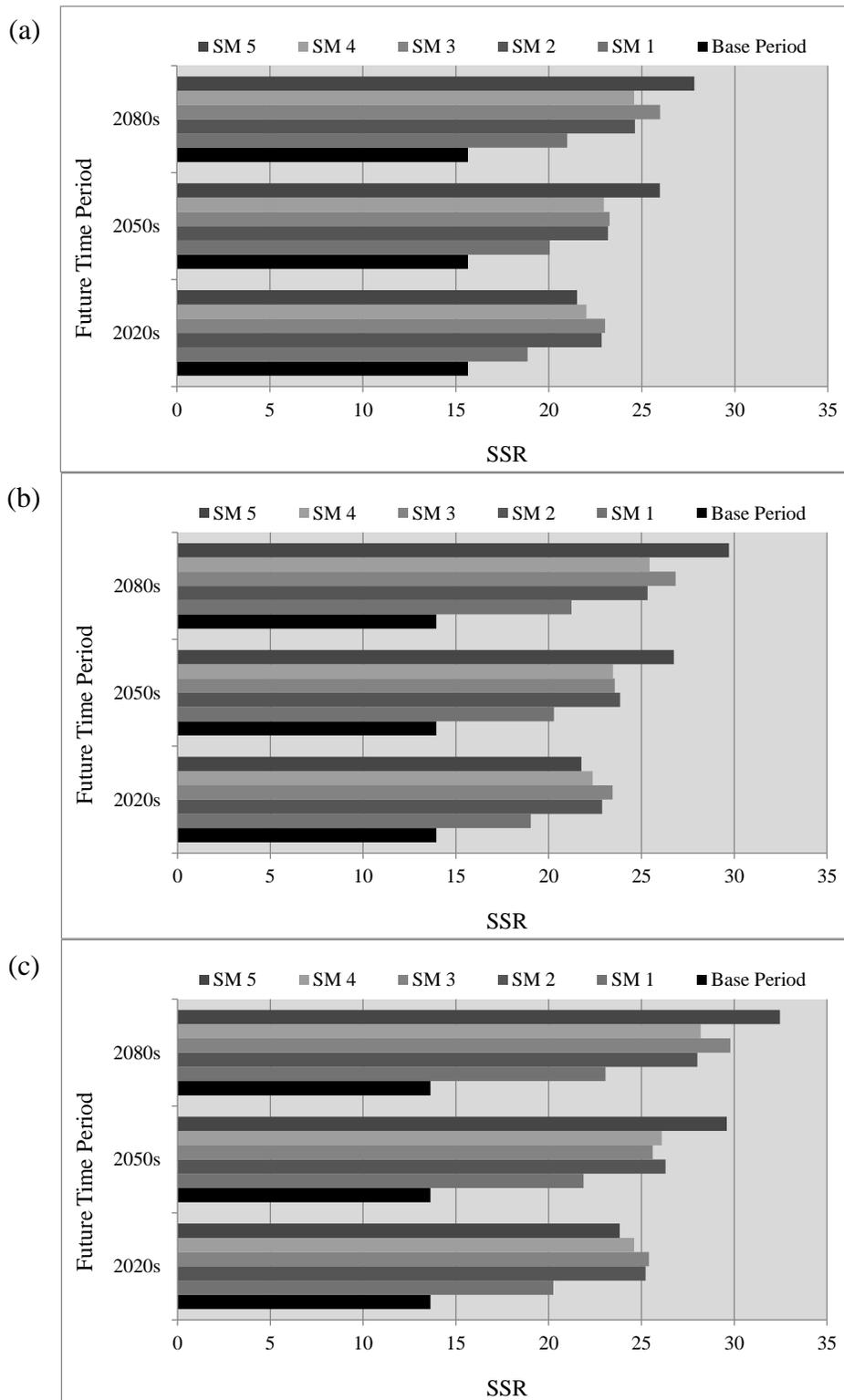


Figure 4.7: Mean SSR values for the base period, and the mean predicted SSR values for three future time periods (2020s, 2050s, and 2080s) using the five selected climate change scenarios in the SMW at elevations of (a) 1500 m, (b) 2000 m, and (c) 2500 m.

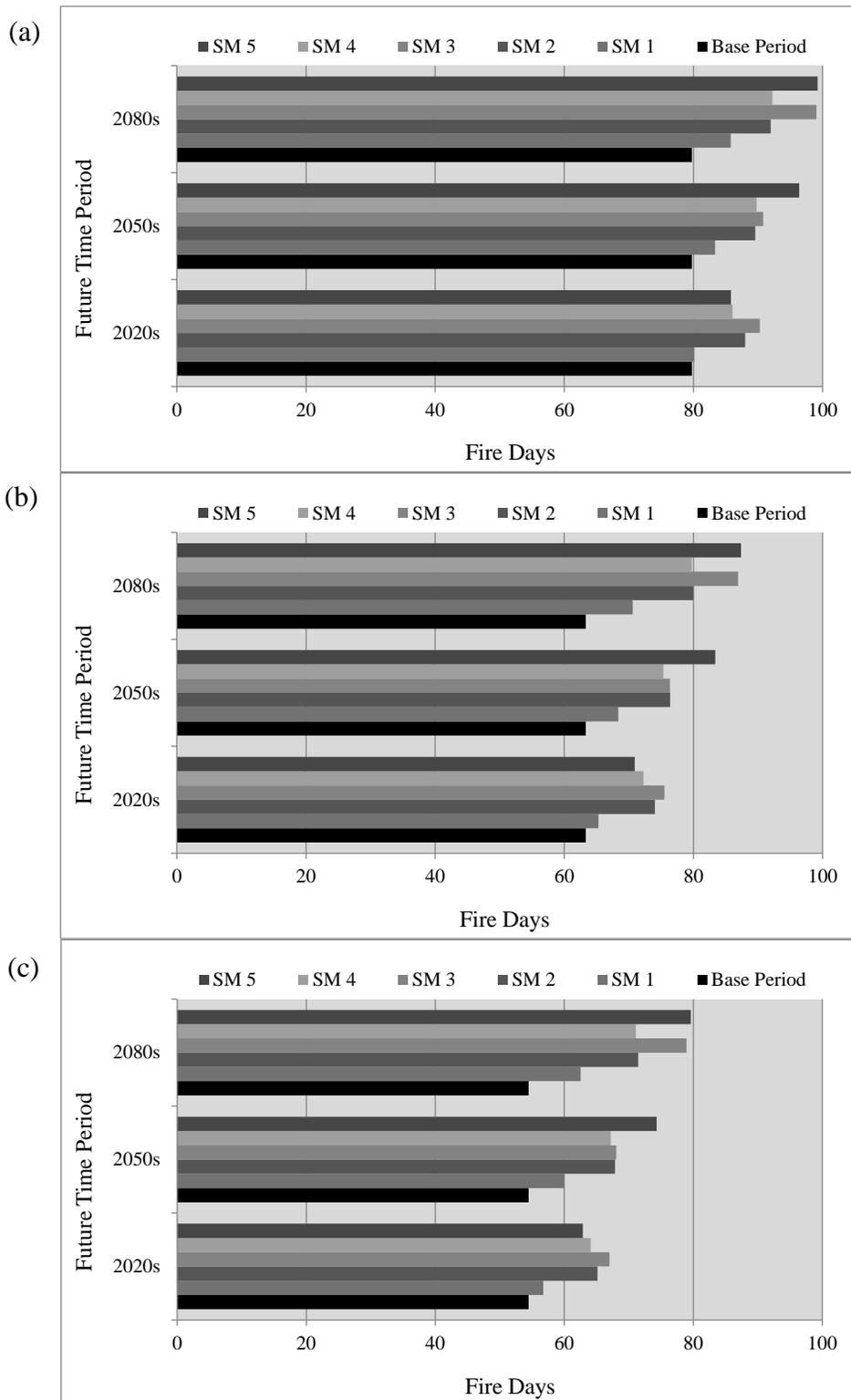


Figure 4.8: Mean number of fire days per fire season for the base period, and the mean predicted number of fire days per fire season for three future time periods (2020s, 2050s, and 2080s) using the five selected climate change scenarios in the SMW at elevations of (a) 1500m, (b) 2000m, and (c) 2500m.

The amount of change in the fire hazard variables that was projected for the period of 1960 to 2100 was determined spatially across the watershed. Although it had been determined that greater fire hazard was predicted in lower regions, the areas at higher elevations were found to have a greater degree of change per decade than lower regions. This held true for both SSR (Figure 4.9) and the seasonal count of fire days (Figure 4.10). The SM1 scenario saw the least amount of change in SSR and number of fire days. Under this scenario, some regions were found to slightly decline in the number of fire days. Most of these areas were at high elevations and often had north facing slopes. Although some areas were found to decline in the number of fire days under this scenario, most areas within the basin were found to increase in number of fire days from 1960 through the year 2100. The SM5 scenario predicted the greatest amount of change throughout the watershed for both fire hazard indices. The remaining three climate scenarios predicted change within the bounds outlined by the SM1 and SM5 scenarios.

Statistical analysis was performed using the Mann-Kendall test to investigate the future trends (Table 4.5). For each of the elevation bands examined, the trends were found to be positive, meaning that forecasted fire hazard increased through 2100. However, many of these trends were not found to be statistically significant. This can be attributed to the high fire hazard values in the 1990s and the 2000s relative to the base period (see Chapter 3). The SM1 scenario trends were not found to be significant at the 95% or 99% confidence levels. SM5 was the only scenario to predict a statistically significant trend at all tested altitudes for SSR and seasonal fire days over time.

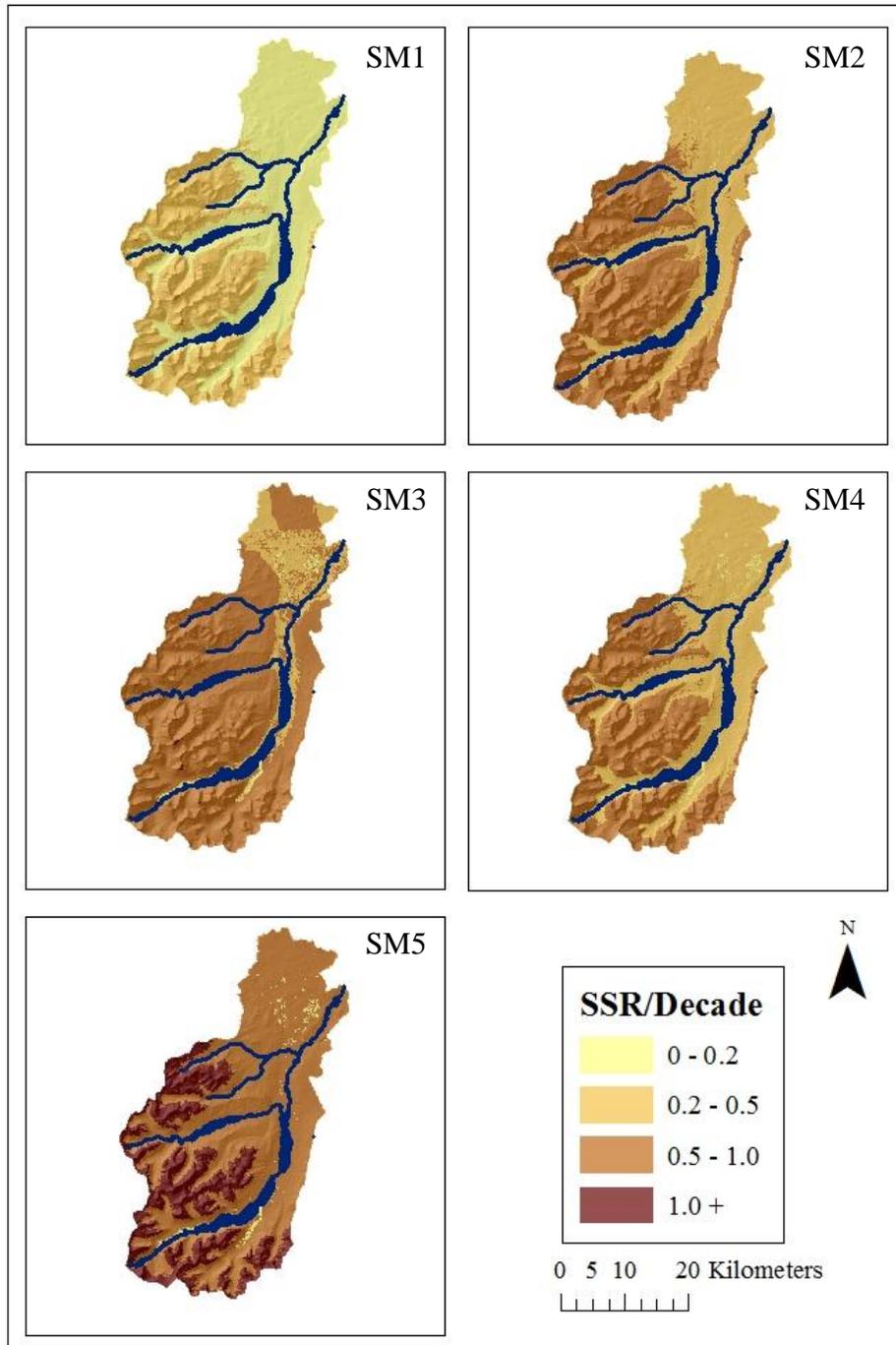


Figure 4.9: Overall projected change in SSR values from 1960-2100 under the five selected climate change scenarios in the SMW. Values are presented in the change in SSR values per decade.

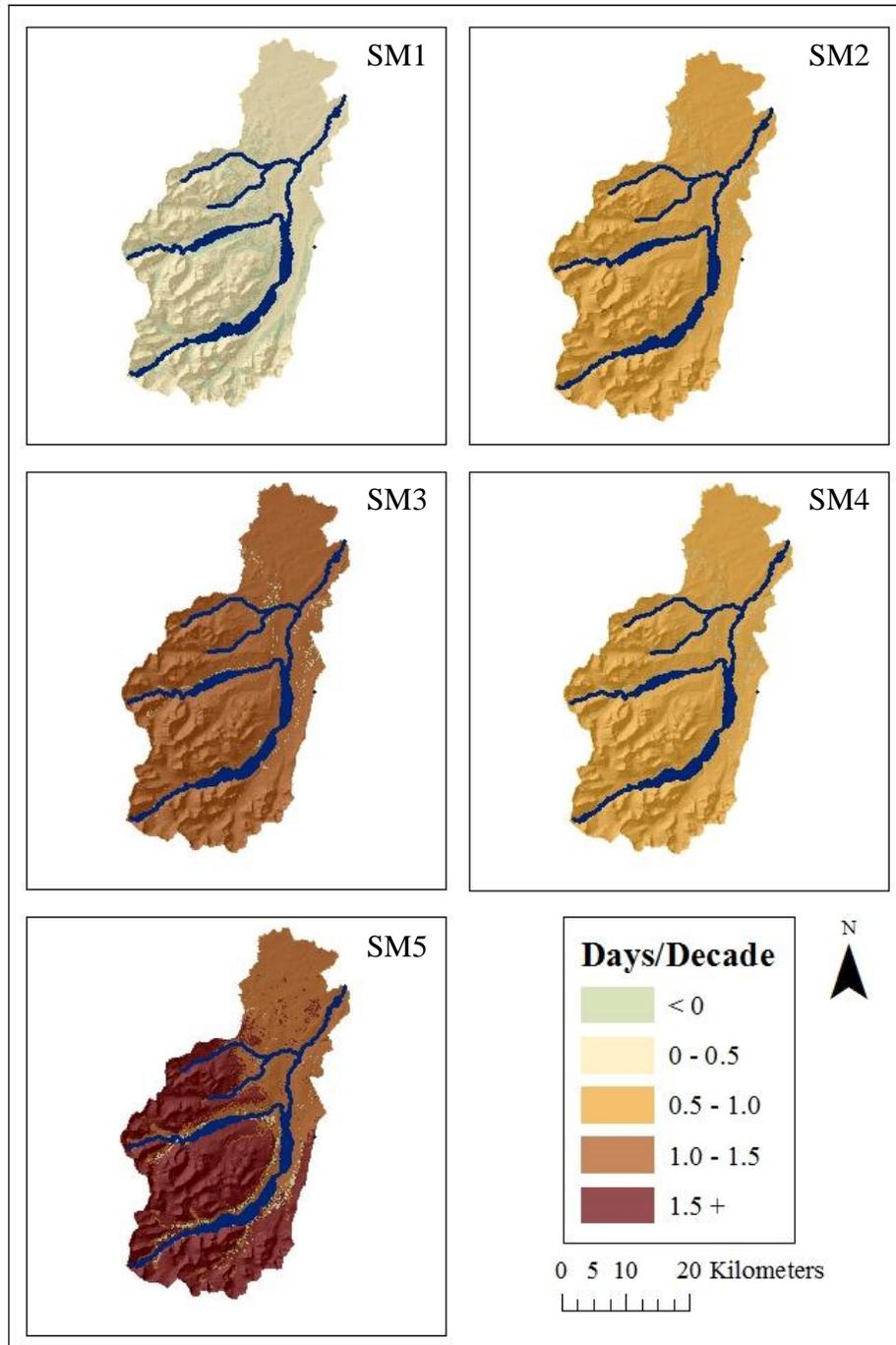


Figure 4.10: Overall projected change in number of fire days per fire season from 1960-2100 under the five selected climate change scenarios in the SMW. Values are presented in number of fire days per decade.

Table 4.5: Trend statistics from 1960-2100 in the SMW using the Mann-Kendall test. The highest significance level, α , is presented. A hyphen indicates the trend was not significant at the 95% or 99% confidence levels.

	Elevation	SM1	SM2	SM3	SM4	SM5
SSR	1500 m	-	-	-	-	0.01
	2000 m	-	-	0.05	-	0.01
	2500 m	-	-	0.05	-	0.01
Fire Days	1500 m	-	-	0.01	-	0.01
	2000 m	-	0.05	0.01	0.05	0.01
	2500 m	-	0.05	0.01	0.05	0.01

4.3.3 Sensitivity Analysis Comparison

Step-wise changes in air temperature and precipitation were applied to the base period datasets for the North Saskatchewan and St. Mary watersheds. Incremental air temperature increases between 1 °C and 5 °C, and precipitation changes between -20% and +20% were added to the base period data. In addition, the SSR was calculated for changes in precipitation without an increase in air temperature to examine the effects of changing precipitation on fire hazard. The differences between the base period SSR and the SSR under climate change were calculated for the NSW (Table 4.6) and the SMW (Table 4.7). In most cases the same climate changes would likely result in greater SSR increases in the SMW where historical values were already greater than the NSW. When a 1°C increase in air temperature and a 10% increase in precipitation were applied, a slightly greater increase in SSR was predicted for the NSW than the SMW. In the case of a 1°C increase in maximum and minimum air temperatures and a 20% increase in precipitation, both watersheds show a decline in SSR with a slightly greater decline occurring in the SMW. For every increase in predicted SSR, the NSW demonstrated a greater percent increase than the SMW, although SSR values were still lower in the NSW. In the most extreme fire weather projections (5°C air temperature

increase and 20% precipitation decrease) estimations for SSR were shown to increase by 3.7 units overall in the NSW and by 7.3 units in the SMW, which represents increases of 94% and 55%, respectively.

This analysis was found to be a useful tool for determining the sensitivity of forest fire hazard to changing climates. It also allowed for comparisons between the two study watersheds as the same degree of change in climate variables were assessed. The downfall in using this method was that the same temperature and precipitation changes were applied every day between May 1st and September 30th when it is common in future climate change studies, for the changes in air temperature and precipitation to vary monthly.

Table 4.6: Sensitivity analysis of SSR at Bighorn Dam in the NSW under an array of air temperature and precipitation changes, showing the change in SSR units and percent change.

		ΔT					
		+0 °C	+1 °C	+2 °C	+3 °C	+4 °C	+5 °C
ΔP	-20%	+0.8 (+20%)	+1.3 (+34%)	+1.8 (+47%)	+2.4 (+62%)	+3.0 (+77%)	+3.7 (+94%)
	-10%	+0.4 (+10%)	+0.9 (+22%)	+1.3 (+34%)	+1.8 (+47%)	+2.4 (+61%)	+3.0 (+77%)
	0%	0 (0%)	+0.4 (+11%)	+0.9 (+22%)	+1.4 (+35%)	+1.9 (+47%)	+2.4 (+61%)
	+10%	-0.3 (-8%)	+0.1 (+3%)	+0.6 (+14%)	+1.0 (+25%)	+1.4 (+37%)	+1.9 (+49%)
	+20%	-0.5 (-13%)	-0.1 (-3%)	+0.3 (+8%)	+0.7 (+18%)	+1.1 (+29%)	+1.6 (+40%)

Table 4.7: Sensitivity analysis of SSR at St. Mary in the SMW under an array of air temperature and precipitation changes, showing change in SSR units and percent change.

		ΔT					
		+0 °C	+1 °C	+2 °C	+3 °C	+4 °C	+5 °C
ΔP	-20%	+2.2 (+17%)	+3.2 (+24%)	+4.2 (+32%)	+5.2 (+39%)	+6.3 (+48%)	+7.3 (+55%)
	-10%	+1.0 (+8%)	+1.8 (+14%)	+2.7 (+21%)	+3.6 (+27%)	+4.6 (+34%)	+5.6 (+42%)
	0%	0 (0%)	+1.0 (+8%)	+1.8 (+13%)	+2.8 (+21%)	+3.6 (+27%)	+4.6 (+34%)
	+10%	-0.7 (-5%)	+0.2 (+1%)	+0.9 (+7%)	+1.9 (14%)	+2.8 (+21%)	+3.7 (+28%)
	+20%	-1.1 (-8%)	-0.4 (-3%)	+0.3 (+2%)	+1.1 (+8%)	+2.1 (+16%)	+3.0 (+22%)

4.4 Discussion

There are a number of uncertainties in projecting future fire hazard in the methods presented here. As demonstrated by the multiple GCM climate predictions from PCIC, a wide range of temperature and precipitation patterns are possible. The method used to perturb precipitation is a known source of error. By only adjusting the amount of precipitation in a given event, and not changing the number of days per season that received precipitation, the number of future fire days may be affected. That is, if more days receive precipitation than was experienced historically, there may be more days in future years with conditions too wet for fires to burn. No changes were made to future wind speeds, due to the greater uncertainties that that would present. This study has

demonstrated that depending on the scenario, fire hazard response could greatly vary. Although, based on the results from this study with minor exceptions, the fire hazard in both watersheds is likely to increase. The uncertainty lies in the amount of increase in fire hazard that could take place.

The range of future fire hazard values demonstrated in this study are consistent with results presented in other studies across North America that used the CFFWIS. The FWI is generally expected to increase as climate warms from a doubled CO₂ concentration (Flannigan et al., 2001). In west-central Alberta, a doubled CO₂ scenario would increase the FFMC by one point, which could have a substantial impact on fire activity (Li et al., 2000). An average increase of 46% in SSR was predicted across Canada under a future climate influenced by a doubling of CO₂ (Flannigan & Wagner, 1991). Throughout North America, regional variability is predicted with an upward shift in SSR by 10-50% under a doubled CO₂ climate (Flannigan et al., 2000). Under a tripled CO₂ concentration, the area burned in Canada would be expected to increase by 74-118% due to the increased warming (Flannigan et al., 2005b). The results of the sensitivity analysis are well within the ranges presented in these studies.

The rise in predicted future fire weather severity found in this study were consistent with many other studies for western North America (Flannigan et al., 2000; Dale et al., 2001; Westerling et al., 2006; Nitschke and Innes, 2008; Flannigan et al., 2009). Overall, greater fire hazard was predicted in the SMW than in the NSW. This held true for both the SSR and the total number of fire days. Under the selected GCM-driven climate scenarios, as well as the sensitivity analysis, greater change was predicted for the SMW over the NSW. However, the trends in fire hazard over time were not always significantly positive.

Although fires are essential to forest ecosystems (Flannigan, 1991; Girardin, 2007; McCoy and Burn, 2005; Stocks et al., 2003), increases in forest fire activity can result in numerous negative side effects. Many Canadians rely on the North Saskatchewan and St. Mary rivers for water supply. Forest fires are known to decrease water quality by increasing the nitrates, sulfates, and chloride found in the water (Mast and Clow, 2008), as well as increasing mercury deposition (Witt et al., 2009). As forest fire activity increases, it is plausible that the water quality in these rivers and their tributaries could decline. A large portion of the SMW is in Glacier National Park, and is therefore fairly undisturbed. However, timber harvesting is an important industry in the NSW (NSWA, 2005). As fires clear larger regions, it follows that the forestry industry could suffer negative economic consequences. In addition, an increase in forest fires in both watersheds could harm human health and adversely affect recreational uses (Dale et al., 2001).

Increasing fire hazard can cause negative impacts for fire management agencies. In Canada, fire management organizations already spend an average of 500 million dollars on fire suppression every year (Flannigan et al., 2009). As forest fire activity rises, these costs for fire suppression could increase substantially making forest management difficult (Flannigan et al., 2009; Nitschke and Innes, 2008). It may only be another decade before forest fire management organizations can no longer uphold their existing levels of success (Flannigan et al., 2009). Furthermore, in warmer climates, a greater number of fires could spread before fire management groups are able to attend the fire, resulting in larger fire areas (Stocks, 1993). It is suggested that forests be harvested for their fuels to aid in suppression efforts (Chapin III et al., 2009). It follows that greater funding would likely be needed for fire suppression in the North Saskatchewan and St. Mary watersheds as climate changes causes an increase in fire hazard.

4.5 Conclusion

Future fire hazard severity was assessed at 100 m resolution in the North Saskatchewan and St. Mary watersheds. Fine-scale meteorological variables, including air temperature, precipitation, relative humidity, and wind speed, have been simulated throughout the study regions. Ensemble climate scenarios were chosen to represent a wide range of possible future climates. Using the predictions for future meteorological variables, future fire hazard was calculated daily through the year 2100. The possible changes in SSR and number of fire days were evaluated. In addition to the GCM driven climate change scenarios, a sensitivity analysis was performed to demonstrate the impacts that an array of air temperature and precipitation changes would have on SSR. Although it is the general consensus among scientists that air temperature is expected to rise in the coming decades, uncertainty is expressed in future precipitation changes (IPCC, 2007). For this reason, it was important to study a range of possible future climates, and examine how air temperature and precipitation changes can influence fire weather.

In the NSW, future fire hazard was predicted as follows:

- SSR was predicted to increase through the year 2100 under all five GCM driven climate change scenarios. The scenarios predicting the warmest and driest climates exhibit the greatest SSR. The coolest and wettest climate scenarios portray the lowest increases in SSR.
- With the exception of NS1, all the climate scenarios predicted greater numbers of fire days compared to the base period for all three time periods. By the 2080s, NS1 was also predicting more fire days than the base period.
- Regions of lower elevations are expected to experience the greatest SSR values

and number of fire days. These are the areas where generally air temperatures are highest and precipitation volumes are lowest.

- The greatest change in SSR and number of fire days is predicted at lower elevations.

In the SMW, future fire hazard was predicted as follows:

- The SSR was shown to increase under all five GCM-driven climate scenarios. Climate scenarios predicting the warmest and driest environments foresee the greatest SSR, and scenarios predicting the coolest and wettest climates foresee the lowest SSR.
- The number of fire days is expected to increase under climate change, with the exception of a few regions under the SM1 scenario.
- Regions with lower elevations are expected to have the highest future fire hazard and regions at higher elevations predict the lowest future fire hazard.
- Greater change in SSR and fire days was seen at higher elevations.

CHAPTER 5:

Conclusions

5.1 Thesis Summary

In this thesis, a methodology was presented for determining the possible effects of climate change on forest fire hazard at fine-scale resolution within the Rocky Mountains. Two study areas were chosen: the basins surrounding the headwaters of the North Saskatchewan and St. Mary rivers. In order to perform the necessary fire hazard calculations, fine-scale meteorological variables were first simulated throughout the basins using the GENGRID model. Midday values of air temperature, relative humidity, and wind speed, and 24-hour precipitation accumulation, were simulated throughout the watersheds. The daily meteorological variables were entered into the CFFWIS model to spatially determine daily fire weather severity. The SSR and the number of fire days were calculated each year based on the defined fire season of May 1st to September 30th. Through the use of GCM-driven climate change scenarios, projections were made for future fire hazard through the year 2100. In addition, a sensitivity analysis was performed to determine how an array of climate changes would affect a forest's vulnerability to fire.

Historically, it was found that the SMW experienced greater fire weather severity than the NSW. Additionally, while the NSW saw a decline in SSR and fire day numbers from 1960 to 2010, the SMW saw an increase in the same fire weather variables for this time period. On average, both watersheds experienced the greatest fire hazard in regions with lower elevations, as these were the areas calculated to have less precipitation accumulation and highest air temperature values. However, some years did experience

greater SSR values at higher elevations, which can be attributed to the positive association of wind speeds with altitude.

Future projections indicated the impending climate change will likely increase fire hazard in both study watersheds. If only minor increases in air temperature are seen in the upcoming decades, and are combined with increases in precipitation, it is possible that very little change will be seen in fire weather severity. However, as most climate studies predicted greater increases in air temperature than 1°C, fire hazard values would likely rise even with an increase in precipitation. The worst case scenario for both watersheds would include increases in air temperature and decreases in future precipitation, as this would result in the greatest potential for forest fire occurrence. By the 2080s, the NSW could see greater than fifty days per fire season with high or extreme hazard. In the SMW, this number approaches one hundred. The increase in projected future fire weather severity is in agreement with the findings of most future climate studies (Flannigan et al., 2000; Dale et al, 2001; Westerling et al, 2006; Nischke and Innes, 2008; Flannigan et al., 2009).

The most challenging aspect of this study was simulating the meteorological variables in alpine environments. Due to the lack of available meteorological data, especially at high elevations, model calibration and validation proved difficult. However, the purpose of this study was to examine the impacts that a changing climate could potentially have on fire hazard in the northern watersheds. Thus, it was determined that the methodologies illustrated were sufficient for simulating the changes in future fire hazard regimes based on the multitudes of available climate studies.

The study was important as it quantified fire hazard at high resolution within mountain watersheds. Most studies report fire hazard values at much larger scales, some based on simple interpolations from base station data. This study is unique in that fire hazard values are presented for small areas, and are adjusted for variations in elevation and land cover type. Variability in fire hazard within small geographic areas has been shown. This can be beneficial for fire management officials, as well as those with homes or businesses in high elevations, because more accurate estimations of fire hazard can be made. Meteorological variables are influenced by elevation, which in turn affect the sensitivity of the environment to fire. It was shown that fire hazard can vary greatly in a relatively short distance due to the altitudinal changes of daily weather variables throughout alpine environments. As climate change progresses, it is important to understand the possible implications on forested regions so that mitigation strategies can be implemented. Both study regions rely on the forest for industrial reasons (NPS, 2011; NSW, 2005). In addition, both areas serve as habitat to a multitude of wildlife. Although wildfire is a natural part of all forested ecosystems, an increase in the frequency, area burned by fire, or the severity of the fires, could prove detrimental to humans and animals alike. In addition, as fires are known to impact the quantity and quality of fresh water, an increase in forest fire activity in the Rocky Mountains could negatively impact the water availability on the Prairies (Shakesby & Doerr; Silins et al., 2009).

5.2 Recommendations

One of the most challenging aspects of this study was the lack of available

meteorological data. By improving datasets, it could be possible to give more realistic estimations of daily weather variables. The modelling approaches in this thesis have proven sufficient for this study, however, a number of recommendations can be made to improve the quality of future studies within this area:

- Hourly data were required for the modelling techniques, yet many stations within the Rocky Mountains do not have these variables available. The lack of available hourly data made model calibration and validation difficult. The installation and monitoring of meteorological stations could aid this problem.
- Simulating data at high elevations is a difficult task. It is made harder to properly simulate these values as there are limited climate stations at high altitudes. Again, the addition of meteorology stations at high elevations would prove beneficial to the calibration and validation of this model, as well as other studies in alpine environments.
- Wind speed proved challenging to estimate within the Rocky Mountains. The benefits of using the GENGRID model are that few input parameters are necessary. However, to properly simulate synoptic conditions, more instrumental data would be required. Additional wind data from climate stations would aid in the accuracy of the model.

This study only assessed the impacts of daily weather variables on fire weather severity. There are a number of other variables that could impact fire regimes that were out of the scope for this study, however, could be possible in future studies. They are as follows:

- Although fire weather severity was calculated for all land cover types, some of the analysis performed in this study included assessing fire hazard variables only within forested regions. As climates warm, patterns of vegetation are expected to change, including rising tree lines and further upward extent of prairie grasses (Soja et al., 2007). This means that areas that are currently forested could potentially lose the sustainability for trees to grow. Alternatively, as tree lines rise, areas that were not initially susceptible to fire could become forested and thus, at risk for fire. It would be note-worthy to study not only changing fire weather hazard patterns, but study forest growth and retreat in the alpine environments, and the effects that that could have on fire susceptibility.
- This study did not assess how the snow pack would impact fire regime. For example, snow melt does not typically occur in the mountains until late spring, when daily weather conditions are often suitable for fire initiation. It would be less likely for forests to have the available fine fuels when the ground is covered in snow. The GENESYS model (MacDonald, 2009) has a routine for simulating snow pack and uses GENGRID output as model input. The GENESYS model could be integrated to include snow pack and snow melt as a parameter in fire weather calculations, as earlier spring melts can increase the length of the fire season (Running, 2006; Westerling et al., 2006).

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Appendix A: The effects of elevation, average air temperature, and precipitation on fire days in the North Saskatchewan and St. Mary watersheds.

