A MODEL ANALYSIS OF WATER RESOURCE AVAILABILITY IN RESPONSE TO CLIMATE CHANGE AND OIL SANDS OPERATIONS IN THE ATHABASCA RIVER BASIN

by

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Abstract

The Athabasca River Basin faces challenging tradeoffs between energy production and water security as climate change alters the seasonal freshwater supply and water demand from the oil sands mining industry is projected to increase. Effective water management will depend on a physical understanding of the scale and timing of water supply and demand. This dissertation aims to synthesize the impacts of water withdrawals and climate change on streamflow in the Athabasca oil sands region, in order to develop a scientific basis for the management of water resources. The combination of a land surface process model and a hydrological routing model is used to evaluate the influence of water withdrawals and climate change on streamflow under a variety of different scenarios, and to evaluate the adaptation options.

Climate warming is projected to be the primary driver of future streamflow availability, with little influence from direct water withdrawals. Seasonal patterns that show a decline in summer flows and an increase in winter flows are consistent with the response of a snowmelt-dominated basin to warming. Increases in the frequency of low flows that are below a threshold of maximum environmental protection suggest that daily bitumen production could be interrupted by up to 2-3 months a year by mid-century. It is also projected that water storage will be required to supplement river withdrawals to maintain continuous bitumen production under the impacts of future climate warming. Based on the model results, a range of water management options are developed to describe the potential tradeoffs between the scale of bitumen production and industry growth, water

storage requirements, and environmental protection for the aquatic ecosystems. This physically-based assessment of future water tradeoffs can inform water policy, water management decisions, and climate change adaptation plans, with applicability to other regions facing trade-offs between industrial development and ecosystem water needs.

Preface

This dissertation is original, unpublished, independent work by the author, Doris Nian-Shiah Leong.

Chapters 3, 4, and 5 have been written in preparation for submission to peer-reviewed journals. Due to this manuscript format, there is some repetition in the introductory and methods content between Chapters 2, 3, 4, and 5.

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For my family

Chapter 1

Introduction

1.1 Research problem

Changes in the magnitude and timing of streamflow can disrupt river ecosystems and human activities that are accustomed to seasonal water availability. Such changes can arise due to shifts in the hydroclimatological regime, and also due to direct anthropogenic alterations to streamflow. In the Athabasca River Basin, the intersection of climate change and a rapidly expanding oil sands industry will pose future challenges for water management to maintain seasonal water availability for both ecosystem and industry needs. The effective management of water resources will require a strong understanding of the climate-driven and human-driven impacts on future water supply, as well as an understanding of projected water demand.

It is uncertain whether the future Athabasca River streamflow, under changing climatic conditions, will be sufficient to support forecasted water use by the oil sands industry. As a result, it may be equally important for future water management to focus on the impacts *on* industry, in addition to the impacts *of* industry. Projected climate change impacts on basin streamflow must be integrated with water use patterns to identify and adapt to future deficits in water availability. Water management can then make informed decisions on tradeoffs between ecosystem protection and industry growth over long-term century timescales.

1.2 Background on the Athabasca River Basin

1.2.1 Geography and hydrology

The Athabasca River Basin (ARB) extends across the Canadian provinces of Alberta, Saskatchewan and a small area of the Northwest Territories (Figure 1.1). It is the southernmost subbasin of the Mackenzie River Basin, which drains northward into the Arctic Ocean. The ARB's major artery is the Athabasca River; at 1538 km long, it is the third longest undammed river in North America. Along with Lake Athabasca, which covers 7,935 km^2, the basin river system drains an area of 269,000 km^2 [MRRB, 2004].

The Athabasca River originates in the Columbia ice fields and flows northeast, traversing a variety of ecozones including the Cordillera/Rocky Mountains, Boreal/Interior Plains, and the Canadian Shield. These regions contain diverse ecosystems including glaciers, alpine meadows, alpine and boreal forests, and muskeg within unique landscapes and wildlife habitat including the Peace-Athabasca Delta, the Cardinal River headwaters, McClelland Lake, and the Richardson Sand Dunes [MRRB, 2004, Holloway and Clare, 2012]. In upland areas, coniferous forest, mixed wood, and deciduous forest are the dominant vegetation, with willow brush, shrubs, black spruce, and sphagnum moss dominating lowland areas [Kerkhoven and Gan, 2006]. Between the town of Athabasca and the city of Fort McMurray, extensive muskeg regions occur [Hamilton et al., 1985].

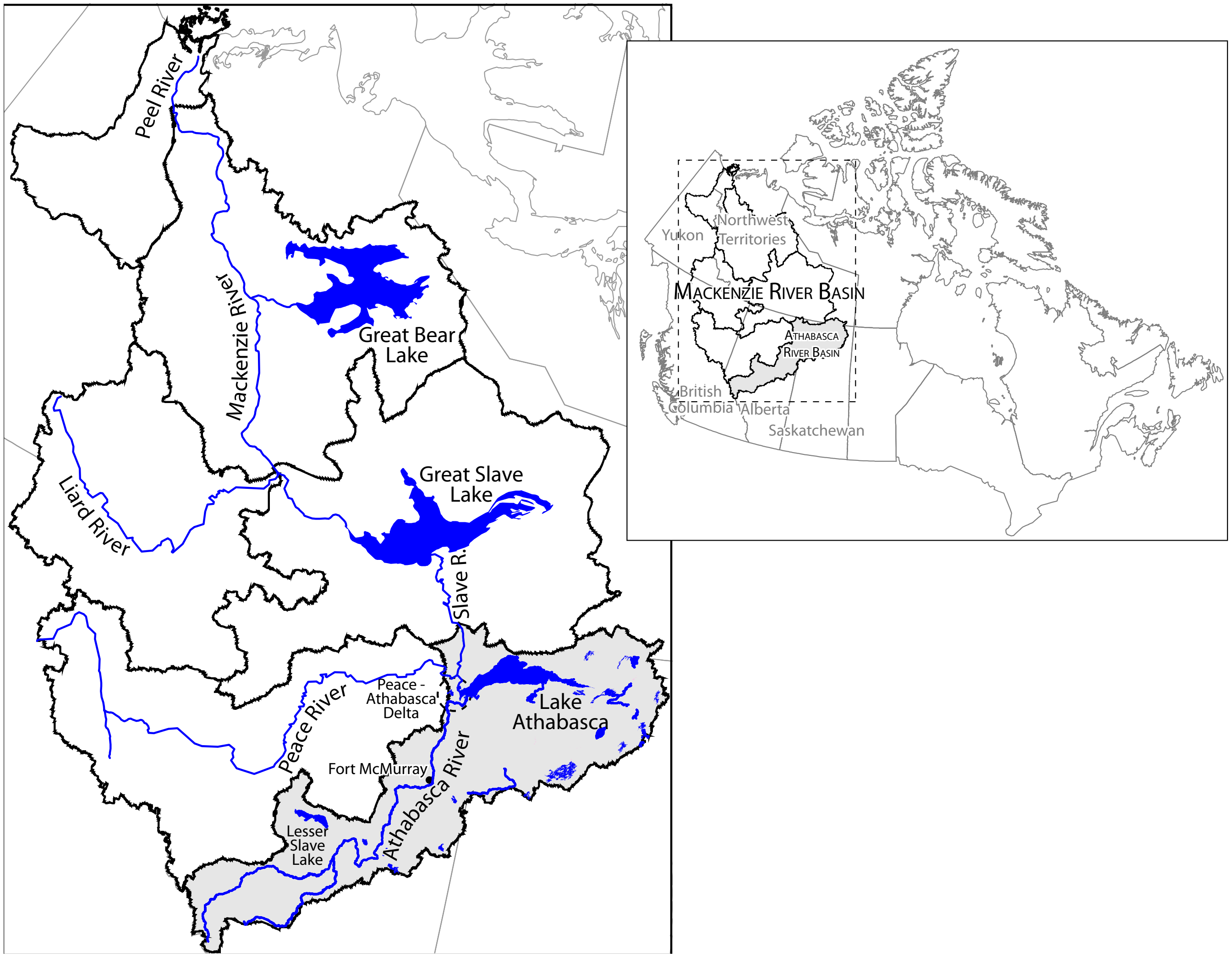

Figure 1.1: The Athabasca River Basin (shaded grey) shown as a sub-basin of the Mackenzie River Basin. Inset shows the basin location within Canada.

The Athabasca River supports over 30 species of fish and serves as an important transportation route (historical trade routes, current recreational activities, etc.). The river environment has also supported large communities of aboriginal people for many centuries. The Athabasca River drains into the Peace-Athabasca Delta (PAD), an ecologically sensitive region comprising a 6000 km^2 complex of wetlands and lakes at the western end of Lake Athabasca. The PAD is an important nesting and staging area for up to one million migratory birds and provides habitat to roughly 5000 bison, along with many other wildlife.

Historically, the ARB has a continental climate with cold, dry winters and short, cool summers. The average annual temperature of the ARB is 2°C [Burn et al., 2004]. Winter daily mean temperatures between mid-October to early April are below 0°C [Kerkhoven and Gan, 2006], with mean January temperatures varying from -15 to -25°C. In the summer, July temperatures range from 10–15°C in the headwaters to 15–17°C near Fort McMurray [Hamilton et al., 1985]. Annual precipitation averages 800 mm in the mountains, 500–600 mm in the central part of the basin, and 400–500 mm in the northeast [Kerkhoven and Gan, 2006, Hamilton et al., 1985]. The majority of precipitation, up to 75%, falls in the summer months between June and October as major rainstorms [Longley and Janz, 1978, Burn et al., 2004].

The flow regime of the Athabasca River is typical of northern rivers, characterized by low flows in the winter and rising discharge due to snowmelt starting in late April and May [Burn et al., 2004]. The bulk of annual discharge occurs in the late spring and early summer, with peak flow in June or July, followed by a gradual recession to low flows in December through February [Choles, 1996]. Together with the adjacent Peace River Basin, the Athabasca River Basin sustains much of the low winter flow of the Mackenzie River [Woo and Thorne, 2003].

The Athabasca River is fed by four major tributaries which together account for under 50% of the total river discharge below Fort McMurray. These are the McLeod River (10%), Pembina River (6%), Lesser Slave River (8%), and Clearwater River (18%). Lesser Slave Lake, roughly 1,160 km^2, drains eastward into the Athabasca River via the Lesser Slave River. The storage capacity of Lesser Slave Lake can dampen the magnitude of peak discharge by delaying the timing of flow from the Lesser Slave River into the Athabasca River, relative to contributions from other tributaries, and can contribute to a broader peak in the annual hydrograph [Choles, 1996].

The lakes and wetlands in the Peace Athabasca Delta experience annual periodic flooding and are highly sensitive to natural variability in river flows and water levels [Peters et al., 2006]. Flow regulation of the Athabasca River therefore has important consequences for these ecological systems [Alberta Environment, 2007]. Although ice jams on the Athabasca River can lead to flooding in the winter that can also contribute to seasonal inundation of the Peace-Athabasca Delta [Kowalcyk and Hicks, 2003, Prowse et al., 2006], most flood activity in the basin occurs during open water season between May and the end of July, and reflects high precipitation or snowmelt runoff [Choles, 1996].

1.2.2 Climate change

High-latitude regions are especially sensitive to the effects of climate warming and are expected to warm more quickly than lower latitudes [Hassol, 2004, IPCC, 2007]. Temperatures in the ARB have increased on average by 1.5–1.8°C between 1961–2000, three times higher than the global average rise of 0.6°C [Bruce, 2006]. Temperatures are expected to continue increasing considerably in the future, with the most recent IPCC projections for Northwest Canada showing a mean annual temperature increase of 2.7°C by the middle of the century and 3.5°C by the end of the century. Previous studies have projected temperature increases of up to 4°C by mid-century, and up to 6°C by the end of the century [Gan and Kerkhoven, 2004, Prowse et al., 2006, Sauchyn and Kulshreshtha, 2008, Kerkhoven and Gan, 2011]. Annual precipitation and potential evapotranspiration are also expected to rise through the 21st century, while winter precipitation that normally falls as snow is expected to increasingly fall as rain [Schindler and Donahue, 2006]. The most recent IPCC projections for the Athabasa River Basin region show an annual precipitation increase of 3% by mid-century and 4% by the end of the century [Christensen et al., 2013].

Summer flows in the Athabasca River have been observed to decline by almost 30% since 1970 due to climate warming [Swainson, 2009]. Warming has also led to the rapid shrinking of glaciers in the basin headwaters by 25% in the last century [Watson and Luckman, 2004] and to the subsequent reduction in flows fed by glacial sources that will eventually cease to exist [Hopkinson and Young, 1998]. Increased temperatures have driven a progressively earlier snowmelt in recent decades [Serreze et al., 2000, Zhang et al., 2001] and since the mid-20th century, observations near Slave Lake show that the number of days winter snow has remained on the ground has decreased by 25% (39 days) and the maximum snowpack depth has declined by 54% (27 cm) [Schindler and Donahue, 2006]. Observations of reduced snowpack accumulation, periodic and earlier snowmelt, and reduced summer flows [Serreze et al., 2000, Zhang et al., 2001, Sauchyn and Kulshreshtha, 2008] are consistent with modelling studies which project that future warming will result in a lower and earlier spring freshet and reduced summer flows due to low snow accumulation and an earlier snowpack melt [Pietroniro et al., 2006, Schindler and Donahue, 2006, Sauchyn and Kulshreshtha, 2008].

Although these general hydroclimatic shifts are projected for all climate scenarios, the degree and direction of estimated change in monthly streamflow is heavily dependent on the climate change scenario [Toth et al., 2006]. While some projections show trends toward increased streamflow volumes, others show an overall decline in streamflow by the end of the century [Toth et al., 2006, Schindler et al., 2007, Swainson, 2009, Kerkhoven and Gan, 2011]. Variability in streamflow projections is due in part to uncertainty in the balance between potential evapotranspiration and precipitation as temperatures increase [Sauchyn and Kulshreshtha, 2008]. Regardless, seasonal declines in streamflow may lead to an increased potential for drought and water supply problems [Lapp et al., 2005], as well as a decrease in the frequency of floods that replenish the lakes and wetlands in the Peace-Athabasca Delta [Prowse et al., 2006, Wolfe et al., 2005, 2008].

1.2.3 Human activity and the oil sands industry

In 2001, the human population of the Athabasca River Basin was 155,000, although rapid growth and urban and industrial development has likely since increased that number significantly. In Fort McMurray, where the majority of the basin resides, an 80% growth in population occurred between 2000 and 2010; the population of Fort McMurray alone is forecasted to increase to 205,000 by 2028 [Regional Municipality of Wood Buffalo, 2010]. There are currently more than 200 populated centres with greater than 2000 people in the ARB [Squires et al., 2009].

Economic activity in the ARB is led by agriculture, forestry, and coal mining in the upstream half of the basin [ERCB, 2010, Holloway and Clare, 2012]. Agriculture accounts for roughly 12% of the basin area and consists primarily of forage crops [Wrona et al., 2000, MRRB, 2004]. Forestry is also a major industry, and is active across the basin, including several sawmills and pulp mills. Commercial fishing and trapping are also prominent industries which have remained relatively static during the past decade. Meanwhile, uranium mining in the basin produces about a quarter of the world supply of rich, high-grade uranium [Pană and Olson, 2009]. In its downstream reaches, alongside a growing conventional oil and gas industry, the Athabasca River Basin is also home to a burgeoning oil sands industry.

Since the late 1990s, the oil sands resource has become an important driver of Alberta's economy and is expected to continue to play a key role in Canada's future economy as world demand for energy continues to rise. Global demand for oil is expected to rise from 85.7 million barrels per day in 2008 to 112.2 million barrels per day in 2035 [Conti and Holtberg, 2011], and Canadian oil sands production is projected to increase from 1.5 to 4.8 million barrels per day over the same time period [Conti and Holtberg, 2011, CAPP, 2012]. As conventional crude oil reserves become depleted, nonconventional sources such as the oil sands have become more important and now account for 60% of Canadian production [Environment Canada, 2014].

The oil sands deposits in northern Alberta constitute a reliable, long-term supply for the growing global demand for crude oil. The Alberta oil sands are estimated to contain as much as 1.7 trillion barrels of bitumen, with reserves (the amount recoverable economically with existing technology) estimated at 170 billion barrels of bitumen [Alberta Environment, 2009]. The deposits span approximately 142,200 km^2 and are divided into three regions: the Athabasca Wabiskaw-McMurray deposit ($\sim$80% of oil reserves), the Cold Lake Clearwater deposit ($\sim$12% of oil reserves) and the Peace River deposit ($\sim$8% of oil reserves). The Athabasca Wabiskaw-McMurray deposit lies within the Athabasca River Basin, and surface mineable bitumen covers a 4800 km^2 area within this deposit, with roughly 602 km^2 currently disturbed [Alberta Environment, 2009].

There are several key environmental concerns associated with oil sands bitumen production. Greenhouse gas (GHG) emissions of carbon dioxide and methane are produced at every stage of the oil sands production life cycle, and exceed the emissions of conventional oil production [Alberta Environment, 2009]. Oil sands operations contribute the single largest source of GHG emissions growth in Canada [Woynillowicz et al., 2005], although technological advancements in equipment, along with a decline in upgrading activity due to increased crude bitumen export, have maintained a generally fixed emissions intensity since 2004 [Environment Canada, 2010]. Over 1400 known pollutants are emitted by oil sands operations [Weinhold, 2011], with the main contaminants being mercury, arsenic, and polycyclic aromatic hydrocarbons [Alberta Environment, 2009, Schindler et al., 2007]. The disposal of waste containing high concentrations of contaminants into tailings ponds may have significant impacts on local soil and groundwater if seepage occurs, potentially leading to downstream water quality and ecosystem degradation [Woynillowicz et al., 2005, Droitsch, 2009, Gosselin et al., 2010]. In addition to water quality, declining air quality is a concern, with recent monitoring showing an increasing trend in nitrogen dioxide [Gosselin et al., 2010] and hydrogen sulphide [Alberta Environment, 2009] due to the burning of fossil fuels during bitumen production. Land disturbance is another concern, as oil sands deposits in the basin require the removal of boreal forest and wetland environments to access deposits during surface mining [Alberta Environment, 2009]. Land reclamation is an ongoing but challenging process due to the high concentrations of contaminants involved, and the rate of tailings pond creation still exceeds the rate of reclamation [Woynillowicz et al., 2005, Gosselin et al., 2010]. Furthermore, ecosystems are not expected to be restored to their original state [Woynillowicz et al., 2005].

One of the key environmental concerns with oil sands operations is its intensive freshwater use. In the ARB, oil sands mining already accounts for the largest consumption of water from the Athabasca River [Schindler et al., 2007]. The oil sands mining industry requires a constant supply of freshwater for continuous bitumen production throughout the year, with water necessary at each stage of oil sands operations, including retrieval, processing, and upgrading. This water demand is projected to rapidly increase in the future as operations expand.

Surface or open-pit mining is used to recover deposits near the surface, while in situ methods are used for the recovery of deposits up to 400 m below the surface. Both surface and in situ mined deposits require water-intensive processing steps to extract the bitumen and upgrade it into marketable commodities such as gasoline, diesel, and aviation fuels. However, while the average oil sands surface mine currently uses roughly two to four barrels of freshwater to produce a barrel of oil, the average in situ project uses only about half a barrel of freshwater to produce a barrel of oil, by making use of recycled and deep-well salt water as an alternative to freshwater when possible [Alberta Environment, 2007]. As a result, concerns over freshwater use are primarily associated with surface mining oil sands operations.

1.2.4 Water use management

Surface water from lakes and rivers is the main source of water withdrawals for domestic, agricultural, commercial, and industrial use in the ARB [AMEC Earth & Environmental, 2007, AWRI, 2011]. In 2005, approximately 760 million cubic metres of surface water in the ARB was allocated annually for human use

[AMEC Earth & Environmental, 2007]. The petroleum sector was the largest user of surface water (65%) in 2005, with the majority (94%) of that surface water withdrawn for oil sands surface mining operations [AMEC Earth & Environmental, 2007]. Projections for 2025 under a high-growth scenario (with many considerations including population growth for the municipal and commercial sectors, livestock growth for the agricultural sector, forecasted economic activity for the commercial sector, proposed projects for the petroleum sector, etc.) estimate that the petroleum sector will continue to dominate surface water withdrawals (78%) with the majority of those withdrawals (86%) for oil sands surface mining [AMEC Earth & Environmental, 2007, Alberta Environment and Sustainable Resource Development, 2014]. The percentage of surface water withdrawals for all other sectors are projected to decline by 2025 [AMEC Earth & Environmental, 2007].

Both the provincial and federal governments have jurisdiction over water use in the ARB. Major water users must obtain licenses from the provincial government which designate the conditions of operation and the amount of permitted water withdrawals, as well as the quality of returned water. The Athabasca oil sands are currently mined by five companies who withdraw water from the Athabasca River - Canadian Natural Resources Ltd., Imperial Oil Limited, Shell Canada, Suncor Energy Inc., and Syncrude Canada Ltd. These oil sands companies currently comply with Phase One of the Lower Athabasca River Water Management Framework, introduced in February 2007, and are currently licensed to withdraw 441 million m^3 of fresh water from the Athabasca River each year [Alberta Environment, 2007]. The framework describes the rules and restrictions on water withdrawals by major oil sands operators, in order to sustain in-stream flow needs in the Athabasca River. A weekly cap is placed on the rate at which oil sands companies can remove water from the Athabasca River, based on the natural and seasonal variability in river flow. The Phase One framework has been criticized for being unenforceable, not establishing incentives for industry to reduce water use, and neglecting the impact of climate change on future river flows [Swainson, 2009]. Phase Two of the water management framework is currently in development and aims to gather further scientific and traditional knowledge to assess the possible limitations of the Phase One framework, as well as to establish a minimum base flow below which withdrawals are no longer permitted [Ohlson et al., 2010]. One of the major drawbacks of the current water management system is that water use reporting from oil sands mining operations remains voluntary [Woynillowicz and Severson-Baker, 2006], and an accurate historical and current record of water demand from these operations is not readily available.

Although water withdrawals from the Athabasca River for oil sands operations currently represent a small fraction of the total river flow, the continued intensification of water withdrawals for expanded oil sands resource extraction may pose a future risk to the sustainable provision of adequate flows [Bruce, 2006, Schindler et al., 2007, Mannix et al., 2010]. In addition, although the magnitude of total river withdrawals is relatively small when expressed as a percentage of annual flow ($\sim 1 - -2\%$), withdrawals can be large relative to low winter flows [Bruce, 2006, AMEC Earth & Environmental, 2007, Alberta Environment, 2007, Weinhold, 2011]. Flow regulation of the Athabasca River therefore requires the careful maintenance of natural flow variation, including seasonal patterns [Alberta Environment, 2007].

1.3 Research objectives and contribution

The overall goal of this research is to synthesize the hydrologic impacts of climate change and water use in order to advance the understanding of future water management challenges in the Athabasca oil sands. The dissertation addresses this overall goal through four overlapping objectives:

- Develop a modelling system that can integrate both climate and human-driven impacts on streamflow in the Athabasca River Basin. This contributes a new method for a large-scale and physically-based hydrological analysis of the region.

- Examine how spatial and temporal variability in the magnitude and distribution of water withdrawals by oil sands operations impacts downstream streamflow timing. The body of data on oil sands water use is compiled from multiple sources and applied to build a comprehensive range of water use scenarios that provide bottom-up estimates of future water demand and the scale of water use impacts on streamflow patterns.
- Explore how climate change will alter future streamflow timing in the basin in combination with, and in contrast to, the impact of water withdrawals. This quantifies the potential range of climate change impacts on future streamflow patterns and the projected variability in future water supply.
- Investigate how water management can adapt to future water supply and demand trajectories. This identifies a full range of water management options with different priorities and tradeoffs in environmental protection and industry growth, which can help to inform future water policy decisions.

1.4 Research strategy

This dissertation takes a physically-based modelling approach that is well suited to simulate the land-surface and hydrological processes and changes in a river basin. Two existing models, the Integrated Biosphere Simulator (IBIS) and the Terrestrial Hydrologic Model with Biogeochemistry (THMB) are used together and adapted to model the Athabasca River Basin. IBIS is a land surface model that simulates the coupled soil-vegetation-atmosphere water and energy budgets [Foley et al., 1996, Kucharik et al., 2000], while THMB is a hydrological routing model that uses prescribed river paths to simulate the storage and transport of water [Coe et al., 2002, 2008]. This approach allows for an assessment of future climate variability across large spatial and temporal scales and the direct integration of human alterations to streamflow such as water withdrawals.

The timing of streamflow is a primary focus throughout the thesis, as it is an important metric of hydrologic alteration that responds to climatic variability as well as direct human intervention [Richter et al., 1996, Döll et al., 2009]. Changes in the seasonality of streamflow are also important in effective water resource management where operational decisions often depend on the timing of flow cycles to match supply and demand, as well as a hydrologic baseline that sustains the flow regime [e.g., Alberta Environment, 2007]. The modelled projected changes in streamflow timing are applied to identify potential threats to future water resource availability and to inform the development of water management adaptation options.

1.5 Structure of dissertation

The chapters in this thesis move linearly through an exploration of different streamflow impacts and their consequences for future water management. Each chapter builds upon the next, but is also self-contained and formatted as an individual manuscript for future submission to target journals. As a result, each chapter includes a description of specific relevant background, concepts, and methods, such that some repetition of these details in each chapter occurs.

Chapter 1 provides a contextual overview of the research, including the theme, purpose and main research goals of the work.

Chapter 2 establishes the modelling methods that are applied to capture the physical processes that drive basin hydrology. A discussion of model parameter adjustments and an evaluation of the model system performance are presented. The simulated historical streamflow established in this chapter provides a baseline for the following chapters to assess future spatial and temporal alterations to streamflow.

Chapter 3 compiles data on current and future oil sands water withdrawals and assesses the streamflow impacts of industry. Different water withdrawal scenarios are examined under historical climate variability.

Chapter 4 simulates the projected climate change impacts on streamflow at the middle and end of the 21^{st} century using the most recent global climate models and climate scenarios available. Climate change impacts are also contrasted with the scale of water withdrawal impacts from Chapter 3.

Chapter 5 integrates the results of Chapter 3 and Chapter 4 to frame an analysis of water management options based on future water supply and demand trajectories. It explores the tradeoffs that may emerge in adapting to future streamflow alterations under a changing climate and given an evolving oil sands industry.

Chapter 6 concludes the dissertation by discussing its significance and contributions to the current research field and the stated research problem in Chapter 1. The strength and limitations of the research are discussed along with comments on potential future work that would expand on the dissertation.

Chapter 2

Model Validation for the Athabasca River Basin

2.1 Introduction

This chapter establishes the modelling methods applied to simulate the hydrology of the Athabasca River Basin (ARB). A combination of two large-scale land surface and ecosystem process models is used. The land surface process model, the Integrated Biosphere Simulator (IBIS) [Foley et al., 1996, Kucharik et al., 2000], and a river routing algorithm, the Terrestrial Hydrology Model with Biogeochemistry (THMB) [Coe et al., 2002] are independent models that have been used together in dozens of large-scale studies, including simulations of continental-scale runoff [Lenters et al., 2000, Coe and Foley, 2001, Li et al., 2005], Amazonian flooding [Coe et al., 2002], and Mississippi nutrient flux [Donner et al., 2002]. IBIS produces surface and subsurface runoff outputs which are then used to drive streamflow routing in THMB (Figure 2.1). Process-based models, in which model parameters are primarily based on real, physical parameters that can be validated with available data, are preferable when extending model application to future hydroclimatic regimes that may respond differently to calibrated parameters. A discussion of IBIS-THMB model parameter adjustments and an evaluation of the model performance in the ARB are presented.

2.2 Model description

2.2.1 Integrated Biosphere Simulator (IBIS)

IBIS simulates the coupled soil-vegetation-atmosphere water and energy budgets by modelling a) land surface biophysical processes, b) ecosystem physiology and carbon balance processes, c) vegetation phenology, d) plant growth, competition and vegetation dynamics, e) nutrient cycling and soil biogeochemistry, and f) water cycling among vegetation, atmosphere, and soils [Foley et al., 1996, Kucharik et al., 2000]. IBIS is forced with daily climate inputs such as temperature, precipitation, cloud cover, and humidity, along with land surface characteristics such as vegetation and soil type and distribution, to yield fluxes of carbon, energy and water from the land surface to the atmosphere, soil ice and water content, soil temperature profiles, and surface and subsurface runoff to streams. These processes are divided into several modules which operate at different timesteps ranging from minutes to years.

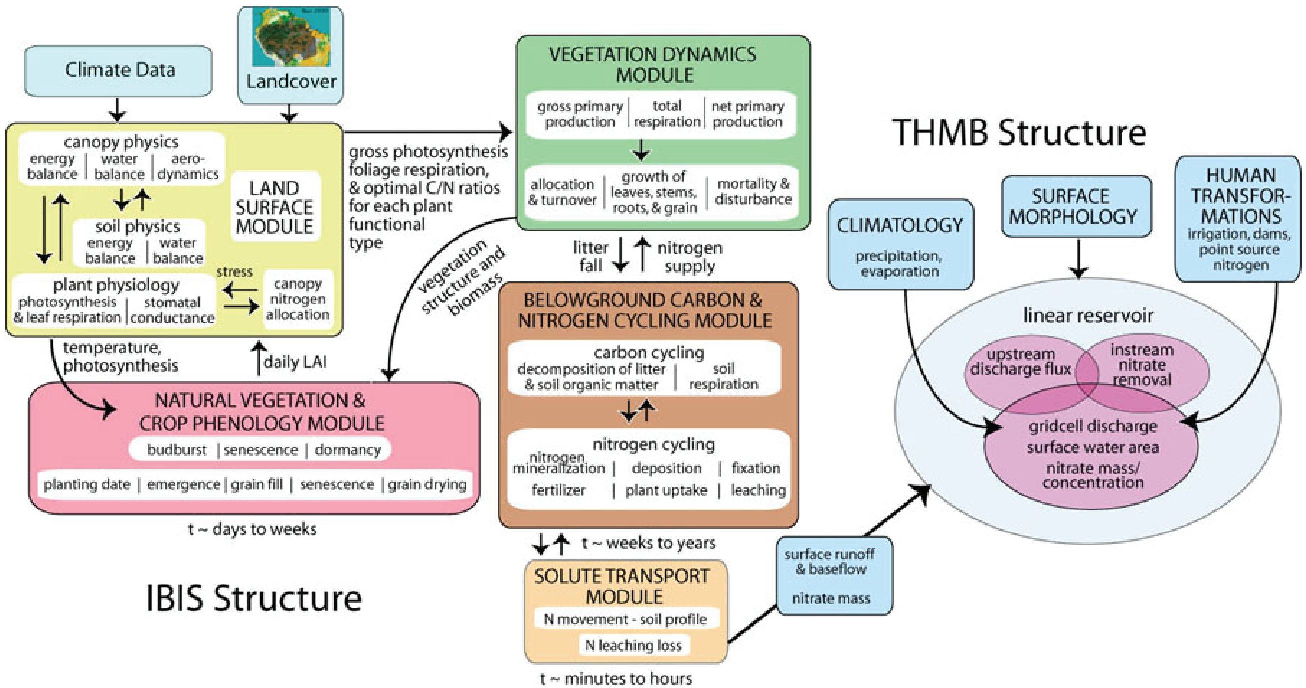

Figure 2.1: Schematic representation of IBIS (left) and THMB (right) models showing the interactions between input climate data, simulated land surface physics, and river dynamics (provided by the Center for Sustainability and the Global Environment (SAGE) at University of Wisconsin).

IBIS is scale independent and has been used at sites ranging from one square kilometre (e.g. farm fields) to hundreds of thousands of square kilometres (e.g. Amazon Basin). The model has been validated against site-specific biophysical measurements (e.g. evapotranspiration, sensible heat flux, vegetation phenology, soil moisture, snow cover and depth, soil temperature, groundwater recharge and river discharge), as well as spatially extensive ecological data (e.g. total and living biomass) [Delire and Foley, 1999, Lenters et al., 2000, Coe and Foley, 2001, Coe et al., 2002, Botta and Foley, 2002, Botta et al., 2002, Vano et al., 2006], including in cold regions such as Canadian boreal forest ecosystems [El Maayar et al., 2001, Liu et al., 2005] and the Yukon River Basin [Yuan et al., 2010]. The result of IBIS when forced with climatic data is a comprehensive description of the fluxes of carbon, energy and water from the land surface to atmosphere, the soil ice and water content, soil temperature profile, and surface and subsurface runoff to streams. In this study, IBIS is run on a 0.375° x 0.375° geographic grid chosen to match the available climate re-analysis resolution for the region.

The soil module can be set to any appropriate number and thicknesses of soil layers to describe the diurnal and seasonal cycles of soil ice and water, and the dynamics of soil volumetric ice and water content are simulated for each layer. The soil moisture simulation is based on Richards' equation, where the change in time of the soil moisture in each layer is a function of diffusion, the soil hydraulic conductivity, and plant water uptake. The plant water uptake is a mechanistic process governed by stomatal demands and constrained by root water uptake, which in turn, are complex functions of physical characteristics such as photosynthetic activity, the canopy structure, atmospheric and surface conditions, root structure, and soil moisture profile [Kucharik et al., 2000, Li et al., 2005]. Soil water infiltration is estimated using Darcy's law and the number and thickness of soil layers can be manually adjusted. There are 11 defined soil textures, composed of different sand, silt and clay fractions [Kucharik et al., 2000]. The various soil parameters for each texture, such as the saturated hydraulic conductivity, can be adjusted to satisfy regional characteristics.

For cold-region processes, frozen soils are modelled in IBIS using a soil ice fraction parameter and subsurface flow automatically adjusts to the melting of frozen soil. A simple three layer snow model is used to simulate snow temperature, extension and depth. Version IBIS v2.6b4 was employed in this study. For more details about IBIS, please see Foley et al. [1996] and Kucharik et al. [2000].

2.2.2 Terrestrial Hydrology Model with Biogeochemistry (THMB)

The Terrestrial Hydrology Model with Biogeochemistry (THMB), formerly HYDRA, is a river routing algorithm that translates the surface and subsurface runoff outputs from IBIS into the flow of water through rivers, lakes and floodplains [Coe et al., 2002]. THMB has been extensively applied and validated at global and continental scales, including Canada's Arctic-draining rivers [Coe, 2000, Coe and Foley, 2001, Coe et al., 2002, Donner et al., 2002, Donner and Kucharik, 2003, Donner et al., 2004, Shankar et al., 2004]. The streamflow routing algorithm applies prescribed river paths to simulate the storage and transport of water, where the total water within a grid cell at any point is the sum of the land surface runoff, subsurface drainage, precipitation and evaporation over the surface waters, and the flux of water between grid cells. The derived hydrological network and morphology are linked at 5-minute horizontal resolution to a linear reservoir to simulate the stage and discharge of rivers at a 1-hour timestep. The streamflow output of THMB, when forced with climate data and IBIS runoff are spatially explicit representations of the river discharge.

River discharge at a given time step is controlled by the effective velocity of the river, u. The effective river velocity is a function of the topographic gradient as well as the scale of the river [Coe et al., 2008]. This ensures that the river velocity increases downstream due to the momentum of flow, despite a shallower gradient. The effective river velocity is given by:

$$u = u_o \left[\frac{i_c}{i_o} \cdot \frac{p_c}{p_o} \right]^{0.5} \tag{2.1}$$

where u_o (m/s) is the effective reference velocity, i_c (m/m) is the downstream gradient, i_o (m/m) is a latitude adjusted reference gradient, p_c (m) is the wetted perimeter and p_o (m) is a reference wetted perimeter. The wetted perimeter is a function of total discharge and constrained according to river bankfull characteristics, where

$$p_{max} = 2h_i + w_i \tag{2.2}$$

and h_i and w_i are the bankfull height and width respectively.

THMB can also estimate the seasonal flood extent over the river floodplain [Coe et al., 2008]. In order to preserve numerical stability in the model, however, floodplain flows are not explicitly subtracted from or added to the river volume, and therefore do not impact river transport. When the river volume rises above the flood initiation stage, the excess water amount is allocated from the river to a floodplain reservoir, which can then flow across the land surface to neighbouring grid cells. Storage and transport of water on the floodplain is given by

$$\frac{dW_f}{dt} = F_r + \sum F_{in} + (P_W - E_W)A_f - F_{out} \tag{2.3}$$

where the change in W_f (m^3), the floodplain reservoir, over each time step is the sum of the flux between river and floodplain F_r, the contribution from all upstream floodplain grid cells $\sum F_{in}$, the difference between precipitation and evaporation over the floodplain surface $(P_W - E_W)A_f$, minus the amount transported to downstream floodplain grid cells F_{out}. The inundated area and height are calculated from the floodplain volume based on the sub-grid topography, and the floodplain flow direction is dictated by the water height. The floodplain flow velocity is calculated in the same manner as the river velocity, with the floodplain wetted perimeter based on the flooded fraction and the grid cell length instead.

The version of THMB (v1f) developed by Coe et al. [2008] was employed in this study. For more details on THMB, please see Coe [1998] and Coe et al. [2002, 2008].

2.3 Data sources

2.3.1 Climate

Climate input data for the 30-year time period of 1981–2010 was retrieved from the NOAA National Operational Model Archive and Distribution System (NOMADS), which provides access to a 3-hour-averaged North American Regional Reanalysis (NARR) dataset [NOAA, 2013]. The NARR product uses the National Centers for Environmental Prediction (NCEP) Eta model as its backbone and is output on a 33 km native resolution grid. The 33 km native projection is a Lambert Conformal Conic grid projection which was re-projected in a regular latitude-longitude geographic grid of 0.375 degree resolution using a simple inverse distance squared interpolation. The NARR product was chosen over NCEP or Climatic Research Unit (CRU) products due to its improved assimilation of precipitation observations over North America. The seven NARR data fields retrieved were specific humidity and temperature at 2 m above the surface, meridional and zonal wind speed vectors at 1000 mb, total cloud cover fraction in the atmosphere column, and total pressure and precipitation at the surface. This data was then averaged into daily data files for input into IBIS.

2.3.2 Soil and vegetation

Soil surface properties (clay and sand fractions) were obtained from the ISRIC-WISE soil database [Batjes, 2000]. Each layer of the soil column in IBIS is assigned one of eleven defined soil textures based on these soil surface properties [Kucharik et al., 2000]. The properties of each soil texture, as well as their distribution, can be varied to better represent regional soil characteristics and soil climate. The dominant surficial soils in the ARB are glacial soils (silt, clay and sands), glaciolacustrine soils (clay loam to heavy clay) and glaciofluvial soils (sandy loam to sands), while peat soils extend over much of the basin ranging from 0.3 to 1 m in depth [Kerkhoven and Gan, 2006].

Vegetation type input maps at 0.375 degree resolution were based on the Boston University MODIS (MOD12C1) data set [Friedl et al., 2001] and land cover types were converted to match IBIS vegetation and land cover classifications as follows: evergreen needle leaf forest $\rightarrow$ boreal evergreen forest/woodland, mixed forests $\rightarrow$ mixed forest/woodland, woody savannas $\rightarrow$ savannas, croplands $\rightarrow$ grassland/steppe, open shrublands $\rightarrow$ tundra, barren/sparsely vegetated $\rightarrow$ tundra.

2.3.3 Geomorphology and hydrology

Global geomorphology input files for THMB were retrieved from the Center for Sustainability and the Global Environment (SAGE) at the University of Wisconsin-Madison. These files have a 5'x5' resolution and provide data on basin definition, elevation, river directions, lake area, and lake sill elevation and location [Coe, 2000]. Finer resolution 1 km topographic data from the Shuttle Radar Topography Mission (SRTM) [Farr et al., 2007] was used to define the sub-grid-scale topography within each 5' grid cell in order to calculate fractional flooding using a statistical representation of floodplain morphology, following the method of Coe et al. [2008].

The river directions in the SAGE data were derived from the Global DEM5 digital elevation model [GETECH, 1995] and modifications were made to improve accuracy. The original digital elevation data incorrectly prescribed the flow directions in some parts of the ARB, particularly for the headwaters of the Athabasca River. As a result, river directions in applicable grid cells were manually corrected using physical river maps of the ARB and verified using the known drainage area at hydrometric stations. A total of 123 out of 6514 river directions in the basin were modified. The basin definition was re-calculated based on the new river directions and lake area and outlet locations were then adjusted to be consistent with the new basin boundary.

Table 2.1: Hydraulic and geomorphic observations of river reaches in the ARB (from Kellerhals et al. [1972]).

River	Station	Long-term mean Discharge (m^3/s)	Long-term mean Velocity (m/s)	2-yr flood Discharge (m^3/s)	2-yr flood Width (m)	2-yr flood Depth (m)	2-yr flood Velocity (m/s)	Sinuo-sity
Athabasca	Near Jasper	90.33	1.13	453.07	114.91	1.74	2.26	1.10
Athabasca	At Entrance/Hinton	186.89	1.10	906.14	191.11	2.59	1.83	1.00
Athabasca	At Athabasca	430.42	0.88	1868.91	316.99	3.84	1.55	1.20
Athabasca	Below McMurray	645.62	1.07	2208.71	539.50	3.14	1.31	1.00
Athabasca	At Embarras Airport	767.39	0.76	2605.15	441.96	5.33	1.10	1.35
Wildhay	Near Hinton	8.01	0.67	48.14	39.62	0.85	1.40	1.20
McLeod	Above Embarras River	20.42	0.34	158.57	67.36	2.07	1.13	2.00
McLeod	Near Wolf Cr/Edson	38.79	0.55	305.82	110.64	1.68	1.68	1.80
Wolf Creek	At Highway #16	3.28	0.18	28.32	29.26	1.34	0.73	2.40
Freeman	Near Fort Assiniboine	8.55	0.55	79.29	60.66	1.01	1.28	1.80
Pembina	Below Paddy Creek	15.21	0.43	96.28	51.21	2.01	0.94	1.70
Pembina	Near Entwistle	18.75	0.40	155.74	68.58	1.71	1.34	2.10
Pembina	At Harvie	41.34	0.58	189.72	79.55	2.44	0.98	2.00
Lobstick	Near Entwistle/Styal	3.88	0.30	17.56	21.64	1.01	0.79	1.90
Paddle	Near Rochfort Bridge	2.24	0.43	28.32	17.07	1.07	1.52	1.50
Little Paddle	Near Mayerthorpe	1.05	0.09	12.74	16.15	1.25	0.58	1.60
Lesser Slave	Slave Lake/At Highway #2	43.89	0.55	68.81	50.90	2.16	0.64	2.00
West Prairie	Near High Prairie	4.62	0.52	62.30	25.91	2.07	1.16	1.80
East Prairie	Near Enilda	6.51	0.70	79.29	29.87	1.80	1.46	1.40
Swan	Near Kinuso	12.91	0.46	148.66	42.06	3.78	0.94	1.70
Clearwater	Above Christina River	80.70	0.76	172.73	115.82	1.52	0.98	1.04
Clearwater	At Draper	135.07	0.73	424.75	137.77	2.93	1.04	1.50

Optimizing THMB for the ARB requires geomorphological observations for developing relationships between flow and key hydraulic variables, but there are few published observations in the river basin since the 1970s. Hydraulic and geomorphic observations of river depth, width, velocity and sinuosity for 22 river reaches in the ARB (Table 2.1), were taken from observations conducted for a wider channel survey program in Alberta [Kellerhals et al., 1972]. This data was used to compute rating curves for the bankfull height, width, and initiation volumes (see Section 2.4.2).

Long-term mean discharge and 2-year flood discharge observations (Table 2.1) were also obtained from the Alberta channel survey program [Kellerhals et al., 1972] to parameterize floodplain flow. The 2-year flood discharge data was used instead of bankfull discharge, due to the number of missing values in the recorded bankfull characteristics. The 2-year flood discharge is a reasonable alternative since bankfull discharge is generally expected at 1.6 to 1.8 year recurrence intervals [Leopold, 1994].

Observations of monthly-averaged river discharge are available through the Water Survey of Canada Hydrometric Data database [Environment Canada, 2010]. Only four hydrometric stations along the Athabasca River contained long-term discharge observations over the complete 30-year historical time period of interest, and these were selected for use (Figure 2.2, Table 2.2).

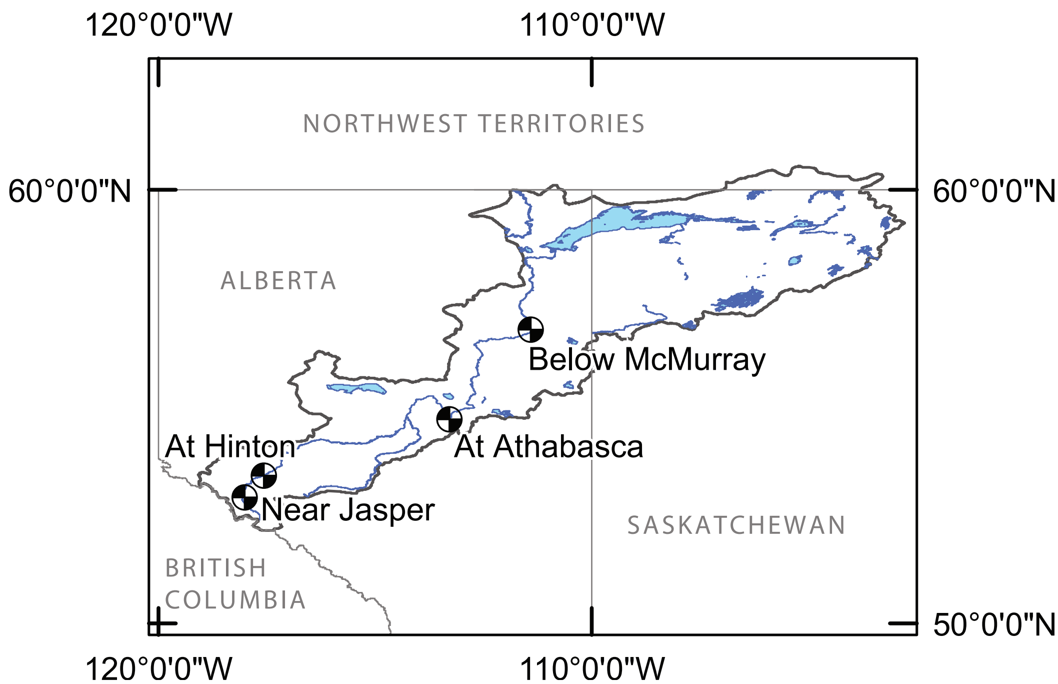

Figure 2.2: Map of hydrometric stations in the Athabasca River Basin.

Table 2.2: Hydrometric stations on the Athabasca River measuring monthly discharge and with recorded data within the 30-year time period of interest, 1981–2010.

Station ID	Station Name	Data Years	Latitude (°N)	Longitude (°W)
07AA002	Near Jasper	1913–2010	52.9100	118.0586
07AD002	At Hinton	1961–2011	53.4242	117.5692
07BE001	At Athabasca	1913–2011	54.7219	113.2878
07DA001	Below McMurray	1957–2011	56.7083	111.4019

2.4 Model parameterization

The magnitude and timing of peak annual discharge, as well as the rise and recession limbs of the hydrograph are dependent on accurate parameterization of the vertical water budget in IBIS, and the lateral water budget in THMB. Parameters that impact the water balance include those that adjust the soil moisture physics and control flow velocity. Relevant model parameters in both IBIS and THMB were adjusted based on known physical parameters, if available, or otherwise tuned to improve reproduction of the observed 30-year average hydrograph. Each parameter was systematically tested to determine how it influenced simulated results.

2.4.1 Vertical water budget

IBIS calculates evapotranspiration, surface, and subsurface runoff through its atmosphere, soil and vegetation modules. The default soil parameters produced a low subsurface to surface runoff ratio that resulted in a winter streamflow deficit and poor peak flow timing. The shape of the total runoff was sensitive to the partitioning of surface and subsurface flows, which differed in their annual distributions. For example, subsurface runoff tended to peak roughly one month later than surface runoff and was responsible for winter runoff. The relative contributions of surface and subsurface runoff control the hydrograph response of streamflow in THMB, changing the timing of peak flows and the magnitude of winter flows.

It was expected that some IBIS soil parameters may require adjustment from their default values in order to optimize simulations for the boreal environment of the ARB (D. Price, pers. comm.). A sensitivity analysis of the various IBIS module parameters was performed to investigate the dominant controls on the vertical water balance in the ARB in order to simulate more realistic ratios of surface and subsurface runoff. Three IBIS soil parameters were identified as the dominant controls which govern:

1. the thickness of the top soil layer

2. the total soil depth

3. the saturated hydraulic conductivity of soil types

The parameters were systematically tested (Figure 2.3) to determine their effects on average monthly actual evapotranspiration and surface and subsurface runoff patterns at the hydrometric station location on the Athabasca River 'Below McMurray'. During testing, the runoff and actual evapotranspiration in all grid cells upstream of this station were summed to represent the total upstream contribution to the local water balance over a shorter five year time period 1984–1988.

The first parameter, the thickness of the top layer of soil, is expected to control infiltration capacity and evapotranspiration. Increasing the layer thickness was observed to increase the ratio of subsurface to surface runoff (Figure 2.3a,b) and broaden the peak runoff (Figure 2.3c). This effect translated into higher streamflow later in the year. Varying the top soil layer thickness produced little impact on the distribution of actual evapotranspiration (Figure 2.3d).

The second parameter, the total soil depth, is expected to control the residence time of subsurface runoff in the soil column. The total soil depth was adjusted across a range below the maximum soil depths that have been observed in different locations of the basin, as documented in the Alberta Soil Survey Reports 27, 29, 31, 42, 43, 44, 58-1, 64-1, and 64-2 ([Dumanski et al., 1972, Holland and Coen, 1983, Kjearsgaard, 1973, Knapik and Lindsay, 1983, Lindsay et al., 1957, 1963, Turchenek and Lindsay, 1982, Wynnyk et al., 1963, 1969]. Increasing the soil depth was observed to decrease the surface runoff (Figure 2.3e) and redistribute the subsurface runoff more uniformly across the seasons (Figure 2.3f). Increasing the soil depth effectively increased the total runoff in the winter months by increasing the residence time of water in the soil column. The shape of the total runoff distribution was primarily controlled by surface runoff, regardless of soil depth (Figure 2.3g). Again, actual evapotranspiration was not significantly altered by changing the total soil depth (Figure 2.3h). Although actual soil depths varied across a basin, IBIS specifies a single soil depth for the entire modelled area to avoid discontinuities between grid cells.

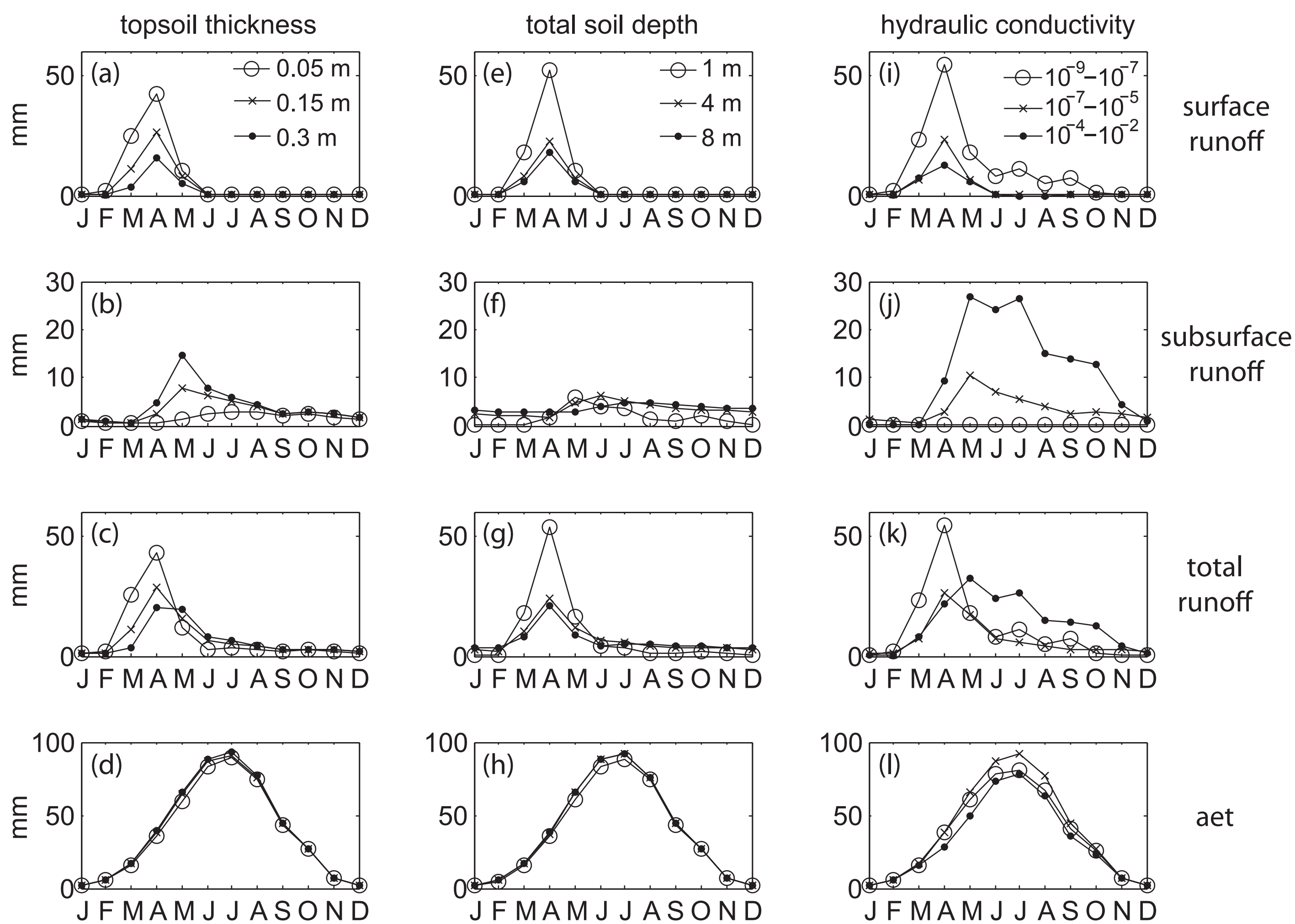

Figure 2.3: Systematic variation of three IBIS parameters (top soil layer thickness (a–d), total soil depth (e–h), saturated hydraulic conductivity (j–l)) and the effects on runoff and actual evapotranspiration (aet) patterns. Each parameter was varied while keeping the others at the following default values: top soil layer thickness = 0.2 m, soil depth = 2 m, hydraulic conductivity = $10^{-7} - 10^{-5}$ m/s. The IBIS output shown for each month is an average over a five year time interval, 1984–1988.

The third parameter, the vertical saturated hydraulic conductivity (k_s) is defined in IBIS for each soil texture class ranging from sand (highest k_s) to clay (lowest k_s) and is expected to control infiltration and percolation through each soil layer. The magnitudes of k_s were adjusted within the observed range of field measurements reported at a site within the ARB [Coen and Wang, 1989]. The ratio of subsurface to surface runoff increased as k_s of all texture classes was increased, and the subsurface runoff distribution broadened (Figure 2.3i,j). As k_s was increased (by the same order of magnitude for each texture class), a greater fraction of the total runoff occurred in later months (Figure 2.3k). Meanwhile, actual evapotranspiration decreased (Figure 2.3l), and may indicate that a greater fraction of runoff percolated into deeper soil layers beyond the rooting depth as k_s was increased. The vertical saturated hydraulic conductivities used are on the high end of the observed range of field measurements at the Athabasca site reported in Coen and Wang [1989].

Since observations of surface and subsurface runoff were unavailable for the ARB, the soil parameter values were systematically adjusted to minimize the difference between the simulated and observed seasonal hydrograph. The final IBIS parameter set consisted of a 0.2 m top soil layer thickness, a 1.5 m total soil depth (5 soil layers), and a k_s range of 10^{-5}–10^{-3} m/s (Table 2.3).

Other IBIS modules and parameters that could affect the water content of soils were also considered in tuning the vertical water balance. Snowmelt processes have been modelled using different approaches of varying complexity, ranging from simple methods based only on temperature measurements [Morris, 1985] to complex multilayer models based on an energy balance [Jordan, 1991, Marks et al., 1999]. A simple three layer snow model, such as the algorithm implemented in IBIS, is adequate to model snowpack physics on the continental scale, based on ground and surface radiation temperatures and accounting for snowpack ripening that characterizes snowpack growth and ablation [Lynch-Stieglitz, 1994, Stieglitz et al., 2001]. The density of snow controls the accuracy of snow cover simulation and is important to soil moisture distribution and timing. While snow density is

Table 2.3: Final saturated hydraulic conductivities (k_s) assigned to IBIS soil textures.

Texture Class	k_s
Sand	5.83x10^{-3}
Loamy Sand	1.703x10^{-3}
Sandy Loam	7.19x10^{-4}
Loam	3.67x10^{-4}
Silty Loam	1.89x10^{-4}
Sandy Clay Loam	1.19x10^{-4}
Clay Loam	6.39x10^{-5}
Silty Clay Loam	4.17x10^{-5}
Sandy Clay	3.33x10^{-5}
Silty Clay	2.50x10^{-5}
Clay	1.67x10^{-5}

approximated using the density of the snowpack in IBIS, Vano et al. [2006] found that it was better to approximate snow density using the density of snowfall despite resulting overestimates of the snow depth. Decreasing the density of snow in IBIS produced an increase in drainage, however this change was small relative to the effects of adjusting k_s, and the snow density was subsequently left unchanged.

Additional IBIS soil parameters were also investigated, but each was observed to have little impact on runoff output. These included the maximum allowed puddle depth on the surface of the soil, which is expected to affect the amount of infiltration that occurs, and the boundary layer permeability at the bottom of the soil column, which controls the gravitational drainage of water. The default soil module infiltration equations, based on Darcy's law, were also tested against the Green-Ampt infiltration equations [Green and Ampt, 1911], which are expected to increase infiltration into the soil column [Li et al., 2005]. However, the introduction of the Green-Ampt equations was not observed to increase the subsurface to surface runoff ratio significantly relative to the three main soil parameters, and was therefore not implemented.

Lastly, various soil data sets were substituted to test if they improved model performance. The International Geosphere-Biosphere Programme soils data available with IBIS v2.6b4 (general distribution), is of a coarser resolution and results in a lower subsurface to surface runoff ratio than the ISRIC-WISE soils data set used. The soil profiles from the CanSIS database included an organic soil type and no clay soils, which produced a small improvement in the peak runoff timing, but also led to very high rates of evapotranspiration and were unsuitable. In addition, only one grid cell in the ARB was assigned the organic soil type in this data set.

2.4.2 Lateral water budget

Adapting the THMB code to a specific river basin requires identifying suitable parameter values for the river velocity and floodplain algorithms.

River velocity

The timing and movement of streamflow between THMB gridcells for the ARB is primarily controlled by the grid cell flow velocity, u, which in turn is controlled by the wetted perimeter. The river bankfull height (h_i) and width (w_i) which define the wetted perimeter are calculated as power-law functions of the upstream area. To adapt THMB to the ARB, simple statistical relationships ($p < 0.01$) were derived using the empirical measurements of the 2-year flood width and depth characteristics for the Athabasca River [Kellerhals et al., 1972] (Table 2.1), and are given by

$$d_i = 0.3201 \cdot A_u^{0.2108} \tag{2.4}$$

$$w_i = 0.6765 \cdot A_u^{0.5453} \tag{2.5}$$

$$\tag{2.6}$$

where A_u is the upstream area of each grid cell.

River sinuosity (s) also affects the calculation of river velocity by changing the river length in each grid cell. Based on observations of sinuosity for rivers in the

ARB [Kellerhals et al., 1972], the approximate power-law relationship ($p < 0.05$) between river sinuosity and upstream area was calculated to be

$$s = 2.7755 \cdot A_u^{-0.0696} \tag{2.7}$$

This was applied to calculate a spatially varying river sinuosity for each gridcell in the basin.

Other THMB parameters related to sub-grid drainage and reference velocities were set to values used in past studies [Coe, 2000, Donner, 2002]. The surface runoff timing constant was set as a function of the average grid cell length and the effective reference velocity. The subsurface runoff residence time was set to 15 days, and the groundwater residence time was set to 180 days; Donner [2002] concluded that the timing of simulated monthly river discharge in continental-scale river basins was not sensitive to these parameters. The effective reference velocity ($u_o = 0.35$ m/s) in THMB was set based on a global study of continental-scale river basins by Miller et al. [1994]. The reference gradient (i_o = 1x10^{-4}), reference wetted perimeter (w_o), and reference velocities for river and floodplain were then simultaneously tuned to improve streamflow output timing.

Floodplain dynamics

The calculation of the flood initiation volume followed three steps. First, the bankfull flux in each grid cell was calculated from the simulated average daily flux over a 10-year period from 1990–1999, using an empirical rating curve relationship. This rating curve was updated for the ARB using observations of the long-term mean discharge and 2-year flood discharge data (Table 2.1), and was derived ($p < 0.01$) to be:

$$F_i = 15.0962 + 4.6560\bar{F} - 0.0017\bar{F}^2 \tag{2.8}$$

where F_i is the bankfull flux and $\bar{F}$ is the long-term mean flux. Second, the cross-sectional area of the river was calculated based on the bankfull flux F_i and the average (hourly) river velocity over the 10-year period. Lastly, the bankfull flood initiation volume was calculated as the product of the cross-sectional area and the river length.

The floodplain algorithm in THMB was originally designed to describe the spatial extent of seasonal flooding in the Amazon Basin, but not to simulate the effect of floodplain inundation on river discharge [Coe et al., 2008]. For this study, the flooding algorithm was updated in order to improve the accounting of exchange between floodplain and river reservoirs, and to test for a possible influence of floodplain dynamics on streamflow. In the initial THMB code, water in an individual grid cell could be added to a floodplain reservoir, but was not subtracted from the river reservoir, such that the calculated floodplain flow had no effect on downstream flow. The algorithm was updated to allow floodplain water levels to influence the integrated downstream velocity of the river channel and floodplain waters by computing a weighted average velocity based on the fractional grid cell coverage of the river channel and inundated areas:

$$u = uA_r + u_f A_f \tag{2.9}$$

where A_r and A_f are the grid cell fractional areas for river and floodplain respectively and u_f is the floodplain flow velocity. This allowed the floodplain flow to modulate river flow while still maintaining numerical stability in the model by avoiding direct exchanges between the river and floodplain reservoir volumes. The reference floodplain velocity was arbitrarily set at $u_{fo} = 0.27$ m/s to roughly represent the slower expected movement of floodplain waters. The floodplain wetted perimeter was then tuned to improve streamflow timing.

Ultimately, flood occurrences were infrequent in the ARB and generally accounted for a small fraction of the total grid cell volume, such that the streamflow timing was not sensitive to the temporal and spatial extent of flooding. Although observational data was not available to validate the simulated floodplain area in THMB, its calculation does serve to parameterize sub-grid surface water flow, as distinct from the main river movement within a grid cell. The new floodplain algorithm may also be useful in future applications of THMB to other river basins with available floodplain observations.

In an effort to obtain streamflow resolution and estimate inundated area at a finer scale, a simplified version of the THMB model was also tested for the ARB. This simple model required only climate and topography as input and calculated the river directions at each time step as a function of water head. Model runs were performed at 1 km resolution using the SRTM topography data, however streamflow flux calculations became unstable for several grid cells, an indication that the water volume was too high for this method to be useful in the ARB. THMB was also tested using predicted instead of prescribed lake areas, but this was found to reduce the accuracy of streamflow simulations.

2.5 Model performance

An optimal parameterization was derived from the systematic comparison of adjusted model parameter values in both IBIS and THMB, to the extent that they can be validated using streamflow observations. The suite of parameter values were chosen that generated the observed conditions for average annual streamflow, seasonality of flow, and timing of peak flow at the hydrometric station location Below McMurray. Model simulations were evaluated based on calculated errors between observed and modelled annual and seasonal flow, and by applying statistical model performance ratings to the monthly flow time series.

2.5.1 Annual and seasonal variability

The model output captured the shape of the average hydrograph, including the broad peak flow, reasonably well at Below McMurray (Figure 2.4a). The flow regime of the Athabasca River is typical of northern rivers with mountainous headwaters and downstream plains, and is characterized by low flows in the winter, followed by rising discharge associated with snowmelt in the lowlands, and leading to a broad peak flow due to convective summer storms and possibly sustained by glacier and high-elevation snowmelt in its headwater areas [Woo and Thorne, 2003, Kerkhoven and Gan, 2006]. The simulated hydrograph began to rise as expected in (late) April, followed by a sharper rise to a broad peak in June and an increase to maximum flow in July.

Statistical comparisons between simulated and observed annual, seasonal, peak, and minimum flows showed best model performance at Below McMurray, the most downstream monitoring station (Table 2.4). The simulated mean annual flow and peak monthly flow was within 2.5% of the observations over the 30-year time period. Average summer flows (July-October) best agreed with observations to within 1%, and although average winter flows (November-March) were not as well simulated, the minimum flow was within 5% of observations.

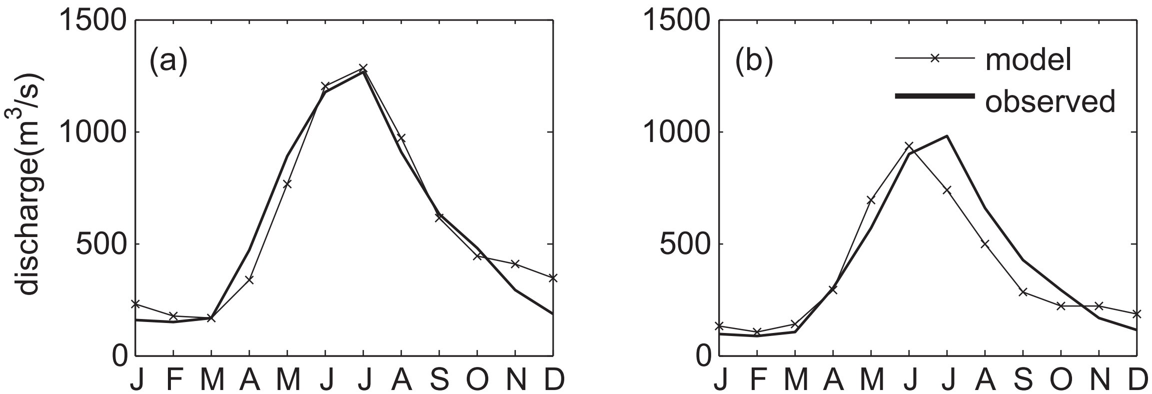

Figure 2.4: Model runs over the historical period of 1981–2010 compared to streamflow observations at the monitoring stations (a) Below McMurray, (b) At Athabasca.

Table 2.4: Average annual and seasonal statistics at four gauging stations between 1981–2010, comparing model output to observed data. Values are model discharge as a percentage greater (+) or less (-) than observed discharge, while the shift in peak flow between model and observations is in days. Seasons are summer (July–October), winter (November–March), and spring (April–June).

	Below McMurray	At Athabasca	At Hinton	Near Jasper
annual flow	+2.4%	-5.8%	+17.4%	-15.3%
peak flow	-2.3%	-9.7%	+22.8%	-16.9%
peak shift	+13 d	-18 d	-34 d	-46 d
minimum flow	+4.6%	+7.8%	+43.5%	+73.0%
minimum shift	-4 d	+1 d	+42 d	+80 d
spring flow	-9.2%	+7.7%	+101.4%	+48.3%
summer flow	0.5%	-26.4%	-48.7%	-70.8%
winter flow	+40.7%	+38.3%	+91.5%	+136.8%

Further upstream at the At Athabasca monitoring station, the average annual flow was reasonably well simulated, within 6% of observed magnitudes (Figure 2.3b). The lower model accuracy at the two far upstream stations of Near Jasper and At Hinton is expected; these stations drain a small number (3–4) of mountainous grid cells, an area over which precise streamflow simulation is not realistic from a large-scale model. Since the mean elevation for a given IBIS grid cell in the mountains is much lower than the actual peak elevations within the cell area, IBIS cannot describe the heterogeneous processes of ablation and high elevation snowmelt that extend peak flows later into the year. In basins with glaciated headwaters, the ablation of glaciers intensifies in the summer and this, together with snowmelt at high elevations, prolongs the high flows into summer [Woo and Thorne, 2003]. This results in simulated flow with a narrow, earlier seasonal peak in runoff at the upstream stations (Figure 2.5), which indicate an underestimate of upstream water storage. Therefore, the spatial variability in model performance likely arises in the generation of IBIS runoff. This scale problem in the mountainous grid cells has little effect on basin-scale streamflow timing, as evidenced by the realistic simulation of flow at the At Athabasca and Below McMurray stations. There was limited flow data for locations downstream of Fort McMurray, so the model performance further downstream could not be verified. For example, the Regional Aquatics Monitoring Program and Water Survey of Canada hydrometric stations for the Athabasca River near the Embarras Airport only have available data for less than a third of the historical time period.

2.5.2 Interannual variability

Further evaluation of model performance focused on the Below McMurray station, the closest location to the oil sands mining operations. The monthly-averaged simulated flow at Below McMurray over the 30-year time period was well correlated ($r = 0.73$, $p < 0.01$) with observations (Figure 2.6). In the last decade of the time period (2001–2010), flows were consistently over-predicted by 25% or more in the late spring and early summer (June–August), approximately 70–80% more frequently than in the other two decades.

No definitive criteria for evaluating model performance have been established in the literature yet. However, three quantitative statistical methods for hydrological time series analysis performed on a monthly time step, have been recommended by Moriasi et al. [2007]: the Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and a ratio of the root mean square error to the standard deviation of measured data (RSR). These methods have been used extensively in the statistical evaluation of streamflow in both large- and small-scale river basins [e.g., Li et al., 2009, Bekele and Knapp, 2010, Srinivasan et al., 2010], and were used to assess model accuracy of streamflow output from IBIS-THMB (Table 2.5).

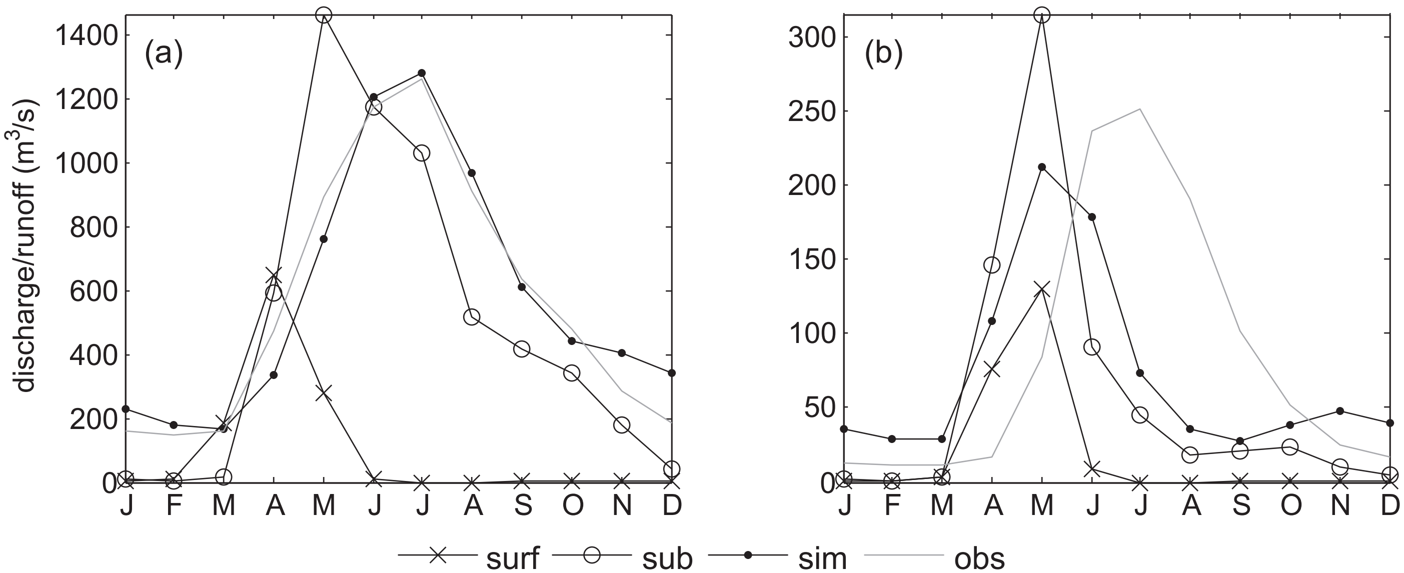

Figure 2.5: Comparison of the surface (surf) and subsurface (sub) runoff generated by IBIS for (a) downstream (Below McMurray) and (b) upstream (Near Jasper) locations, along with simulated (sim) and observed (obs) streamflow. Runoff values are summed from all grid cells upstream of the station location.

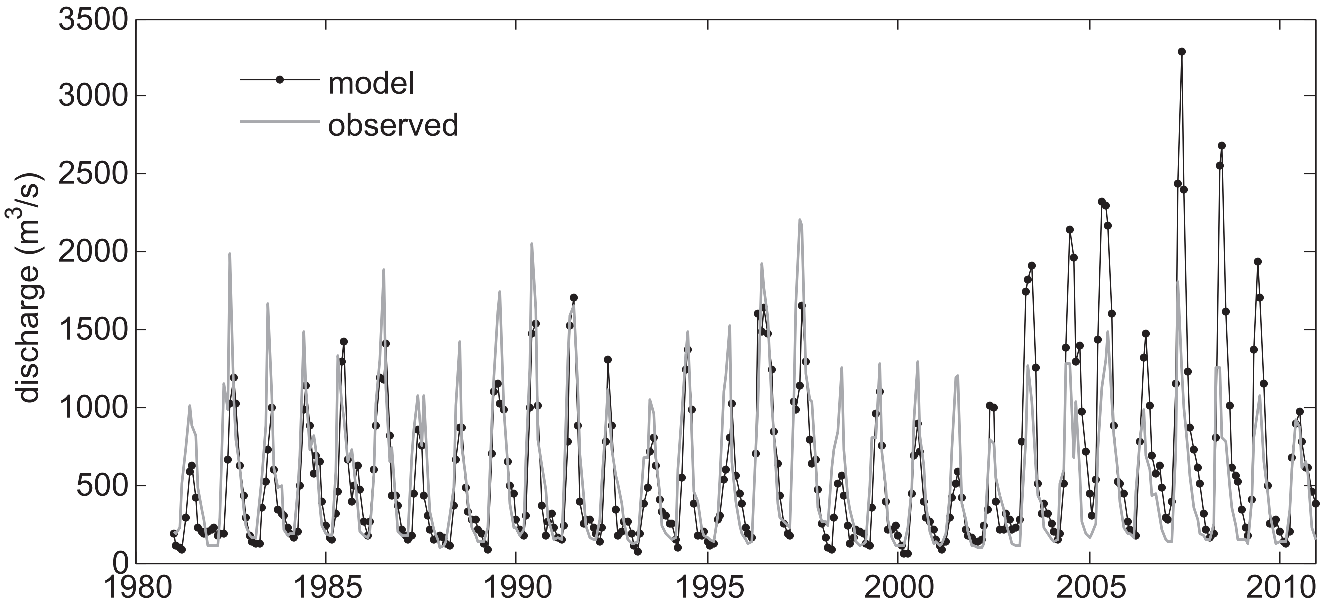

Figure 2.6: Monthly simulated and observed discharge over the 30-year time period 1981-2010, at the Below McMurray location.

The NSE statistic determines the relative magnitude of the residual variance to the measured data variance, and is given by

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n} (Y_i^{obs} - Y^{mean})^2} \right] \tag{2.10}$$

where Y_i^{obs} is the ith observation, Y_i^{sim} is the ith simulated value, and Y^{mean} is the mean of the observed data for n total observations. NSE indicates how well the observed and modelled flow fits a 1:1 line, and ranges between $-\infty$ and 1.0 where 1.0 is the optimal value.

The PBIAS statistic measures the percentage of residual variance, which gives the average tendency of the simulated data to overestimate or underestimate observations. Low absolute magnitude values indicate higher accuracy, with the optimal value being 0.0%. PBIAS is expressed as:

$$\mathrm{PBIAS} = \left[\frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim}) \cdot 100}{\sum_{i=1}^{n} Y_i^{obs}} \right] \tag{2.11}$$

The RSR statistic is the root mean square error (RMSE) normalized by the standard deviation of the observations and is given by

$$\mathrm{RSR} = \left[\frac{\sqrt{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2}}{\sqrt{\sum_{i=1}^{n} (Y_i^{obs} - Y^{mean})^2}} \right] \tag{2.12}$$

The RSR provides scale to the error indicated by RMSE. The optimal value of RSR is 0, with lower values indicating better model performance.

When applied over the entire 30-year time period at the Below McMurray location, the NSE and RSR statistical tests indicated unsatisfactory model performance (Table 2.5), as defined by Moriasi et al. [2007]. Model performance improved to satisfactory or good across all three statistics when tested separately over the first and second decades, with best performance in the second decade. The unsatisfactory model performance in the third decade across all three statistics, with the PBIAS test showing strong model overestimation, reduced the overall model performance across the 30-year time period.

To examine whether the reduced predictive skill of the model at the Below McMurray station during the final decade, 2001–2010, may be driven by climatological input data or unrepresented anthropogenic activities (land use and land cover changes or water use and withdrawals related to oil sands or other resource projects) that were unaccounted for in the model simulations, model performance at the At Athabasca station, which lies upstream of all oil sands projects, was also evaluated (Table 2.5). Model performance at At Athabasca was satisfactory under the NSE and RSR statistical tests over the entire 30-year validation period, in contrast to test results at Below McMurray, suggesting that recent human activity affecting streamflow that is not accounted for in the model runs may be responsible for lower downstream model performance at Below McMurray.

Unsatisfactory model performance at At Athabasca in the third decade, as well as at Below McMurray, further suggests that some of the discrepancy between modelled and observed monthly streamflow may also be due to the climatological inputs. For example, the NARR climate data is known to have regional problems with the precipitation analysis over Canada, due to a limited set of gauge observations [Mesinger et al., 2006]. A comparison between Environment Canada monthly precipitation observations at Fort McMurray between 1981-2010 and the monthly NARR precipitation inputs, demonstrated that the NARR precipitation in the last decade of the time period (2001–2010), was higher by 25% or more between May and July, approximately 30–70% more frequently than in the other two decades. This is consistent with the overpredicted modelled streamflow in the last decade and suggests that precipitation inputs drive the disagreement with observed streamflow.

Table 2.5: Evaluation of model performance (streamflow output) using three statistics for monthly timesteps. Performance ratings in brackets are either unsatisfactory (u), satisfactory (s), good (g) or very good (v), as defined by Moriasi et al. [2007]. The model was evaluated over the entire time period of interest, as well as over each decade.

statistic	1981-2010		1981-1990		1991-2000		2001-2010	
	Below McMurray	At Athabasca	Below McMurray	At Athabasca	Below McMurray	At Athabasca	Below McMurray	At Athabasca
RSR	0.81 (u)	0.70 (s)	0.62 (s)	0.67 (s)	0.53 (g)	0.56 (g)	1.30 (u)	0.92 (u)
NSE	0.35 (u)	0.50 (s)	0.61 (s)	0.55 (s)	0.72 (g)	0.69 (g)	-0.68 (u)	0.16 (u)
PBIAS	-2.44 (v)	5.79 (v)	18.48 (s)	20.25 (s)	16.83 (s)	18.86 (s)	-50.82 (u)	-27.06 (u)

Table 2.6: Comparison of month-averaged daily streamflow outputs with monthly streamflow outputs using three statistics. Performance ratings in brackets are either unsatisfactory (u), satisfactory (s), good (g) or very good (v), as defined by Moriasi et al. [2007]. The simulations were evaluated over the entire time period of interest, as well as over each decade, at Below McMurray.

streamflow driven by monthly IBIS output				
statistic	1981-2010	1981-1990	1991-2000	2001-2010
RSR	0.00 (v)	0.00 (v)	0.00 (v)	0.00 (v)
NSE	1.00 (v)	1.00 (v)	1.00 (v)	1.00 (v)
PBIAS	0.00 (v)	0.00 (v)	0.00 (v)	0.00 (v)
streamflow driven by daily IBIS output				
RSR	0.13 (v)	0.18 (v)	0.15 (v)	0.12 (v)
NSE	0.98 (v)	0.97 (v)	0.98 (v)	0.99 (v)
PBIAS	0.58 (v)	0.88 (v)	1.46 (v)	-0.20 (v)

Daily streamflow was also simulated and compared to the monthly simulated streamflow. A comparison was made between

1. monthly THMB-simulated streamflow driven by monthly IBIS-simulated output

2. month-averaged daily THMB-simulated streamflow driven by daily IBIS-simulated output

3. month-averaged daily THMB streamflow driven by monthly IBIS outputs

The RSR, NSE and PBIAS statistics were calculated between 1) and 2), and 1) and 3) (Table 2.6). All comparisons showed only minor differences in simulated streamflow between daily and monthly timesteps. As a result, for computational efficiency, the study results are based on monthly THMB streamflow simulations driven by monthly IBIS outputs.

2.5.3 Uncertainties

Comprehensive observations are needed to fully validate both the vertical and horizontal water budgets in soils and river transport. In the Athabasca River Basin, a more extensive and continuous hydrologic monitoring network is needed to validate model simulations of streamflow, particularly further downstream in the basin. For IBIS, observations of soil moisture and subsurface runoff in the ARB are limited, and parameter adjustments must be validated indirectly and in combination with other parameters, through streamflow observations. For THMB, empirical data on river velocity, floodplain morphology and inundation is needed to better parameterize the flow network, but is also limited for the ARB. Such observations are required to validate the new floodplain equations and to confirm that they improve the accounting of surface waters and streamflow timing. Data on inundated surface area based on multiple satellite observations [Prigent et al., 2001] so far lack accuracy for western Canada, including the ARB region. Some progress has been made in the use of satellite data to map soil moisture [e.g., Temimi et al., 2010] by translating SSM/I passive microwave and MODIS images into a water surface fraction. Future validation of soil moisture may be possible via the Soil Moisture Active Passive Mission (SMAP) [Entekhabi et al., 2010], scheduled to launch by 2014.

Accurate parameterization and validation of floodplain and soil processes could also advance the modeling of other basin processes that affect streamflow, such as the spatial and temporal variability of wetland areas which play an important role in flow connectivity across a landscape, and therefore the timing of river flows. In addition, although soil physics is expected to play a larger role in driving streamflow timing, better parameterization of river transport, including accounting for dynamic ice effects, could also refine streamflow simulations. Like other large-scale models of northern rivers, THMB does not represent river-ice freeze, melt, and ice jam cycles, which may influence the flow of the Athabasca River [Andres, 1980, Burn et al., 2004, de Rham et al., 2008, Beltaos, 2013]. Ice dynamics and their influence on flow are well known to be difficult to simulate due to the lack of high-resolution data for model development and the difficulty in parameterizing the exact timing of freeze-up and melt, as well as the mechanics of ice jam release [Prowse and Beltaos, 2002, Prowse et al., 2007, Beltaos, 2007, Peters et al., 2014]. Land use change is also not accounted for in the streamflow simulations, and this may add to model uncertainies. The currently disturbed area of oil sands mining operations (602 km^2) constitute only a fraction of an IBIS grid cell and is expected to have a negligible impact on runoff and subsequent downstream flow, relative to upstream basin contributions. The recent spread of mountain pine beetle in the Upper Athabasca [Forcorp Solutions Inc., 2012] may however result in considerable deforestation that can lead to runoff impacts over a wider area.

2.6 Conclusions

This chapter describes the implementation of a two-model system, IBIS and THMB, to simulate the movement of water in the Athabasca River Basin between the atmosphere and soil, through streams and lakes, and over topography. Model parameters were calibrated to reflect the physical characteristics of the basin, where the water budget is largely controlled by the vertical movement of water through soils in IBIS and the velocity of water through the river network in THMB. The THMB routing algorithm was modified to improve the accounting of floodplain waters, and to enable floodplain flow to impact river flow velocity and therefore the timing of discharge.

The IBIS-THMB modelling system reproduced the annual hydrograph well at the basin location that will be important to assessing water use in the following chapters. The simulated time series of monthly flow, which represents the sensitivity of streamflow to interannual variations in climate, was over-predicted 70–80% more frequently in the most recent decade, possibly due to a combination of consumptive water use in the lower basin and input data.

While model performance is limited by a lack of available observations on parameters that control the vertical and horizontal water balance, the IBIS-THMB simulations of streamflow can be applied to assess relative streamflow impacts.

The realistic sensitivity of model-simulated streamflow to climate variability suggests the models may be well-suited to simulate streamflow in different climate regimes. The historical streamflow simulation established in this chapter provides a baseline for the following chapters to assess future spatial and temporal changes due to human water withdrawals and climate change in the Athabasca River Basin.

Chapter 3

Sensitivity of Streamflow to Water Withdrawals for the Athabasca Oil Sands

3.1 Introduction

One of the major environmental concerns associated with oil sands operations is the intensive freshwater demand. Extracting, processing and upgrading crude bitumen from oil sands (a mixture of sand, water, bitumen, heavy metals and other contaminants), all require a constant water supply. In the Athabasca River Basin (ARB), oil sands mining operations already account for the largest sectoral water allocations (62%) and actual water use (57%), with roughly 93% of actual water use as surface water volume [AMEC Earth & Environmental, 2007]. Oil sands operations draw water from a variety of sources including surface water (rivers, runoff), fresh groundwater wells, saline aquifers, recycled water, and storage water. The majority of the surface water use is withdrawn by mining operations, which primarily divert water from the Athabasca River. The Athabasca River, a tributary of the Mackenzie River, drains into the Peace-Athabasca Delta (PAD), an ecologically sensitive region of wetlands and lakes that is highly responsive to natural variability in river flows and water levels [Peters et al., 2006]. Along with the Peace River, the Athabasca also supplies much of the winter low flow of the Mackenzie River, which drains northward into the Arctic Ocean [Woo and Thorne, 2003]. Increased water withdrawals may affect the volume and timing of downstream flows required to sustain freshwater and estuarine ecosystems and the goods and services that those ecosystems provide.

The impact of oil sands water withdrawals on the Athabasca River streamflow will depend upon the scale of future operational expansion. The oil sands deposits in northern Alberta constitute a reliable, long-term supply for the growing global demand for crude oil. In 2012, annual crude bitumen production from surface mining reached 338 million barrels per year [ERCB, 2013] and at these rates, mining production could last for over a century. New operations and planned expansions for existing mines are expected to increase production capacity by nearly 500% through 2035 [The Oil Sands Developers Group, 2013]. As mining activity expands, surface water use demand is projected to rapidly increase, adding pressure to water availability in the ARB [Natural Resources Canada, 2009].

Under compliance with Phase One of the Lower Athabasca River Water Management Framework, oil sands operators are currently licensed to withdraw 1-2% of annual flow from the Athabasca River each year in order to maintain historical median flows [Alberta Environment, 2007], although water use reporting remains voluntary. While the overall annual allocations are relatively small, sustained bitumen production rates throughout the year, together with seasonality in flow, means that withdrawals can be large relative to low winter flows [Swainson, 2009]. Phase Two of the Lower Water Management Framework is currently under development and aims to establish best management practices under a high-growth scenario [Ohlson et al., 2010], but stakeholders have been unable to achieve consensus on a final set of water management rules. While studies have shown that a long-term approach to applying water restrictions is needed [e.g., Mannix et al., 2010], there is a lack of physically-based analyses that identify the response of streamflow to withdrawals within the context of the basin's hydrological regime and the location and timeline of current and planned water withdrawals.

This chapter describes a first attempt to explore the sensitivity of streamflow in the Athabasca River to water withdrawals for oil sands operations by linking two independent, process-based models: the Integrated Biosphere Simulator (IBIS) [Foley et al., 1996, Kucharik et al., 2000], a land surface process model, and the Terrestrial Hydrology Model with Biogeochemistry (THMB) [Coe et al., 2002], a hydrological routing model. IBIS and THMB have been used together in dozens of global, large-scale studies, including simulations of continental-scale runoff in North America [Lenters et al., 2000, Coe and Foley, 2001] and Africa [Li et al., 2005], Amazonian flooding [Coe et al., 2002], and Mississippi nutrient flux [Donner et al., 2002]. Here, the models are first validated for the ARB and then applied to simulate streamflow under new oil sands water use scenarios developed from data on current and planned oil sands projects. The impacts of water withdrawals are assessed based on relative changes to streamflow magnitude and the frequency of occurrence of low flows.

3.2 Methods

3.2.1 Model description: IBIS

The Integrated Biosphere Simulator (IBIS) is a process-based land surface model that simulates the coupled soil-vegetation-atmosphere water and energy budgets [Foley et al., 1996, Kucharik et al., 2000]. IBIS is scale independent and has been used at sites ranging from one square kilometre (e.g. farm fields) to millions of square kilometres (e.g. Amazon Basin). The model has been validated against site-specific biophysical measurements (e.g. evapotranspiration, sensible heat flux, vegetation phenology, soil moisture and ice, snow cover and depth, soil temperature, groundwater recharge and river discharge), as well as spatially extensive ecological data (e.g. total and living biomass) [Delire and Foley, 1999, Lenters et al., 2000, Coe and Foley, 2001, Coe et al., 2002, Botta and Foley, 2002, Botta et al., 2002, Vano et al., 2006] including in cold regions such as Canadian boreal forest ecosystems [El Maayar et al., 2001, Liu et al., 2005] and the Yukon River Basin [Yuan et al., 2010].

IBIS is forced with daily climate inputs and land surface characteristics including vegetation and soil type. Climate data was retrieved for the 1981–2010 period from the 3-hour-averaged North American Regional Reanalysis (NARR) dataset of the NOAA National Operational Model Archive and Distribution System (NOMADS) [NOAA, 2013] and averaged into daily files. The NARR product uses the National Centers for Environmental Prediction (NCEP) Eta model as its backbone with output on a native 33 km Lambert Conformal Conic projection grid, which was re-projected in a regular latitude-longitude geographic grid of 0.375 degree resolution using a simple inverse distance squared interpolation. The retrieved NARR data fields were specific humidity and temperature at 2 m above the surface, meridional and zonal wind speed vectors at 1000 mb, total cloud cover fraction in the atmosphere column, and total pressure and precipitation at the surface.

Vegetation type maps at 0.375 degree resolution were developed from the Boston University MODIS (MOD12C1) data set [Friedl et al., 2001] and converted to match IBIS vegetation and land cover classifications. Each layer of the soil column was assigned one of 11 defined soil textures [Kucharik et al., 2000] based on soil surface properties (clay and sand fractions) obtained from the ISRIC-WISE soil database [Batjes, 2000]. The properties of each soil texture, as well as their distribution, can be varied to better represent regional soil characteristics and soil climate.

Runoff in the ARB was primarily controlled by three IBIS soil parameters that govern the thickness of soil layers, the total soil depth, and the saturated hydraulic conductivity of soil types. These parameters were systematically tested to determine their relative controls on average monthly actual evapotranspiration, and surface and subsurface runoff patterns (see Figure 2.3 in Chapter 2). Based on this analysis, the soil parameter values were adjusted to minimize the difference between streamflow simulations and observations. The final IBIS simulations employed a top soil layer thickness of 0.2 m, a soil depth of 1.5 m and a final hydraulic conductivity range of $k_s = 10^{-5} - 10^{-3}$ m/s for the 11 soil texture classes, with all parameter values within the range of regional field observations.

Version IBIS v2.6b4 was employed in this study. For more details about IBIS, please see Foley et al. [1996], Kucharik et al. [2000].

3.2.2 Model description: THMB

The Terrestrial Hydrology Model with Biogeochemistry (THMB) [Coe et al., 2002] is a river routing algorithm that translates the surface and subsurface runoff outputs from IBIS into the flow of water through rivers, lakes and floodplains. The output of THMB is a spatially explicit representation of river discharge and flooding extent. THMB has been extensively applied and validated at global and continental scales, including Canada's Arctic-draining rivers [Coe, 2000, Coe and Foley, 2001, Coe et al., 2002, Donner et al., 2002, Donner and Kucharik, 2003, Donner et al., 2004, Shankar et al., 2004]. The streamflow routing algorithm applies prescribed river paths to simulate the storage and transport of water, where the total water within a grid cell at any point is the sum of the land surface runoff, subsurface drainage, precipitation and evaporation over the surface waters, and the flux of water between grid cells. The derived hydrological network and morphology are linked at 5-minute horizontal resolution to a linear reservoir model to simulate the stage and discharge of rivers at a 1-hour time step.

Global geomorphology at 5'x5' resolution for THMB was retrieved from the University of Wisconsins Center for Sustainability and the Global Environment (SAGE) to define the basin drainage area, elevation, river directions, and lake area, location, and sill elevation in THMB [Coe, 2000]. The river directions data, derived from the Global DEM5 digital elevation model GETECH [1995], was manually corrected using physical river maps at grid cells where flow directions were inaccurate. Finer resolution 1 km topographic data from the Shuttle Radar Topography Mission (SRTM) [Farr et al., 2007] was used to define the sub-grid-scale topography within each 5' grid cell in order to calculate fractional flooding using a statistical representation of floodplain morphology, following the method of Coe et al. [2008].

The timing and movement of streamflow between gridcells in THMB is primarily controlled by the effective velocity of the grid cell or river, u, which is a function of the topographic gradient as well as the size of the river [Coe, 2000, Coe et al., 2008]. The river velocity is estimated in part by calculating the wetted perimeter, which is a function of the total discharge volume in the river and is constrained by the bankfull depth (d_i) and width (w_i). Simple statistical relationships for bankfull depth and width as a function of upstream area ($p < 0.01$) were derived from empirical 2-year flood width and depth characteristics collected for 22 river reaches in a channel survey program of Alberta [Kellerhals et al., 1972] (Table 2.1), and given by

$$d_i = 0.3201 \cdot A_u^{0.2108} \tag{3.1}$$

$$w_i = 0.6765 \cdot A_u^{0.5453} \tag{3.2}$$

$$\tag{3.3}$$

where A_u is the upstream area (km^2) of each grid cell. The 2-year flood data was used instead of bankfull data, due to the number of missing values in the recorded bankfull characteristics, and was a reasonable alternative since bankfull discharge is generally expected at 1.6 to 1.8 year recurrence intervals [Leopold, 1994]. The river sinuosity (s) also affects the calculation of river velocity by changing the river length in each grid cell. Based on observations of sinuosity for Alberta rivers [Kellerhals et al., 1972], the approximate power-law relationship ($p < 0.05$) between river sinuosity and upstream area was

$$s = 2.7755 \cdot A_u^{-0.0696} \tag{3.4}$$

and was applied to calculate a spatially varying river sinuosity for each gridcell in the basin.

The THMB version THMB.v1f Coe et al. [2008] used in this study was provided by M. Coe (pers. comm.). For more details on THMB, please see Coe [1998], Coe et al. [2002, 2008].

3.2.3 Water withdrawals

The Athabasca Wabiskaw-McMurray deposit within the Athabasca oil sands area is the only deposit where crude bitumen occurs near the surface and can be recovered economically by open-pit mining. This deposit is contained within an area north of Fort McMurray that constitutes 3% of the total oil sands area, with roughly 1% of the available area currently disturbed and 99% of the area under lease [Alberta Energy, 2013]. Between 1981 and 2010, five companies operated six oil sands surface mining sites, and four additional mine sites have since been granted regulatory approval (Table 3.1). In total, twenty licensed source locations of water withdrawals for these mine sites were included in the study (Figure 3.1).

Although licensed water allocations exist for each mine, water use reporting remains voluntary and the actual withdrawal amounts used in this study were compiled from a combination of reported and licensed water use and oil production. Four data sources were used to assess current and future water use for oil sands operations. First, historical annual water use data by operator for 2005–2012 was obtained from the Data Library hosted by Alberta Environment and Sustainable Resource Development [Energy Resources Conservation Board, 2010] and supplemented with information on the breakdown of water use by source (N. Adhikari, pers. comm.).

Table 3.1: Water withdrawal source locations for all current and planned oil sands mining operations.

Operator	Mine	Start Date	Withdrawal Source	Withdrawal Location
Suncor Energy Inc.	Millennium	1967	Athabasca River (SL1)	57.0068°N, -111.4612°E
			surface runoff (SL2)	56.9910°N, -111.3607°E
			surface runoff (SL3)	56.8614°N, -111.2329°E
			surface runoff (SL4)	56.8941°N, -111.3872°E
	North Steepbank	2012	surface runoff (SB1)	57.0104°N, -111.4141°E
	Fort Hills	2016	Athabasca River (SF1)	57.3121°N, -111.6655°E
			surface runoff (SF2)	57.4234°N, -111.3917°E
Syncrude Canada Ltd.	Mildred Lake	1978	Athabasca River (YD1)	57.0269°N, -111.5006°E
			surface runoff (YD2)	57.0431°N, -111.5549°E
	Aurora North	2001	surface runoff (YA1)	57.2831°N, -111.4217°E
Shell Albian Sands	Jackpine	2010	Athabasca River (HJ1)	57.2540°N, -111.6385°E
			tributaries and surface runoff (HJ2)	57.2540°N, -111.3676°E
	Muskeg River	2002	Athabasca River (HG1)	57.2540°N, -111.6385°E
			surface runoff (HG2)	57.2526°N, -111.5333°E
Canadian Natural Resources Limited	Horizon	2008	Athabasca River (CH1)	57.3268°N, -111.6789°E
			Tar River, tributaries, surface runoff (CH2)	57.3849°N, -111.9495°E
Imperial Oil Limited	Kearl	2012	Athabasca River (IK1)	57.5630°N, -111.4967°E
			Muskeg & Firebag Rivers, tributaries, surface runoff (IK2)	57.5630°N, -111.4967°E
Total E&P Canada Ltd.	Joslyn North	2018	Athabasca River (TJ1)	57.2758°N, -111.6656°E
			surface runoff (TJ2)	57.3013°N, -111.6993°E

The second source of data was water allocations by source, available through project water licenses [Alberta Energy Regulator, 2010]. Allocations generally exceeded actual use, in part because they were granted based on volumes needed for operation start-up, which were substantially greater than the volume required for continuous operation [Griffiths et al., 2006]. It was assumed that all licenses would remain valid through 2035, regardless of current expiry dates. Licensed amounts were often delineated based on an expected project phase schedule, and the start year for each phase and associated licensed withdrawal were estimated in these cases.

The third source of data was actual bitumen production by project between 1996–2012 [Alberta Environment and Sustainable Resource Development, 2013], and the fourth source of data was the expected bitumen production capacity by project [The Oil Sands Developers Group, 2013]. Both were used to estimate water withdrawals using the ratio of water use per barrel of oil production, also known as the water use efficiency (WUE), calculated from the most recent actual reported withdrawals and production. The estimated future production capacity in 2035 was based on proposed operations and expansions that had been either recently announced, were under application, or had been granted approval.

The data sources were used to build four scenarios of oil sands expansion in order to assess the sensitivity of streamflow to water withdrawals, relative to a control scenario in which no water is withdrawn. The first oil sands water use scenario assumes that annual withdrawals remain constant at 2010 levels, with 'no-growth' over the model run time period. This was calculated as

$$W_n^E = W_n^A(2010) \tag{3.5}$$

where subscript n denotes the nth water source, W^E, is the estimated water use and W^A is the actual reported water use for the year in brackets.

The second and third scenarios estimate water use based on future oil sands expansion scenarios. The 'capacity-based' expansion scenario estimates annual water withdrawals based on each project's expected oil production capacity in

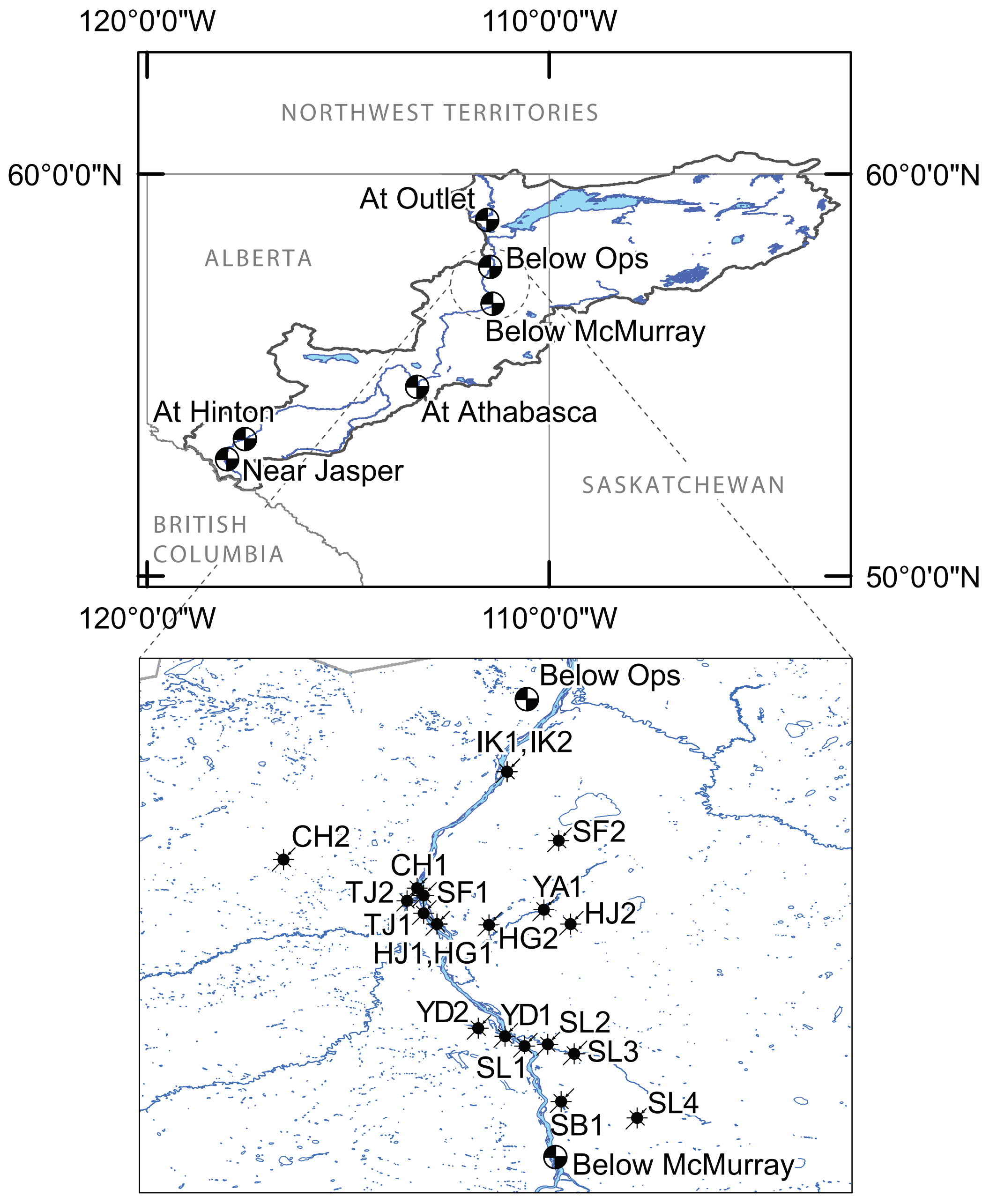

Figure 3.1: Map of the ARB region showing locations of hydrometric stations and model analysis. Inset shows water withdrawal source locations in the oil sands mining region (see Table 3.1 for label references).

2035, and is given by

$$W_n^E = P^C(2035) \cdot \frac{W_n^A(2012)}{P^A(2012)} \tag{3.6}$$

where P^C is the expected production capacity and P^A is the actual reported production for the closest available year (2012, from the available data). The 'license-based' expansion scenario estimates annual water withdrawals based on each project's licensed water allocations in 2035, and is given by

$$W_n^E = W_n^L(2035) \tag{3.7}$$

where W^L is the licensed water use.

The fourth scenario allows for an improvement in the efficiency of water use within the same parameters of the capacity-based scenario. Reductions in water withdrawals are a current focus for oil sands operators and companies have committed to improving their water use efficiency in order to expand operations without increased water allocations. The water use estimate for this 'improved-efficiency' scenario is given by

$$W_n^E = P^C(2035) \cdot WUE(2035) \cdot \frac{W_n^A(2012)}{\sum_n W_n^A(2012)} \tag{3.8}$$

Since 2011, two-thirds of active mining operations have already exceeded planned efficiency targets of a 2:1 WUE [Natural Resources Canada, 2009]. In 2011, estimates from water use and production data show that Suncor and Syncrude mining operations had achieved a WUE of 1.8:1. An extremely optimistic WUE of 1:1 was chosen in the improved-efficiency scenario in order to represent the maximum possible improvement in WUE. This 1:1 ratio is lower than industry projections.

3.2.4 Streamflow simulations

The control scenario (natural flow with no water withdrawals) was used to validate the model against observations of monthly-average river discharge from the Water Survey of Canada Hydrometric Data (HYDAT) database at four locations along the Athabasca River with available long-term observations over the 1981–2010 period (Figure 3.1, Table 2.2). The model was then run under the withdrawal conditions of each oil sands scenario using the same climate input data, in order to capture the range of streamflow responses that could occur under a fixed envelope of typical recent climate variability. For each scenario, the hourly water use rate (m^3/s) for each withdrawal source location was calculated from annual water use assuming sustained water use for 24 hour operations over 365 days of the year, and spatially mapped into model input. Withdrawals were subtracted from the appropriate grid cells at each hourly time step in THMB. The simulated streamflow in each withdrawal scenario was evaluated in terms of changes relative to the control scenario at two selected locations, one immediately downstream of all mining operations (Below Ops), and the second located near the outlet of the ARB (At Outlet), which flows into the PAD.

3.3 Results

3.3.1 Model validation

Statistical comparisons of simulated annual, seasonal, peak, and minimum flows showed best model performance at McMurray, the most downstream monitoring station (Table 2.4). The simulated mean annual flow and peak monthly flow was within 2.5% of the observations over the 30-year time period. Average summer flows (July-October) best agreed with observations to within 1%, and although average winter flows (November-March) were not as well simulated, the minimum flow was within 5% of observations.

The model output captured the shape of the average hydrograph, including the broad peak flow, reasonably well at McMurray (Figure 2.4a). The flow regime of the Athabasca River is typical of northern rivers and is characterized by low flows in the winter, followed by rising discharge associated with snowmelt in the lowlands, and leading to a broad peak flow due to snowmelt in the mountainous headwaters of the basin and convective summer storms [Woo and Thorne, 2003, Kerkhoven and Gan, 2006]. The simulated hydrograph began to rise as expected in (late) April, followed by a sharper rise to a broad peak in June and an increase to maximum flow in July. The interannual variability in simulated flow at McMurray is also well correlated ($r = 0.73, p < 0.01$) with observations (Figure 2.6).

Further upstream at the Athabasca monitoring station, the average annual flow was reasonably well simulated, within 6% of observed magnitudes (Figure 2.4b). The lower model accuracy at the two far upstream stations of Jasper and Hinton is expected; these stations drain a small number (3–4) of mountainous grid cells, an area over which precise streamflow simulation is not realistic from a large-scale model. Since the mean elevation for a given IBIS grid cell in the mountains is much lower than the actual peak elevations within the cell area, IBIS cannot describe the heterogeneous processes of ablation and high elevation snowmelt that extend peak flows later into the year. This results in simulated flow with a narrow, earlier seasonal peak in runoff at the upstream stations (Figure 2.5), which indicate an underestimate of upstream water storage. This scale problem in the mountainous grid cells has little effect on basin-scale streamflow timing, as evidenced by the realistic simulation of flow at the Athabasca and McMurray stations.

Further evaluation of model performance focused on the McMurray station, the closest location to the oil sands mining operations. Model accuracy was assessed using three quantitative statistical methods for hydrological time series analysis recommended by Moriasi et al. [2007]: the Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and a ratio of the root mean square error to the standard deviation of measured data (RSR) (Table 2.5). When applied over the entire 30-year time period at the McMurray location, the NSE and RSR statistical tests indicated unsatisfactory model performance, as defined by Moriasi et al. [2007]. Model performance improved to satisfactory or good across all three statistics when tested separately over the first and second decades, with best performance in the second decade. Unsatisfactory model performance in the third decade across all three statistics, with the PBIAS test showing strong model overestimation, reduced the overall model performance across the 30-year time period.

To examine whether the reduced predictive skill of the model at the McMurray station during the final decade, 2001–2010, may be driven by poor climatological inputs or anthropogenic impacts (land use and land cover changes or water use and withdrawals related to oil sands or other resource projects) that were unaccounted for in the model simulations, model performance at the Athabasca station, which lies upstream of all oil sands projects, was evaluated (Table 2.5). Model performance at Athabasca was satisfactory under the NSE and RSR statistical tests over the entire 30-year validation period, in contrast to test results at McMurray, suggesting that recent human activity affecting streamflow may be responsible for lower downstream model performance at McMurray. Unsatisfactory model performance at Athabasca in the third decade, as well as at McMurray, further suggests that some of the discrepancy between modelled and observed monthly streamflow may also be due to climatological inputs.

Daily streamflow was also simulated and compared to the monthly simulated streamflow. A comparison was made between 1) monthly THMB-simulated streamflow driven by monthly IBIS-simulated output 2) month-averaged daily THMB-simulated streamflow driven by daily IBIS-simulated output and 3) month-averaged daily THMB streamflow driven by monthly IBIS outputs. The RSR, NSE and PBIAS statistics (Moriasi et al., 2007) were calculated between 1) and 2), and 1) and 3) (Table 2.6. All comparisons showed only minor differences in simulated streamflow between daily and monthly timesteps. As a result, for computational efficiency, the study results are based on monthly THMB streamflow simulations driven by monthly IBIS outputs.

3.3.2 Impact of oil sands water withdrawals

The impact of oil sands water withdrawals was evaluated by comparing the control scenario, simulated during model validation, to each withdrawal scenario, in order to control for bias between model simulations and observations. The annual and seasonal flow characteristics of simulated streamflow under each water use scenario were evaluated as a percentage change relative to the control scenario (Table 3.2). Withdrawals based on expected licensed allocations in 2035, the license-based scenario, produced the greatest decrease in streamflow magnitude across all statistics (by 1.3–12.3%), followed by the capacity-based (by 1.0–5.7%), no-growth (by 0.5–2.7%), and improved-efficiency (by 0.5–2.5%) scenarios in order of decreasing impacts.

Across all scenarios, winter and minimum flows experienced the greatest relative decrease in magnitude (by 1.4–6.7% and 2.5–12.3% respectively) due to water withdrawals. In the license-based scenario, winter flows and minimum flows respectively decreased by about two and four times that of mean annual flow. In all scenarios, decreases in the spring, summer, and peak flows were less than those of the mean annual flows by up to 1%. The decreases in streamflow due to water withdrawals were consistently larger at the Below Ops location than the At Outlet location across all scenarios (by 0.1–5.4%), suggesting that additional flows from tributaries and lakes downstream of oil sands disturbance may mitigate the impact of withdrawals.

Table 3.2: Average annual and seasonal statistics of streamflow in each water use scenario, given as a percentage difference relative to the control scenario. The shifts in peak and minimum flows are measured in days.

	'no growth'		'capacity-based'		'license-based'		'improved efficiency'	
	Below Ops	At Outlet	Below Ops	At Outlet	Below Ops	At Outlet	Below Ops	At Outlet
annual flow	-0.71%	-0.41%	-1.48%	-0.85%	-3.15%	-1.81%	-0.65%	-0.37%
peak flow	-0.30%	-0.17%	-0.63%	-0.36%	-1.34%	-0.78%	-0.27%	-0.16%
peak shift	0 d	0 d	0 d	0 d	0 d	0 d	0 d	0 d
minimum flow	-2.67%	-1.50%	-5.74%	-3.22%	-12.26%	-6.87%	-2.50%	-1.40%
minimum shift	0 d	0 d	0 d	0 d	0 d	0 d	0 d	0 d
spring flow	-0.56%	-0.39%	-1.18%	-0.82%	-2.51%	-1.75%	-0.52%	-0.36%
summer flow	-0.49%	-0.26%	-1.02%	-0.55%	-2.18%	-1.18%	-0.45%	-0.24%
winter flow	-1.49%	-0.77%	-3.15%	-1.63%	-6.69%	-3.46%	-1.39%	-0.72%

In each scenario, the models estimate an increase in the frequency of low flows at the Below Ops location. The low flow threshold for each month of the year was defined as the monthly flow magnitude (Q80) that is exceeded 80% of the time over the 30-year time series of simulated flow in the control scenario. To calculate this, the monthly mean flows in each of the 30 different years were ranked and the 80th percentile in flow magnitude was defined as the Q80 threshold for that month. This threshold represents the minimum flow level prescribed by the Alberta Desktop Method to preserve in-stream flow needs [Locke and Paul, 2011], defined as the quantity, timing and quality of water that is required to sustain a healthy aquatic ecosystem [Alberta Environment, 2007]. The low flow frequency was then defined as the percentage of months that flows below the Q80 threshold occur over the 30-year time period.

The models project that the low flow frequency increases the most in the license-based scenario (Figure 3.2), with increases in 8 months of the year, and up to 37% of streamflow occurring as low flows in March, the minimum flow month. The frequency of low flows in the capacity-based scenario is projected to increase for seven months of the year, with low flows occurring up to 33% of the time for some months. The no-growth and improved-efficiency scenarios project the same relative increases in annual low flow occurrence, for five months of the year, up to a 27% low flow frequency. For the four months of June, July, August and November, the models project no increase in the frequency of low flows in any scenario.

3.4 Discussion

3.4.1 Streamflow impacts

Decreases in the magnitude of streamflow due to oil sands water withdrawals were small in all scenarios, demonstrating that water withdrawals will have relatively little impact on overall streamflow magnitudes in the future, even under conditions of maximum permitted withdrawals. Constant water withdrawals throughout the

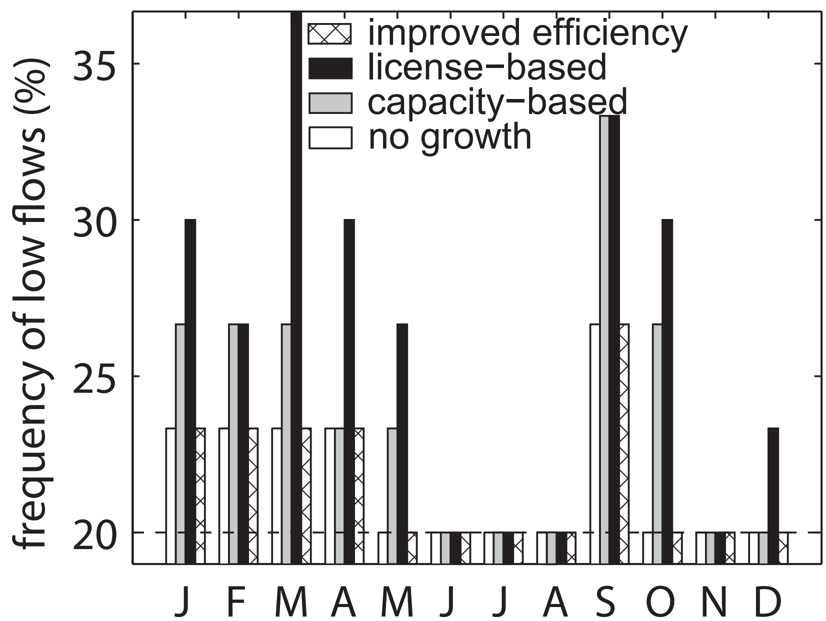

Figure 3.2: Frequency of occurrence of low flows for each month in each withdrawal scenario, at the location Below Ops. In the control scenario, the lowest 20% of flows (dashed line) defines the low flow threshold applied to the other water use scenarios.

year reduce a greater fraction of the streamflow during low winter flow periods as expected.

The frequency of low flows was more sensitive to the intensity of water withdrawals than the flow magnitude was. The low flow frequency is also a better indicator of ecosystem stress, as this determines the length of time that in-stream flow needs are not met. The timing of low flows is an important consideration in water resource management, where operational decisions often depend on the availability of a pre-determined baseline flow at a given time [e.g., Alberta Environment, 2007]. An increase in the frequency of low flows below a threshold such as the Q80 may translate into more frequent restrictions of operational withdrawals, which may disrupt production depending on the regulatory environment. The higher frequency of low flows during eight months of the year in all scenarios suggest that a seasonal operation schedule, in contrast to the current, constant operations year-round, may help to minimize withdrawals during these months, as well as sudden interruptions to production schedules.

A comparison of the no-growth and improved-efficiency scenarios shows that an improvement in water use efficiency under projected 2035 oil sands production levels would reduce the frequency of low flows to those associated with current (2010) practices. The improved WUE of 1:1 used in this study was intentionally optimistic in order to bookend possible future scenarios, as it exceeds planned efficiency targets of 2:1 for most mining operations. It is more likely that future withdrawals in the ARB will involve water use efficiencies between those of the improved-efficiency and capacity-based scenarios, resulting in an up to 10% increase in low flows for some months. As a result, in order to continue meeting in-stream flow needs, limits to the growth of operational withdrawals may need to occur alongside improvements to water use efficiency.

Adaptation of future water use patterns to the projected expansion of water use demand should also consider in-stream flows far downstream of local disturbances. While contributions from tributary flows and lakes did appear to mitigate streamflow reductions in the ARB, even the impacts of low intensity withdrawals under the no-growth scenario did propagate downstream and could become important for larger streamflow reductions. Seasonal recharge in the PAD, for example, depends on a complex network of floodplain lakes, wetlands and channels that are supplied by the Athabasca River [Pavelsky and Smith, 2008].

One of the challenges in interpreting streamflow impacts and adapting management strategies to projected impacts lies in defining the low flow threshold and the level of acceptable risk to in-stream needs. The low flow threshold recently proposed for Phase Two of the Lower Athabasca water management framework [Ohlson et al., 2010] is less restrictive than the Q80 threshold used in this study, yet Phase Two has been unable to achieve consensus on implementing water use restrictions. Although the selection of a low flow threshold should be a function of acceptable mean flow conditions, in reality it will require a balance between maintaining in-stream flow needs with achievable restrictions on oil sands water demand.

3.4.2 Data needs

Comprehensive hydrologic observations including soil moisture, runoff, river and floodplain morphology, and river discharge data are needed to fully validate both the vertical and horizontal water budgets in soils and river transport. However, such information is currently limited for the basin and especially lacking downstream of water withdrawal activities. Observations of soil moisture, soil depth and characteristics, and surface and subsurface runoff would be needed to calibrate soil parameter adjustments in IBIS or any land surface model, while observations of inundated areas would help to better parameterize the flow network in THMB.

A more extensive and continuous hydrologic monitoring network is needed to improve model simulations of future streamflow impacts and the sensitivity to withdrawals. The provincial and national governments have recently invested in a major oil sands monitoring program to be implemented by 2015, which includes a planned expansion of water quantity monitoring sites. Recent industry-funded initiatives like the Regional Aquatics Monitoring Program are also now adding to the observational network.

3.4.3 Water use uncertainties

The calculated water use estimates in each scenario involved a number of uncertainties. First, project timelines of production and associated water use from start-up to final production were estimated based on operator projections. Such projections, however, are dependent on the economic viability of retrieval. The future growth of oil sands operations will be highly dependent on oil prices and changing international markets, which are motivated by concerns about global oil supply [National Energy Board, 2006]. Production capacity could be overestimated if project timeframes are delayed, as has previously occurred with Phase

1B of the Jackpine Mine [Alberta Utilities Commission, 2010], or it could be underestimated if projects proceed ahead of schedule.

Second, future water use will vary as technological innovations improve water use efficiency by reducing the amount of freshwater needed or by increasing water returns to the river. A fraction of the total water use ($\sim 7\%$) used in cooling and drainage diversion processes is currently returned by mining projects [AMEC Earth & Environmental, 2007], but there was insufficient information on the quantity or location of return flows to explicitly include return flows in water use estimates. Water returns can, however, be indirectly accounted for when applying an improved water use efficiency to water withdrawal scenarios. Return flows may become important in water accounting if technologies are developed to allow the return of water used in the processing stages.

Third, the water use efficiency for surface water may also decrease if groundwater use increases. Groundwater is primarily withdrawn from wells or deep saline aquifers for in situ projects, and accounts for less than 10% of water use in mining projects [AMEC Earth & Environmental, 2007]. Such withdrawals were not simulated in THMB, which does not explicitly model deep groundwater flow. Accounting for groundwater withdrawals, along with in situ projects, may be important in assessing future streamflow impacts, as the majority of planned oil sands operations are in situ projects which use primarily groundwater ($\sim 78\%$ [Ko and Donahue, 2011]).

Lastly, the future distribution and timeline of some licensed allocations were uncertain or unknown. For proposed mine sites currently in the application stage, approval for surface water licenses are pending, and there is insufficient information to determine potential water use or the location of withdrawals. Three mine sites, the Teck Resources Limited Frontier Mine (4 phases scheduled for 2021, 2024, 2027, and 2030), the Shell Albian Sands Pierre River Mine (2 phases with the first one beginning 2018), and the Suncor Energy Inc. Voyageur South Mine (no start date scheduled), were therefore excluded from this study, which may underestimate future water use. For operations with active water licenses, the majority expire well before 2035, and future allocations for these operations were assumed to continue. This may either underestimate or overestimate future water withdrawals, depending on how future licensing rules evolve.

In the range of scenarios created, the projected impacts on streamflow magnitude are small, as are the seasonal impacts on the low flow frequency, even at the highest withdrawal intensities. As a result, these overall findings are unlikely to be highly sensitive to the assumptions made in building each scenario.

3.5 Conclusions

Planned growth in oil sands production will continue to increase water use over the next few decades, but the scale of streamflow impacts is uncertain. This study was a first attempt at examining the response of streamflow in the Athabasca River to water use by oil sands surface mining operations. A physically-based modelling approach consisting of a land-surface process model linked to a hydrological transport model was used to simulate the natural flow regime of the Athabasca River Basin together with spatial and temporal patterns of water withdrawals.

Overall, the impact of surface mining water withdrawals on streamflow magnitude was small, even under maximum projected growth and water use intensity. An increase in the intensity of water withdrawals tends to exacerbate already low in-stream flows and these impacts can propagate further downstream. The frequency of low flows, which increases for most months of the years in all scenarios, is more sensitive to the intensity of withdrawals and can be used to indicate an increased threat to in-stream flow needs. The modelled impacts suggest that a combination of increased water use efficiency and restricted growth in oil production will be needed to prevent future increases in the frequency of low flows. In particular, winter flows should be a management priority and may require adapting the timing of water use, and therefore production schedules, to minimize periods of low flows that fall below in-stream thresholds.

Accurate predictions of future streamflow impacts will require a more comprehensive network of observations in the Athabasca River Basin to better validate the models, particularly downstream of oil sands operations. In the meantime, the modelling approach employed in this study provides a useful tool to assess the range of streamflow impacts, based on relative differences between streamflow scenarios, that may occur under different water withdrawal trajectories related to future water allocations or intended production growth.

Chapter 4

Streamflow Availability under Climate Warming in the Athabasca Oil Sands

4.1 Introduction

The Athabasca River Basin (ARB) in northern Canada spans a 269,000 km^2 area (Figure 4.1) drained by Lake Athabasca and the Athabasca River, its main artery which originates in the Columbia ice fields and eventually flows into the Peace-Athabasca Delta. Along the way, the Athabasca River crosses diverse ecosystems including glaciers, alpine meadows, alpine and boreal forests, and muskeg that contain unique landscapes and vital wildlife habitat [MRRB, 2004, Holloway and Clare, 2012]. The ARB is subject to a warming climate as well as increasing water use for an expanding oil sands industry. While the impact of climate warming on the ARB's hydrological regime has been well studied [e.g., Zhang et al., 2001, Prowse et al., 2006, Kerkhoven and Gan, 2011], it is uncertain whether future consumptive water demand will exacerbate and/or be threatened by the impacts of climate change.

Temperatures in the ARB have increased on average by 1.5–1.8°C between

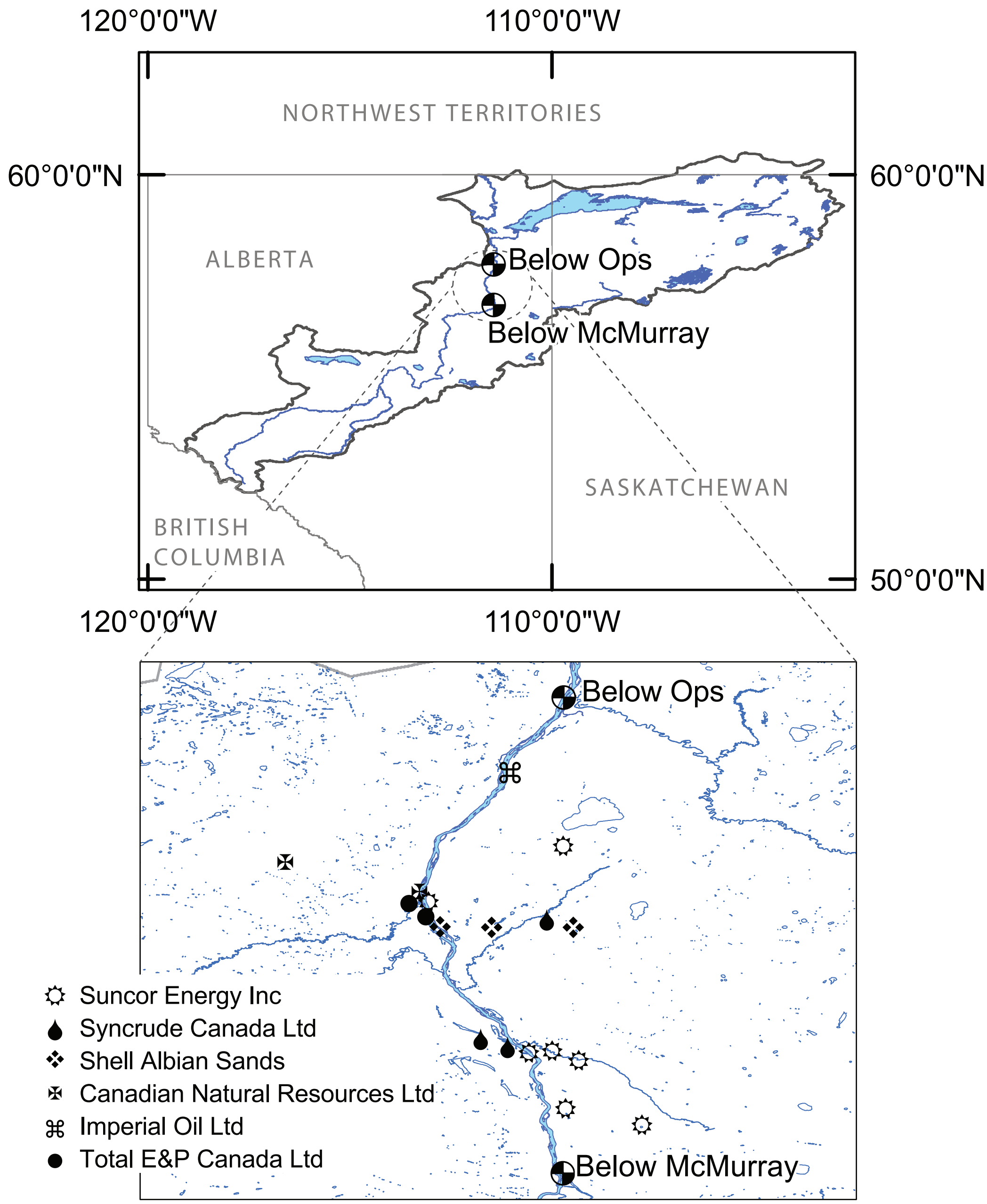

Figure 4.1: Map of the ARB region showing the location of the hydrometric station Below McMurray and the location of analysis for streamflow simulations downstream of oil sands mining operations, Below Ops. Inset shows water withdrawal source locations used in the study (note: there are 20 licenses assigned to 18 physical locations).

1961–2000, three times higher than the global average rise of 0.6°C [Bruce, 2006], and past studies have predicted a continuing rise by up to 3.5–4°C by 2050 [Gan and Kerkhoven, 2004, Sauchyn and Kulshreshtha, 2008]. The most recent IPCC projections for Northwest Canada show a mean annual temperature increase of 2.7°C by mid-century and 3.5°C by the end of the century, along with an annual precipitation increase of 10% by mid-century and 14% by the end of the century [Christensen et al., 2013]. Observations of snowpack decline and periodic winter melting in recent decades in the ARB [Zhang et al., 2001, Sauchyn and Kulshreshtha, 2008] are consistent with model projections of an earlier spring freshet and reduced summer flows under future warming [Pietroniro et al., 2006, Schindler and Donahue, 2006]. These climate-driven changes to streamflow patterns have been linked to a decrease in the frequency of floods that replenish the lakes and wetlands in the Peace-Athabasca Delta [Prowse et al., 2006, Wolfe et al., 2005, 2008], an ecologically sensitive region that provides important nesting and staging areas and habitat for a diverse wildlife population.

In addition to climate change, land use changes and increased industrial water use can also alter streamflow patterns and may explain declining summer flows despite increased flow from melting glaciers [Burn et al., 2004, Schindler and Donahue, 2006, Squires et al., 2009]. The growing Athabasca oil sands mining industry depends on water withdrawals from the Athabasca River in order to extract, process, and upgrade crude bitumen from surface-mined oil sands deposits. In situ mining also occurs under less intensive freshwater usage. Current water use by oil sands operations is licensed to ensure that in-stream flow needs, defined as the quantity, timing, and quality of water that is required to sustain a healthy aquatic ecosystem, are met [Alberta Environment, 2007]. The combined impacts of both climate and industrial drivers on the flow of the Athabasca River is currently unknown.

This study examines the impacts of both climate change and oil sands water withdrawals on streamflow availability for industrial and in-stream flow needs. Two independent, physically-based models are linked to simulate streamflow response in the ARB under multiple future climate and water use scenarios. A large-scale, process-based modelling approach is used here in order to represent the upstream landscape and fluvial processes that are necessary to capturing the sensitivity of downstream flow to natural climate variability and climate change. Impacts on streamflow patterns are assessed as a change in the frequency of occurrence of low flows, which is then applied to estimate future water availability for oil sands mining production.

4.2 Methods

4.2.1 Land surface models

Two models are used together to simulate the land surface processes and streamflow in the Athabasca River Basin. The Integrated Biosphere Simulator (IBIS) is a land surface model that simulates the coupled soil-vegetation-atmosphere water and energy budgets [Foley et al., 1996, Kucharik et al., 2000]. The Terrestrial Hydrology Model with Biogeochemistry (THMB) is a hydrological routing algorithm that uses prescribed river paths to simulate the storage and transport of water [Coe et al., 2002]. IBIS and THMB have been used together in dozens of global, large-scale studies, including simulations of continental-scale runoff in North America [Lenters et al., 2000, Coe and Foley, 2001] and Africa [Li et al., 2005], Amazonian flooding [Coe et al., 2002], and Mississippi nutrient flux [Donner et al., 2002]. IBIS has also been applied to cold, northern regions including Canadian boreal forests [El Maayar et al., 2001, Liu et al., 2005].

IBIS is driven with daily climate inputs at a 0.375° x 0.375° lat-long resolution that matches the available climate re-analysis used to validate the model. Its modules operate at different timesteps ranging from minutes to years and the monthly-averaged surface and subsurface runoff outputs are used here. IBIS and THMB are linked by driving THMB with the runoff outputs from IBIS to simulate the hourly flow of water through rivers, lakes and floodplains at a 5' x 5' lat-long resolution, and subsequently output a spatially explicit representation of monthly river discharge. Validation of both models for the Athabasca River Basin is described in detail in Chapter 2, and demonstrates that IBIS-THMB simulations capture the average hydrograph shape well at the 'Below McMurray' streamgauge location (Figure 2.4), including low flows in the winter followed by rising discharge leading to a broad, late-spring peak in flow. The interannual variability in simulated flow was also well correlated (r = 0.73) with observations (Figure 2.6).

4.2.2 Future climate projections

Projected climate output for a 120 year period from 1981–2100 was obtained from the Coupled Model Intercomparison Project (CMIP5) [Taylor et al., 2012], which provides global climate model (GCM) output using the four IPCC Representative Concentration Pathway (RCP) climate scenarios [Moss et al., 2010]. The climate scenarios range from RCP2.6, an extreme mitigation scenario (with a mid-century peak in radiative forcing), to RCP8.5, the highest radiative forcing scenario, which matches the trajectory of greenhouse gas emissions for the past decade. IBIS requires seven daily climate variables as input: near surface specific humidity, near surface air temperature, eastward and northward near surface wind speed, total cloud fraction in the atmosphere column, precipitation, and surface air pressure. Only three of the CMIP5 GCMs (GFDL-ESM2G, MIROC5, and IPSL-CM5A-LR) provided all seven of the required climate output variables in all four RCPs and at the required temporal resolution, and were therefore selected for use in this study. The three GCMs cover a range of equilibrium climate sensitivities for the region (Table 4.1). Output variables from each GCM were re-projected from a native grid onto the IBIS grid using bilinear interpolation. All variables were obtained at a daily time step with the exception of surface pressure, which was only available in 6-hour intervals and was averaged into daily intervals.

4.2.3 IBIS-THMB simulations

For all simulations in this study, IBIS was driven by daily GCM climate output over a 120-year time period, 1981–2100, to yield monthly average surface and

Table 4.1: CMIP5 global climate models used in this study, their equilibrium climate sensitivities and resolution (from Andrews et al. [2012]).

Model	Equilibrium Climate Sensitivity (°C)	Resolution (°)
GFDL-ESM2G	2.4	2.5 x 2.0
MIROC 5	2.7	1.4 x 1.4
IPSL-CM5A-LR	4.1	3.8 x 1.9

subsurface runoff. Outputs at daily timesteps were considered, however the simulated hydrograph produced with daily IBIS output did not differ significantly from that produced from monthly simulations, so the latter was chosen for computational speed (see Chapter 2).

All GCM-driven monthly outputs from IBIS were adjusted to a historical baseline, before driving THMB. First, IBIS was driven by observation-based North American Regional Reanalysis (NARR) data over a 30-year historical time period between 1981–2010 (see details in Chapter 2). A NARR-driven historical climatology for the IBIS output variables, $NARR_{clim}(\bar{m})$, was calculated from this IBIS output as an average for each month (m) over all 30 years (y). Second, IBIS was driven by GCM outputs over a 120-year time period between 1981–2100 to yield a monthly simulated time series, $GCM_{sim}(m,y)$. A GCM-driven historical climatology, $GCM_{clim}(\bar{m})$, was calculated from the 1981–2010 period of this IBIS output. A default anomaly correction (Equation 4.1) was then applied by multiplying the IBIS simulated outputs by the ratio of NARR-driven and GCM-driven historical climatologies [Arnell and Reynard, 1996], to yield the future projected IBIS outputs for each month and year ($GCM_{proj}(m,y)$).

$$GCM_{proj}(m,y) = GCM_{sim}(m,y) \cdot \frac{NARR_{clim}(\bar{m})}{GCM_{clim}(\bar{m})} \tag{4.1}$$

$$\text{where} \quad \bar{m} = \frac{1}{30}\sum_{y=1981}^{2010} m_y$$

In cases where the GCM-driven historical climatology was zero, the delta change method [Hay et al., 2000] was applied instead by subtracting the GCM-driven historical climatology from the GCM-driven simulation time series, and then adding the NARR-driven historical climatology (Equation 4.2). This was the secondary method for anomaly correction, since the delta-change method can produce negative values for positive-only variables like precipitation and runoff.

$$GCM_{proj}(m,y) = GCM_{sim}(m,y) - GCM_{clim}(\bar{m}) + NARR_{clim}(\bar{m}) \tag{4.2}$$

Since Equation 4.1 can lead to very large adjusted values when $GCM_{clim}(\bar{m}) \ll NARR_{clim}(\bar{m})$, a maximum value for each grid cell was defined to be ten times the maximum of the NARR-driven historical time series. If the anomaly-corrected values using Equation 4.1 exceeded this maximum, the correction was applied using Equation 4.2. This factor of ten threshold was tested on the time series of multiple climate variables and found to be appropriate in removing anomalous spikes that resulted from the default anomaly correction method. The projected (i.e. anomaly-corrected) IBIS outputs were then used to drive THMB to simulate the time-varying volume and flow of surface water through lakes and rivers in the ARB over the 120 year period.

Streamflow impacts were simulated using a combination of different future climate scenarios and different water withdrawal scenarios. Each IBIS-THMB simulation employed one of the four RCPs and either no withdrawals or licensed withdrawals, in order to assess the range of possible streamflow impacts. A total licensed withdrawal rate of approximately 21 m^3/s represented estimates of the maximum future withdrawals and were based on licensing agreements with individual oil sands mining operations (see Chapter 3) at the 20 known withdrawal locations (Figure 4.1). This withdrawal rate was applied over the entire time period in the licensed water withdrawal scenario. Together with the scenario that involves no withdrawals, this effectively bookends the minimum and maximum likely impacts of water withdrawals.

A total of 24 IBIS-THMB simulations were run using a combination of the three GCMs, four RCPs and two water withdrawal scenarios. Water withdrawals were simulated in THMB by extracting the water requirements at each timestep, for each grid cell that corresponds to a licensed withdrawal location. The streamflow output was evaluated at the location 'Below Ops' (57.7083°N, −111.4583°E), which lies downstream of all surface mining oil sands operations. IBIS-THMB outputs were analyzed as running averages over 20-year time windows, with a focus on changes in mid-century (2041–2060) and end-of-century (2081–2100), relative to today (1991–2010).

4.3 Results

4.3.1 Climate projections

Relative to today, the mid-century annual mean air temperature is projected by the three GCMs to rise by 0.9°C to 3.1°C (from 0.9–1.9°C in RCP2.6 to 2.0–3.1°C in RCP8.5), while the end-of-century annual mean air temperature is projected to rise by 0.5°C to 7.0°C (from 0.5–1.9°C in RCP2.6 to 4.4–7.0°C in RCP8.5) (Figure 4.2). The projected change in mean annual precipitation generally increases linearly with temperature ($r^2 = 0.3, p < 0.01$), however it is variable across the three GCMs (Figure 4.2a). IPSL-CM5A-LR projects the largest increase of 56 mm (12%) in RCP8.5 by end-of-century and GFDL-ESM2G and MIROC5 project the largest decrease of 28 mm (6%) in RCP6.0 by mid-century. Overall, IPSL-CM5A-LR projects the greatest increase in warmth and moisture, while GFDL-ESM2G projects the lowest increase. By mid-century and end-of-century, all three GCMs project an increase in precipitation in RCP8.5. The ratio of rain to snow increases linearly in response to warming ($r^2 = 0.6, p < 0.01$), with less variability than the precipitation response. All three GCMs project the largest rain to snow ratios in RCP8.5 by end-of-century (Figure 4.2b). Previous climate change analysis for the ARB conducted by Kerkhoven and Gan [2011] used the Modified Interactions between the Soil-Biosphere-Atmosphere (MISBA) model forced by seven major GCMs using the four IPCC AR4 Special Report on Emissions Scenarios (SRES) [Nakicenovic et al., 2000] climate scenarios. The precipitation changes projected by the GCMs selected for this study are on the lower end of the range of GCMs used in the previous MISBA study.

4.3.2 Streamflow projections

The projected change in mean annual streamflow is variable across the three GCMs. The GFDL-ESM2G-driven simulations project an increase in streamflow for all climate scenarios by the end-of century, while the IPSL-CM5A-LR-driven simulations project a decrease in streamflow for three of the four climate scenarios (Figure 4.3a). By end-of-century in RCP8.5, the IBIS-THMB simulated mean annual streamflow increases by 53% in the GFDL-ESM2G-driven simulations and decreases by 10% and 12% for the MIROC5- and IPSL-CM5A-LR- driven simulations respectively, relative to today.

Streamflow did not show a linear dependence on temperature ($r^2 = 0.0; p = 0.95$), but did linearly increase with precipitation ($r^2 = 0.2, p < 0.01$). (Figure 4.4). This is in contrast to previous MISBA projections where runoff was more strongly correlated with changes in temperature [Kerkhoven and Gan, 2011]. Kerkhoven and Gan [2011] projected a change in mean annual flow of -8 to -54% by 2040–2069, compared to the IBIS-THMB projections of change in mean annual flow of -6.5 to 19.0% by 2041–2060. The results are not directly comparable, however, since the mid-century time periods and the reference baseline years (1957–2007 in Kerkhoven and Gan [2011]) differ between the two studies.

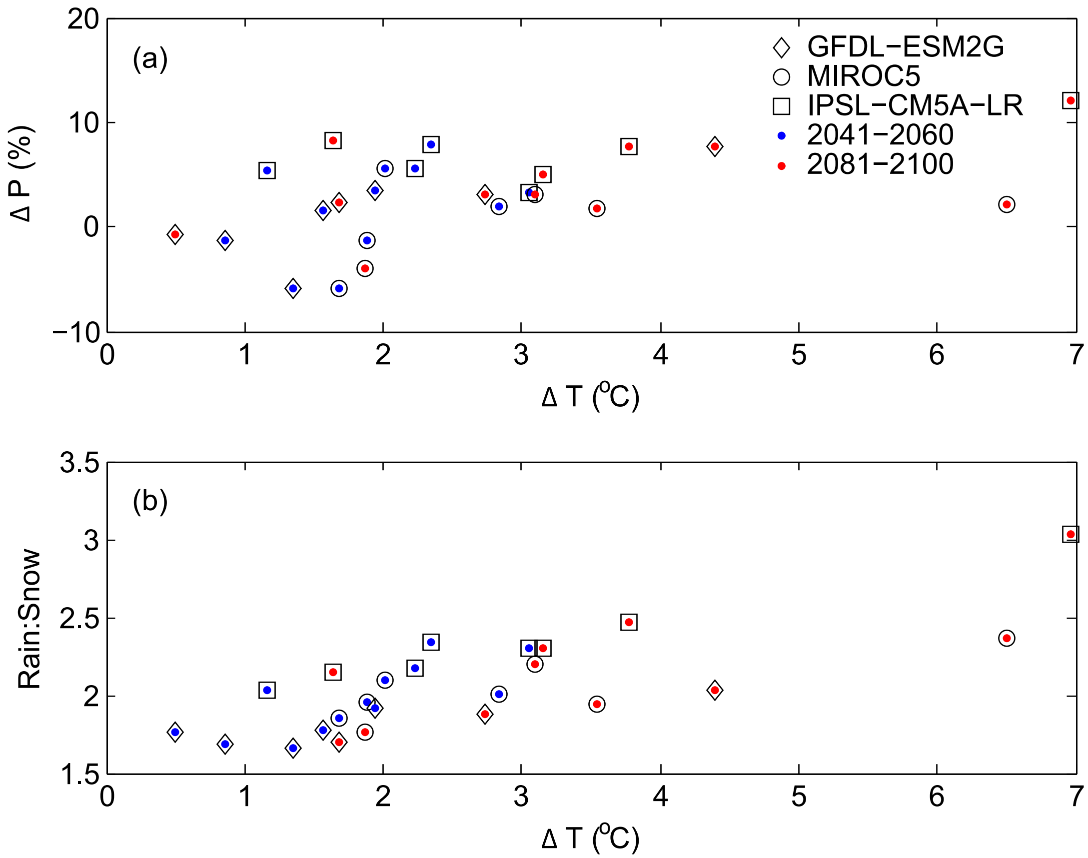

Figure 4.2: Change in (a) annual precipitation (ΔP), and (b) the ratio of rain to snow, relative to the change in annual temperature (ΔT) projected by the three GCMs and four RCPs in mid-century (2041–2060) and end-of-century (2081–2100).

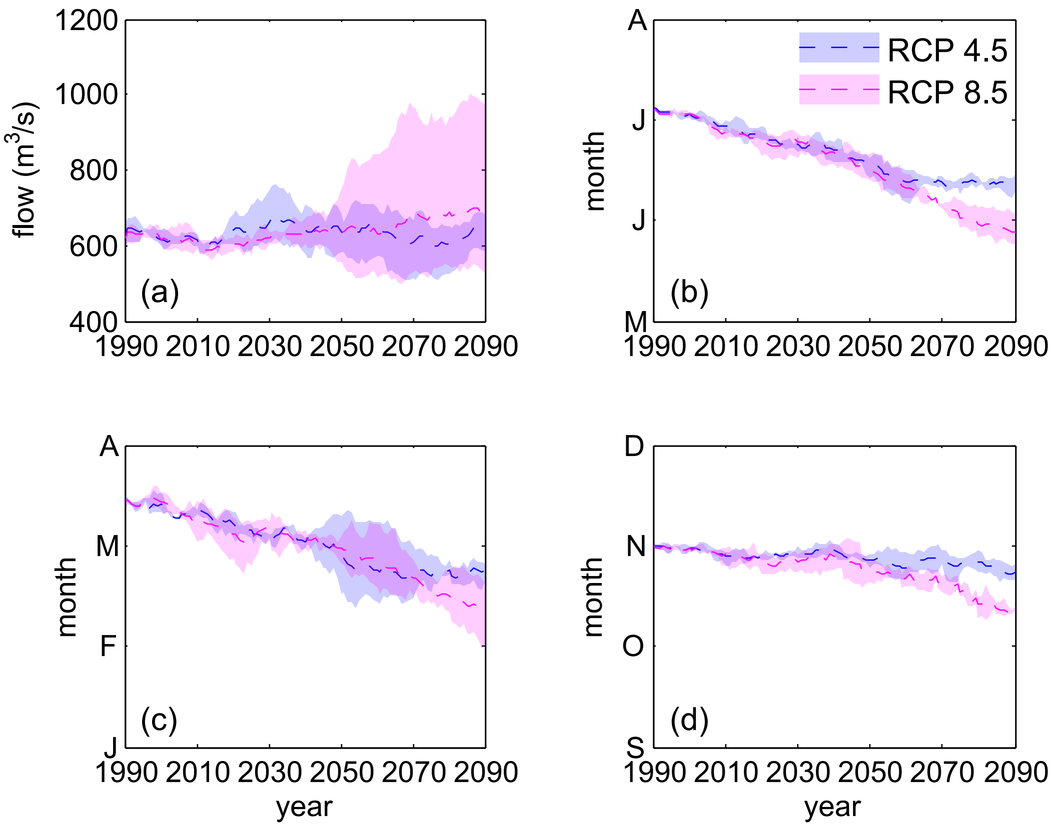

Figure 4.3: Streamflow patterns for the Athabasca River at the location Below Ops: (a) annual mean streamflow, (b) centroid of flow distribution, (c) timing of spring runoff, (d) persistence of flow. Dashed lines show the mean values across all GCMs and shaded areas show the range of values across GCMs. Years are the mid-point of running 20-year time windows over which results are averaged. RCP2.6 and RCP6.0 are omitted for clarity.

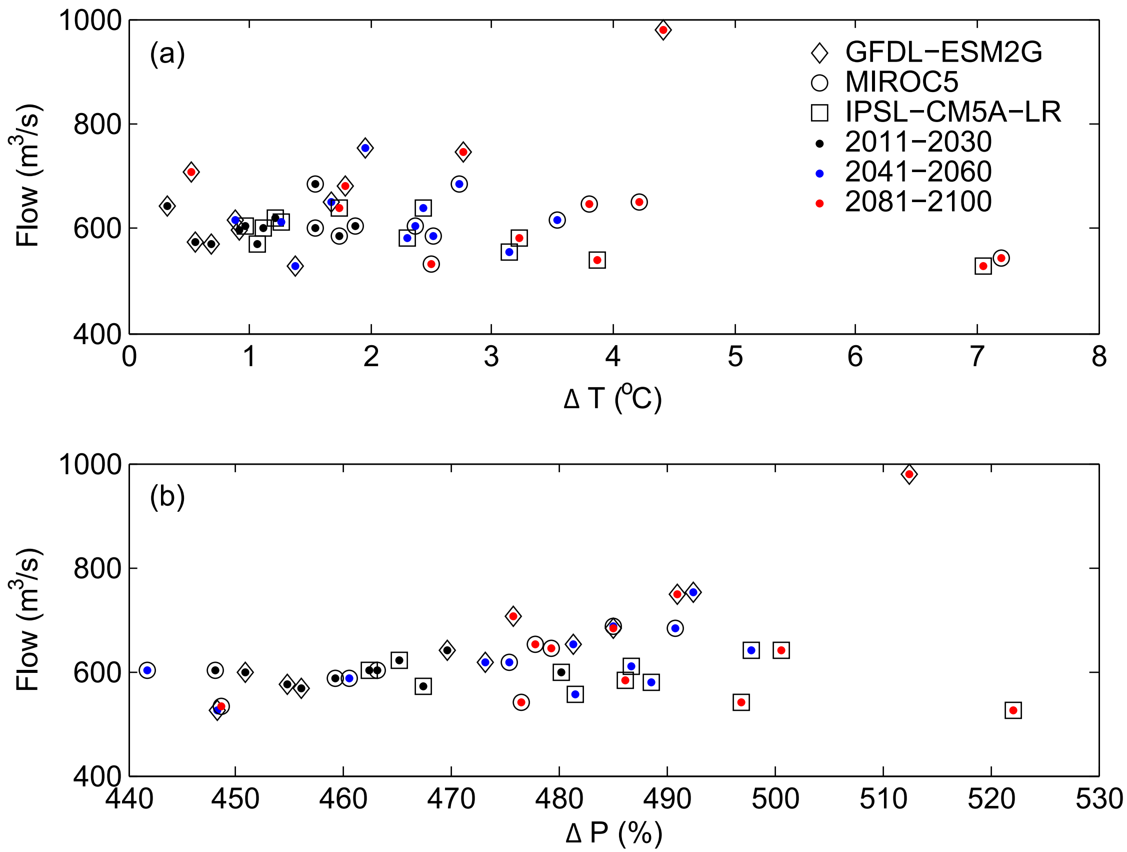

Figure 4.4: Simulated streamflow relative to the (a) change in annual temperature (ΔT), and (b) change in annual precipitation (ΔP) projected by the three GCMs and four RCPs in mid-century (2041–2060) and end-of-century (2081–2100).

Three metrics were used to evaluate shifts in the seasonal patterns of streamflow (Figure 4.3b-d,Figure 4.5), following Burn [2008]. First, the timing of spring runoff was estimated as the date by which 10% of the annual streamflow volume had occurred. Second, the centroid of flow distribution was calculated as the flow-weighted average time of discharge. Third, the persistence of runoff was estimated as the date by which 95% of annual flow volume had occurred.

The annual centroid and spring runoff occurs earlier in all IBIS-THMB simulations by mid-century and end-of-century (Figure 4.3b-c,Figure 4.5a-d). By end-of-century in RCP8.5, all three GCMs project the centroid of flow distribution to occur a month or more earlier, shifting from an average of early July to an average of late-May (Figure 4.3b), as well as the average timing of spring runoff to shift from mid-March to early February (Figure 4.3c). Late season runoff is less persistent by end-of-century, and most of the annual flow occurs earlier in the year, by over half a month, in all three GCMs (Figure 4.3d, Figure 4.5f). The centroid of flow distribution, timing of spring runoff, and flow persistence also occur progressively earlier as the projected proportion of rain to snow increases (Figure 4.6).

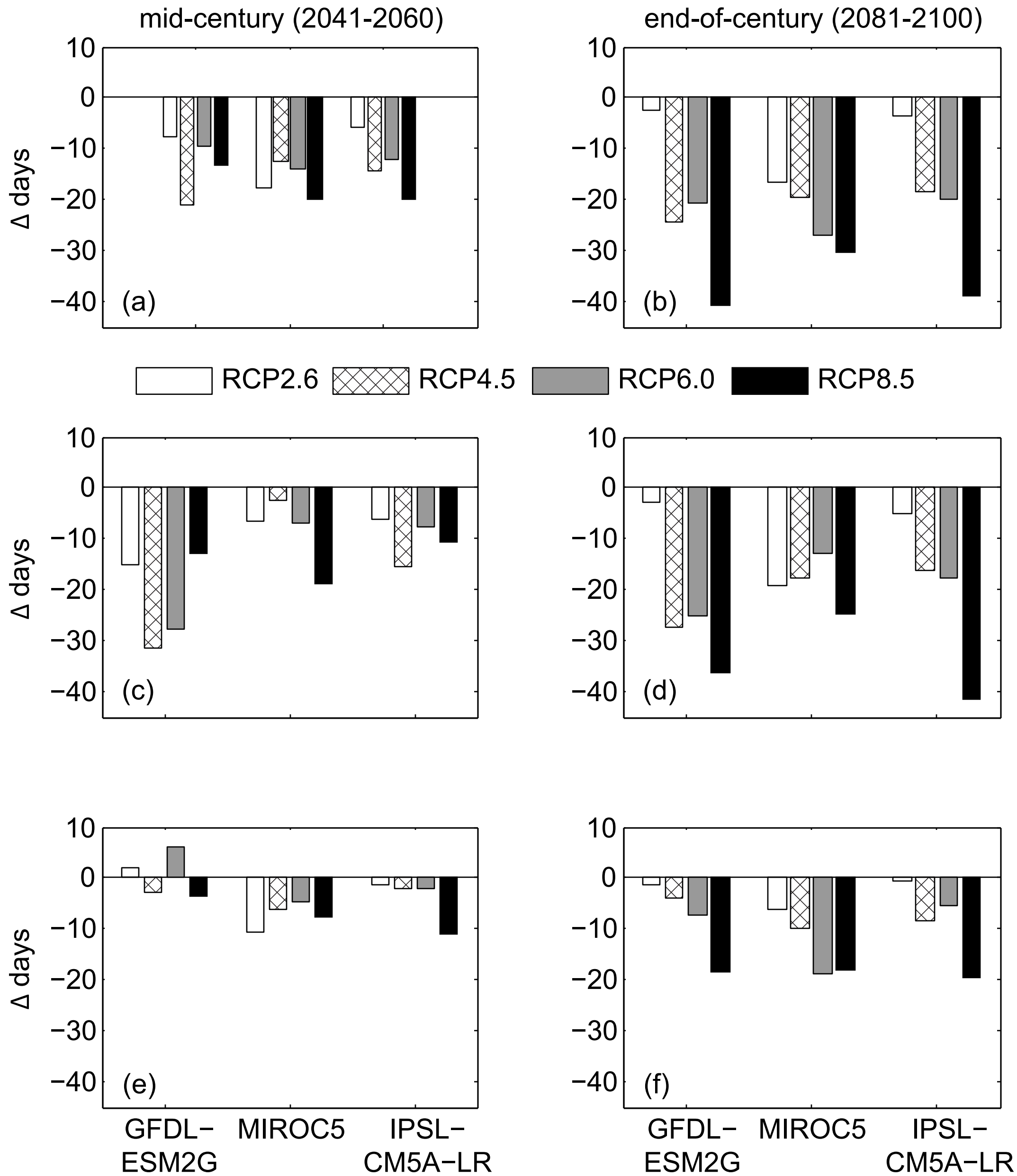

Figure 4.5: Changes in streamflow patterns by mid-century (2041–2060) and end-of-century (2081–2100) relative to today (1991–2010) for the Athabasca River at the location Below Ops: (a–b) shift in the centroid of flow distribution, (c–d) shift in the timing of spring runoff, (e–f) shift in the persistence of flow.

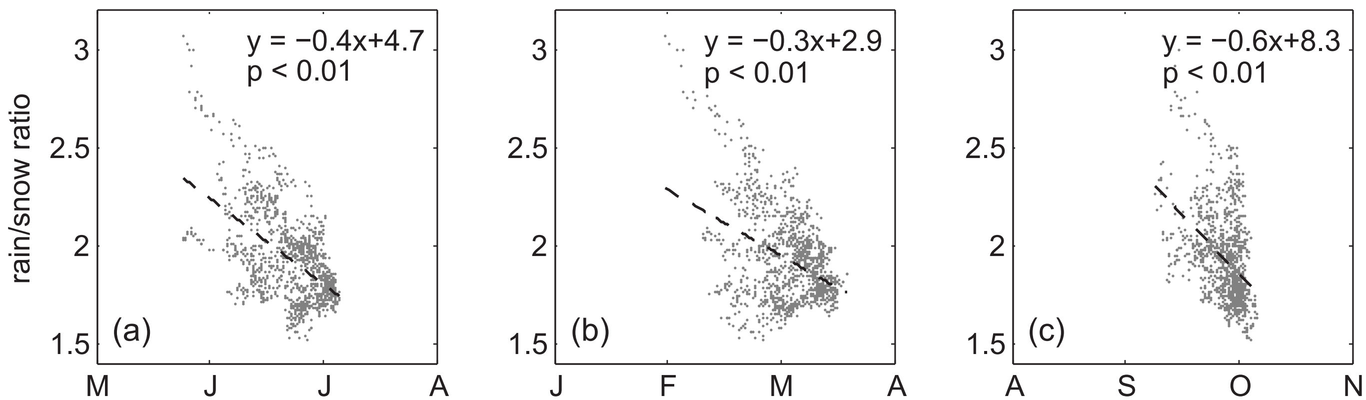

Figure 4.6: Linear relationships between the ratio of rain to snow and the (a) timing of the flow centroid (b) timing of spring runoff (c) persistence of flow.

4.3.3 Frequency of low flows

The frequency of statistical low flows was calculated as a measure of streamflow impact on in-stream flow needs. The analysis focuses on the seasonality of low flows, rather than the seasonality of mean flows or hydrographs, because the low flows are of concern for water management. Low flows were defined for each month relative to a threshold magnitude, computed based on the magnitude of historical flows between 1981 and 2010 that were exceeded 80% of the time in that month [Locke and Paul, 2011]. This corresponds to a threshold flow required to meet full environmental protection of the Athabasca River (i.e. that maintains the conditions of an unaltered natural flow regime).

Patterns of decreasing and increasing low flow frequency occur in the first (January-June) and second (July-December) halves of the year, respectively (Figure 4.7). All three GCMs project an increase in low flow frequency across all climate scenarios (except in RCP2.6) from August–October by mid-century, and from July–November by end-of-century. By the end of the century in RCP8.5, low flows are projected to occur 85% more frequently in August for IPSL-CM5A-LR-driven projections, and 75% more frequently in September for GFDL-ESM2G-driven projections.

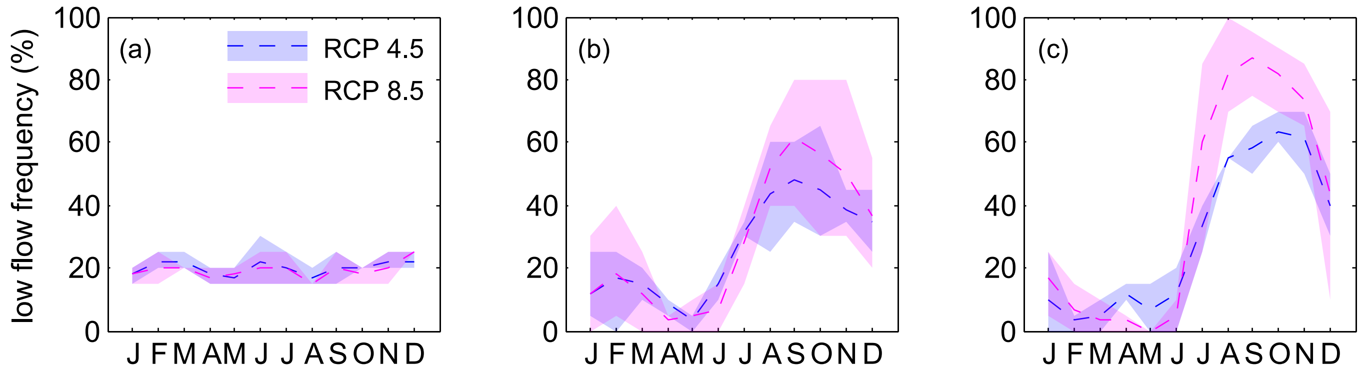

Figure 4.7: Low flow frequency for each month of the year, for three 20-year time windows: (a) today, 1991–2010 (b) mid-century, 2041–2060 (c) end-of-century, 2081–2100. Dashed lines show the mean values across all GCMs and shaded areas show the range of values across GCMs. RCP2.6 and RCP6.0 are omitted for clarity.

4.3.4 Water withdrawals

Simulated water withdrawals decreased projected streamflow by a fixed amount that was generally small compared to the magnitude of projected changes in flow due to climate change (Figure 4.8). For example, by mid-century, between April–June in RCP8.5, the projected low flow frequency decreases on average by 13% due to climate change and increases on average by 1% due to water withdrawals. From August–October in RCP8.5, the projected low flow frequency increases on average by 39% due to climate change and only by an additional 4% due to withdrawals by mid-century. By end-of-century, the relative contribution of water withdrawals to the low flow frequency becomes even smaller. In months (e.g. December) when the relative contribution of water withdrawals to the low flow frequency are similar or greater than that due to climate change, the actual change in low flow frequency is generally small.

The frequency of low flows indicates periods of low water availability that can potentially halt oil sands water withdrawals and therefore bitumen production if the protection of in-stream flow needs is considered. Periods of low water availability for oil sands mining operations were quantified as a change in the number of months in which low flows occurred at mid-century and end-of-century, relative to today (Figure 4.9). By mid-century, all but three streamflow simulations (GFDL-ESM2G in RCP8.5, MIROC5 in RCP4.5, and IPSL-CM5A-LR in RCP2.6) project an increase in the number of months with low water availability (i.e. a decrease in water availability). By end-of-century, all but one simulation (GFDL-ESM2G in RCP2.6) projects a decrease in water availability. Projected water availability is also seasonal, increasing by end-of-century (relative to today) by up to 17% during spring (April–June), while decreasing by up to 75% during summer (July–October). The IPSL-CM5A-LR-driven simulation for RCP8.5 projects the maximum decrease in water availability by mid-century, which translates into a 22% increase in interruptions to oil sands operations relative to today, and equivalent to over two years of oil production per decade. By the end of the century, this rises to a 28% increase in interruptions.

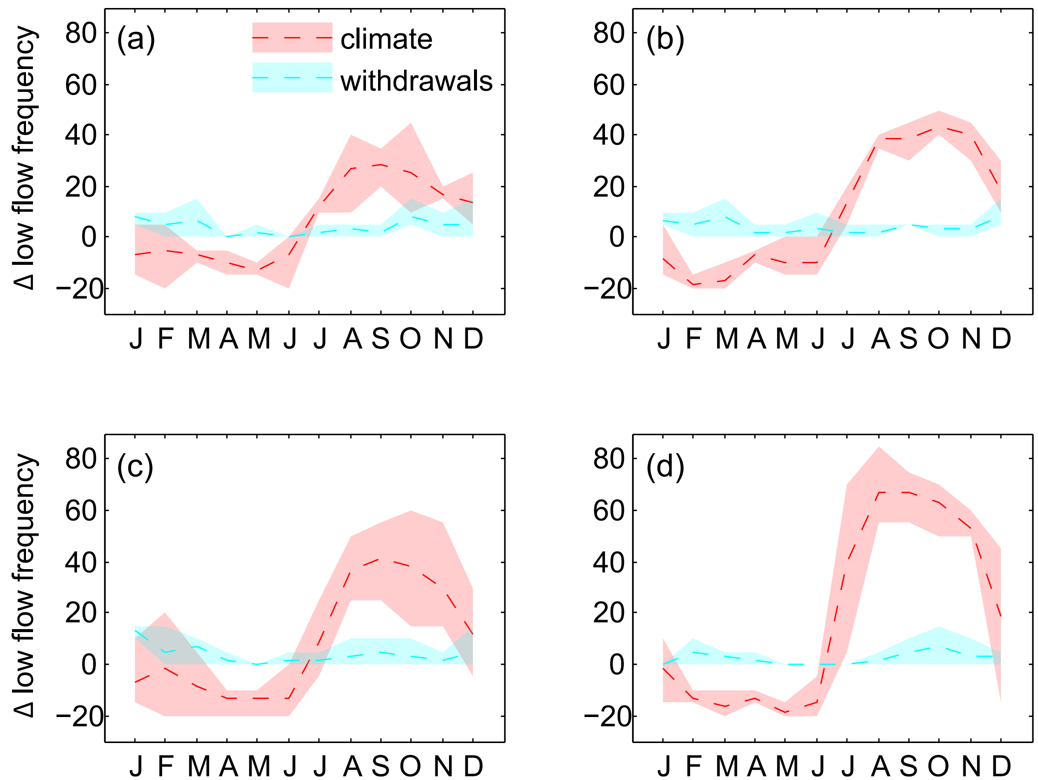

Figure 4.8: Change in low flow frequency relative to today (1991–2010) for (a) RCP4.5 at mid-century (2041–2060), (b) RCP4.5 at end-of-century (2081–2100), (c) RCP8.5 at mid-century (2041–2060), (d) RCP8.5 at end-of-century (2081–2100). Red shows the change due to climate change only and blue shows the change due to water withdrawals. Dashed and dotted lines show the mean value across all GCMs and shaded areas show the range of values across GCMs.

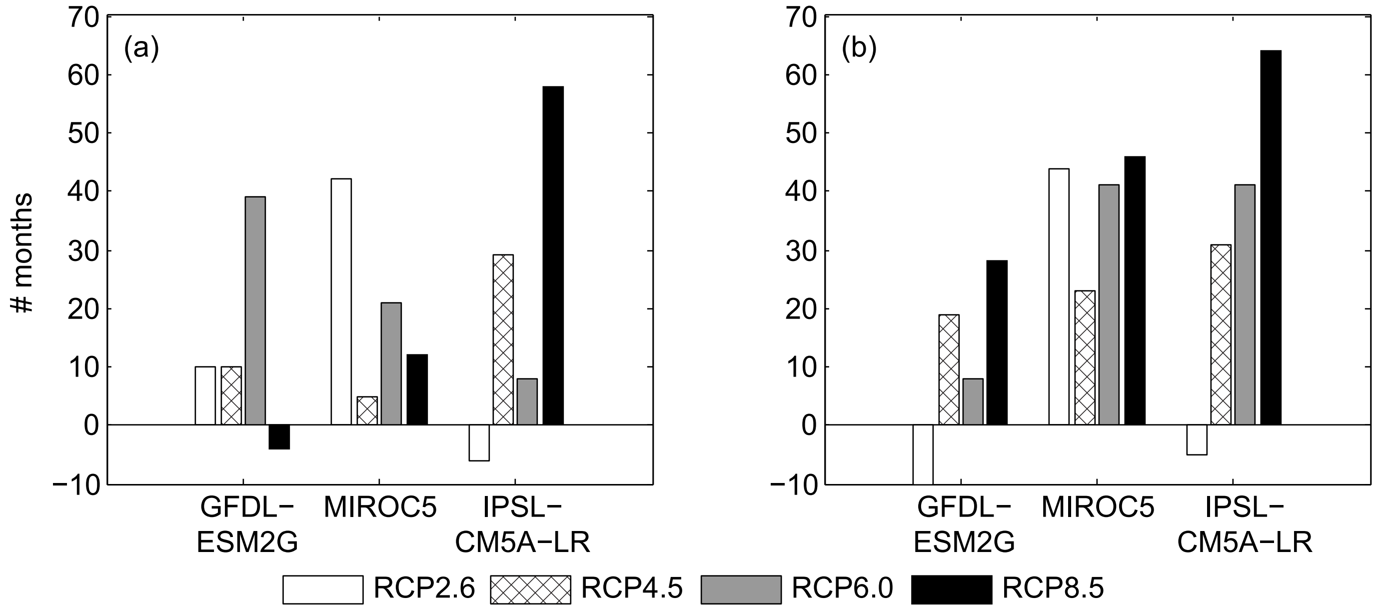

Figure 4.9: Change in the number of months during the mid-century (2041–2060) and end-of-century time (2081–2100) periods that flow falls below the low flow threshold, relative to today (1991–2010), for each climate scenario.

4.4 Discussion

The three climate models used in this study generally agree on the projected frequency of low flows, the primary tool used here for impact assessments of climate change and water withdrawals. Clear seasonal patterns in the frequency of low flows of the Athabasca River are projected to emerge over time as climate warming continues. The models employed in this study project that by end-of-century, low flows (defined based on historical low flow levels) will no longer occur (0% frequency) in some winter months (November–March) and will always occur (100% frequency) in some summer months. In contrast, water withdrawals have a small aggregate effect on low flow frequency; for example, under conditions of maximum water withdrawals and no climate change (an extreme, unlikely scenario), low flows will occur with a maximum 40% frequency and only during the winter (see Chapter 3). Climate warming, however, is projected to increase flow in the winter months and counter the small effect of water withdrawals. With climate change, frequent low summer and late season flows become a primary concern instead, with little contribution from water withdrawals.

These projected shifts in the timing of spring runoff and the seasonality of high and low flows could impact ecosystems such as the perched lakes in the Peace-Athabasca Delta, which are adapted to a historical frequency and timing of recharge [e.g., Timoney, 2002, Wolfe et al., 2005, Prowse et al., 2006]. Streamflow timing can determine whether certain life-cycle requirements are met, and influence the degree of stress or mortality associated with extreme conditions [Richter et al., 1996]. Shifts in the distribution and timing of annual flow can also increase the potential for drought by affecting the availability of water resources for human use later in the year [Lapp et al., 2005].

The projected climate-driven changes in streamflow may have consequences for the ability to continue water withdrawals for oil sands operations. A production stop of up to 58 months, projected by mid-century in one case, would be equivalent to the interruption of roughly 900 million barrels of oil production at Suncor's Millenium and Steepbank mines, based on estimated future production capacity [The Oil Sands Developers Group, 2013]. Athabasca oil sands mining operations are forecasted to continue through much of the mid-century time period, given that the timeline for planned projects currently under regulatory review include the Teck Resources Ltd Frontier mine, with Phase 1 scheduled to begin in 2021 and Phase 4 to begin in 2030, as well as Imperial Oil's Phase 3 of the Kearl mine, to begin in 2020 [The Oil Sands Developers Group, 2013]. At a rate of three million barrels of oil production per day (both mined and in-situ recovery) Alberta oil sands reserves are expected to last for over 150 years [Alberta Environment, 2009]. Assuming that surface mining continues to make up 58% of oil production [The Oil Sands Developers Group, 2013], and since 20% of reserves are recoverable by surface mining [Alberta Environment, 2009], mining operations can be expected to continue for at least 50 years. The mid-century time period is therefore a realistic planning horizon for anticipated bitumen extraction and associated water withdrawals.

The frequency of future water withdrawal restrictions and availability will depend in part on how an acceptable low flow threshold is quantified. A major aim of Phase Two of the Lower Athabasca Water Management Framework, currently under development, is to include an ecosystem base flow which establishes a flow threshold, such as the one defined in this study, below which it is recommended there be no further withdrawals of water [Ohlson et al., 2010]. This serves to protect aquatic habitat and river biodiversity during the lowest flow periods. One challenge in establishing the ecosystem base flow or any low flow threshold is that thresholds based on long-term historical flow are only valid under stationary climate conditions [Dettinger et al., 2004, Stewart et al., 2004]. Another is that the threshold must negotiate the competing needs of industry and aquatic ecosystems for water. Implementing a low flow threshold in the next phase of the water management framework will therefore require that industrial water demand adapt to projected changes in streamflow due to climate change.

Such projected patterns of streamflow and future low flow frequency, and the associated impacts on water availability, are expected to be a product of changes in precipitation amount and type, evapotranspiration, and snowpack accumulation and melt in large western Canadian river basins like the ARB [Schnorbus et al., 2011]. In this study, the projected patterns of flow, particularly the timing of future low flow occurrences, are broadly consistent with the results of previous modelling studies and general understanding of the response of snow-dominated river basins to climate warming [e.g., Sauchyn and Kulshreshtha, 2008, Kerkhoven and Gan, 2011]. The timing of future low flows also demonstrate seasonal shifts in the runoff response that will drive annual averages and extremes in runoff. Differences in the range of projected change in annual mean, minimum and maximum runoff, between this and previous studies like Kerkhoven and Gan [2011], are attributed to differences in the reference baseline years and the timestep of model runs, which prevent direct comparisons. Projected precipitation is highly variable, but is found to generally increase with climate warming. The projected increase in the annual ratio of rain to snow, as temperature increases, is also consistent with the expectation that winter precipitation will increasingly fall as rain [Schindler and Donahue, 2006]. Projections that both the spring runoff and the centroid of flow distribution will occur earlier in the year are consistent with recent observed trends that show increasing temperatures driving a progressively earlier snowmelt, a decline in maximum snowpack depth and persistence, and more frequent periodic winter melting [Serreze et al., 2000, Zhang et al., 2001, Schindler and Donahue, 2006]. Projected shifts in flow persistence were smaller than shifts in the timing of spring runoff and the centroid of flow distribution, possibly resulting from increased (summer) precipitation contrasted with an earlier spring runoff that is expected to reduce future summer flows [Sauchyn and Kulshreshtha, 2008].

Projected flow patterns are also sensitive to the temporal and spatial variability in temperature and precipitation patterns across different climate scenarios and GCMs [Prowse et al., 2006, Toth et al., 2006]. For example, a warmer and drier scenario could increase evaporation relative to precipitation and result in reduced runoff. On the other hand, less warming in a wetter scenario could result in increased snowpack accumulation and runoff [Hinzman et al., 2005]. The selected

GCMs in this study project an annual precipitation increase of 2 to 5% for the ARB in RCP4.5 by the end of the century. This represents the middle of the range in precipitation change, -4 to 14%, projected by all CMIP5 models for West North America (28.6°N to 60°N, 130°W to 105°W) [Christensen et al., 2013], which contains the Athabasca River Basin. Employing a wider selection of GCMs in this study might broaden the range of future projected streamflow; however, such analysis was not possible for this study because current available output from the other CMIP5 models lack the complete set of daily climate variables needed to force IBIS for all climate scenarios.

4.5 Conclusions

Climate change in the Athabasca River Basin is projected to be the primary driver of future low flow patterns. Seasonal increases and decreases in future low flow frequency during the respective historical summer and winter periods are projected to affect the seasonal availability of water for oil sands water withdrawals. The frequency of low flows can be used to quantify the frequency of future interruptions to water availability for oil sands production, assuming that restrictions will exist on water withdrawals during low flow periods. As a result, a tradeoff arises between meeting industrial and ecological water demands. Future water use in the Athabasca oil sands may require operational decisions that adapt the timing of water withdrawals to the timing of available flows. Projected changes in streamflow due to climate warming can inform such decisions by providing a tool to estimate the magnitude and uncertainty of change in future water availability.

Chapter 5

Future Water Supply and Demand Management Options in the Athabasca Oil Sands

5.1 Introduction

Water management strategies in recent decades have undergone paradigm shifts that have focused attention first on the protection and restoration of the natural flow regime [e.g., Poff et al., 1997, 2010, Gleick, 2000], and second on the importance of adapting to future climate change impacts on human water resource use [e.g., Vörösmarty et al., 2000, Milly et al., 2008]. In the Athabasca River Basin (ARB), the ongoing development of a water management framework for the Lower Athabasca River that recognizes these objectives has been challenging [Alberta Environment, 2007, Ohlson et al., 2010]. Future development of oil sands bitumen production in the region, and its associated water use, is forecasted to continue on a high-growth trajectory [The Oil Sands Developers Group, 2013, ERCB, 2013]. At the same time, future climate change in the ARB is projected to shift the seasonal hydrograph, and may change the availability of winter and summer flows for water withdrawals (see Chapter 4). These will be important considerations for the future management of water withdrawals from the Athabasca River as tradeoffs are made between maintaining continuous bitumen production and protecting in-stream flow needs.

Restrictions on water use by oil sands companies are currently regulated according to the Alberta Government's Phase One Water Management Framework, which specifies the amount of water that each company can withdraw from the Athabasca River throughout the year based on calculated threats to in-stream flow needs, primarily fish life cycle and habitat needs [Alberta Environment, 2007]. Phase Two of the Water Management Framework (P2F) has been in development since 2007, and aims to balance long-term industry withdrawals with social, environmental, and economic interests. In developing the P2F, the multi-stakeholder P2F committee considered multiple water management alternatives which were projected to remain robust under future climate change in all but the most extreme climate scenarios. These alternatives were evaluated only in the context of a high-growth scenario for oil sands bitumen production, and did not consider scenarios of more restricted growth [Ohlson et al., 2010]. Despite efforts to define a new framework, final consensus on a specific set of water management rules has not yet been achieved. The final, industry-preferred alternative proposed by the P2F committee could not reach consensus over water use restrictions and exemptions during low flow periods and this has remained a roadblock to actual implementation of a new water management framework.

A broad analysis of future water management options that includes the full range of potential tradeoffs between oil sands industry growth and environmental protection is still lacking. In this study, we applied streamflow simulations from IBIS-THMB, a combined land surface process model and streamflow routing algorithm (see details in Chapter 2), driven by recent CMIP5 GCM outputs using the IPCC AR5 Representative Concentration Pathway (RCP) climate scenarios [Moss et al., 2010], to develop two water use scenarios that bookend the possible approaches to basin water management. One scenario prioritizes a high-growth trajectory for bitumen production and associated water withdrawals, while the other prioritizes maximum environmental protection of the Athabasca River, which maintains the conditions of an unaltered natural flow regime. Together, these scenarios cover a range of both industry and environmental protection options. For each scenario, we evaluated the water supply needed to meet the estimated average industry demand, and the amount of storage water, in addition to direct river withdrawals, that would be required to maintain constant bitumen production over the mid-century time period. Using this approach, we examined the water tradeoffs that emerge when adapting water rules to projected climate change impacts on streamflow, and explored the range of management options available to balance future water supply and demand in the Athabasca oil sands.

5.2 Methods

5.2.1 Water management scenarios

Two water management scenarios were defined to bookend the range of future water supply and demand options. The first scenario, labelled as the 'industry-first' scenario, is a high-growth oil sands development scenario that is defined to have a production rate of 3.5 million barrels per day, requiring an average industry water withdrawal rate of 16 m^3/s and a maximum water withdrawal rate of 29 m^3/s based on planned pipe diameters for river water intake [Golder Associates Ltd., 2009]. The P2F committee applied this high-growth assumption to all water management alternatives that they considered. The industry-first scenario applies the same high-growth assumption under new climate change scenarios to provide a direct comparison to the P2F analysis. Since the high-growth assumption is based on a 2008 long-term forecast which includes both announced and potential future projects [Ohlson et al., 2010], the average industry withdrawal rate is higher than that calculated in Chapter 3, which estimates water use based on a bottom-up approach that only includes announced future projects (as of 2013).

The industry-first scenario adopts the water withdrawal rules and thresholds outlined in the P2F committee's final recommendation, Option H. The water withdrawal rules divide the year into five sets of different weeks (Table 5.1). Between November and mid-April, three flow threshold conditions determine the permitted withdrawal amount. For the remainder of the year, the only flow threshold is the ecosystem base flow (EBF), a flow threshold of 87 m^3/s, based on a 1 in 100 year winter (January) low flow statistic [Ohlson et al., 2010]). Typically, an EBF is a threshold flow below which all water withdrawals must cease in order to avoid irreversible stress on aquatic ecosystems. However, the industry-first scenario (Option H) rules permit a water withdrawal rate of 4.4 m^3/s below the EBF for specific oil sands operators in order to prevent mining infrastructure from freezing during cold winter months (Albian Muskeg River, Canadian Natural Horizon), as well as exemptions for the oldest operations (Suncor, Syncrude) which lack water storage capabilities.

The second scenario, labelled as the 'environment-first' scenario, is a scenario describing maximum environmental protection for the Athabasca River. The water withdrawal rules and thresholds are defined according to the Alberta Desktop Method [Locke and Paul, 2011], which was developed as a means to prescribe full protection of river environments in the absence of available site data. The water rules of the environment-first scenario permit 15% of river flow to be withdrawn when flow is above the weekly or monthly 80% flow exceedance value (Q80), and no withdrawals below the Q80 threshold.

Table 5.1: Annual water withdrawal rules for the industry-first scenario. For each set of weeks, a water rule (R) defines the maximum permitted withdrawal rate when the river flow (F) meets a specified threshold (T) condition (adapted from the Option H rules in Ohlson et al. [2010]).

Week	R1 (m^3/s) If Flow in River F > T1 allow up to:	T1 (m^3/s)	R2 (m^3/s) If Flow in River T1>F>T2 allow up to:	T2 (m^3/s)	R3 (m^3/s) If Flow in River T2>F>T3 allow up to:	T3 (m^3/s)	R4 (m^3/s) If Flow in River T3>F allow up to:
1–15	16	270	6% of flow	150	9	87	4.4
16–18	16	87	4.4				
19–23	20	87	4.4				
24–43	29	87	4.4				
44–52	16	200	8% of flow	150	12	87	4.4

Unlike the scenarios considered by the P2F committee, this scenario is not constrained to a high industry growth rate. Two demand-side options were considered in the environment-first scenario to explore water supply needs under different demand options; the high-growth average industry withdrawal rate of 16 m^3/s, and the 2010 average industry withdrawal rate of 6 m^3/s. As with the industry-first scenario, the maximum water withdrawal rate in this scenario is also 29 m^3/s, based on pipe infrastructure limitations.

5.2.2 Climate scenarios and models

Climate projections in this study used output from three CMIP5 GCMs (GFDL-ESM2G, MIROC5, and IPSL-CM5A-LR) driven by the most recent IPCC climate scenarios: RCP4.5, a moderate climate change mitigation scenario and RCP8.5, the highest IPCC emissions scenario which roughly corresponds with the current emissions trajectory. These projections are used to drive a combination of a land surface process model, IBIS [Foley et al., 1996, Kucharik et al., 2000], and a hydrological routing algorithm, THMB [Coe et al., 2002] to simulate daily streamflow. IBIS and THMB have been used together in dozens of global, large-scale studies, including simulations of continental-scale runoff in North America [Lenters et al., 2000, Coe and Foley, 2001] and Africa [Li et al., 2005], Amazonian flooding [Coe et al., 2002], and Mississippi nutrient flux [Donner et al., 2002]. For full model details, see Chapter 2, and for full simulation details, see Chapter 4.

Streamflow simulations in this study are therefore based on the most recent IPCC climate scenarios, in contrast to the streamflow projections considered by the P2F committee, which were developed using the Modified Interactions between the Soil-Biosphere-Atmosphere (MISBA) hydrologic model [Kerkhoven and Gan, 2006] forced by seven major GCMs using the four IPCC AR4 Special Report on Emissions Scenarios (SRES) [Nakicenovic et al., 2000]. In the P2F commitee's analysis of climate change impacts, the projected percent changes in minimum and mean flows were used as indicators of the percent change in winter and summer flows respectively, and applied as percent modifiers on a 50-year data set of winter (December to March) and summer (June to August) flows. In contrast, projected climate change impacts in this study were analyzed using the full monthly time series of IBIS-THMB simulated streamflow. The IBIS-THMB streamflow simulations project that climate change will advance the timing of spring runoff and shorten the persistence of late-season flow in the Athabasca River by mid-century, leading to an increase in streamflow in the first half of the year, and a decrease in streamflow in the last half of the year (see details in Chapter 4). Differences between the reference baseline years and the timestep of model runs used in the IBIS-THMB and MISBA projections prevent a direct comparison of the two model results, however, the IBIS-THMB projections of seasonal runoff timing are broadly consistent with the response of a snow-dominated basin to climate warming.

5.2.3 Simulating water supply and demand

Mid-century (2041–2060) streamflow was simulated by IBIS-THMB for the six (3 GCMs and 2 RCPs) climate change scenarios. For each water management scenario, the water withdrawal rules and thresholds were calculated and then applied to the simulated streamflow. In the environment-first scenario, Q80 thresholds for each calendar month were calculated based on 30 years of simulated historical flow between 1981–2010 at the location of the Water Survey of Canada 'Below McMurray' hydrometric station. The Q80 thresholds were calculated independently for each GCM-driven simulation to account for the small differences in simulated flow over 1981–2010. The range of Q80 thresholds varied by approximately 4% between the different simulations.

The water withdrawal rules were applied to weekly streamflow to yield a weekly permitted river withdrawal rate. If this amount was less than the expected average industry withdrawal rate, an additional water supply, drawn from available stored water, was required to maintain bitumen production. If permitted withdrawals exceeded the industry withdrawal rate, the excess amount could be stored for later use. Therefore, as the water rules were applied to the time series of mid-century streamflow in each scenario, permitted withdrawals in excess of the industry withdrawal rate were used to fill storage, while deficits in river withdrawals were supplemented with storage water to meet the industry withdrawal rate.

In the industry-first scenario, storage filling is possible during open water season in weeks 19 through 43, where the prescribed water rules allow withdrawals in excess of the industry demand. In the environment-first scenario, storage filling can occur when the river flow is above the Q80 threshold and the average industry water withdrawal rate is met. In all cases however, additional water can only be stored if storage reservoir space is available. Over the 20 year mid-century time period considered here, the capacity of water storage reservoirs must be large enough to supply water when needed through multiple fill and use cycles during mid-century. The cycle of storage fill and use was calculated for each management and climate scenario combination, along with the minimum storage volume needed to maintain the industry withdrawal rate over consecutive periods of storage use. The calculation of storage fill and use assumed that the storage volume was initially filled to maximum capacity.

5.3 Results

Application of the industry-first scenario water rules to mid-century IBIS-THMB simulated streamflow showed that river flows can supply an average industry withdrawal rate of 16 m^3/s in all climate scenarios between weeks 18–38 (May to September) (Figure 5.1a). For January to mid-April, early November, and late December (weeks 1–15, 44–46, and 52), the available river flow cannot supply the average industry withdrawal rate in any climate scenario, and industry withdrawals will require an alternate supply of water from other sources. The minimum required storage capacity in RCP8.5 was similar to the P2F committee recommended storage capacity of 104 Mm^3 required for a 1 in 200 year low flow occurrence, while the minimum required storage capacity in RCP4.5 was closer

Table 5.2: The minimum storage capacity (Mm^3) in each management scenario that is required to maintain the indicated average industry water withdrawal rate across all GCM-driven streamflow projections for mid-century (2041–2060). The number of days that the storage volume can supply demand at the average industry withdrawal rate, is also shown.

	Industry-first 16 m^3/s		Environment-first 16 m^3/s		Environment-first 6 m^3/s	
	(Mm^3)	(days)	(Mm^3)	(days)	(Mm^3)	(days)
RCP4.5	87	63	424	307	120	231
RCP8.5	103	75	939	679	113	218

to the 91 Mm^3 required for a 1 in 100 year low flow occurrence (Table 5.2).

During the open water season (weeks 16-43), the calculated Q80 thresholds in the environment-first scenario (Table 5.3) were much higher than the EBF threshold in the industry-first scenario (Table 5.1). In contrast, the Q80 thresholds of the environment-first scenario during the winter (weeks 1–15, 44–52) were consistently lower than the T1 thresholds in the industry-first scenario. In general, the water rules in the environment-first scenario were more restrictive in the summer months and less restrictive in the winter months, relative to the industry-first scenario.

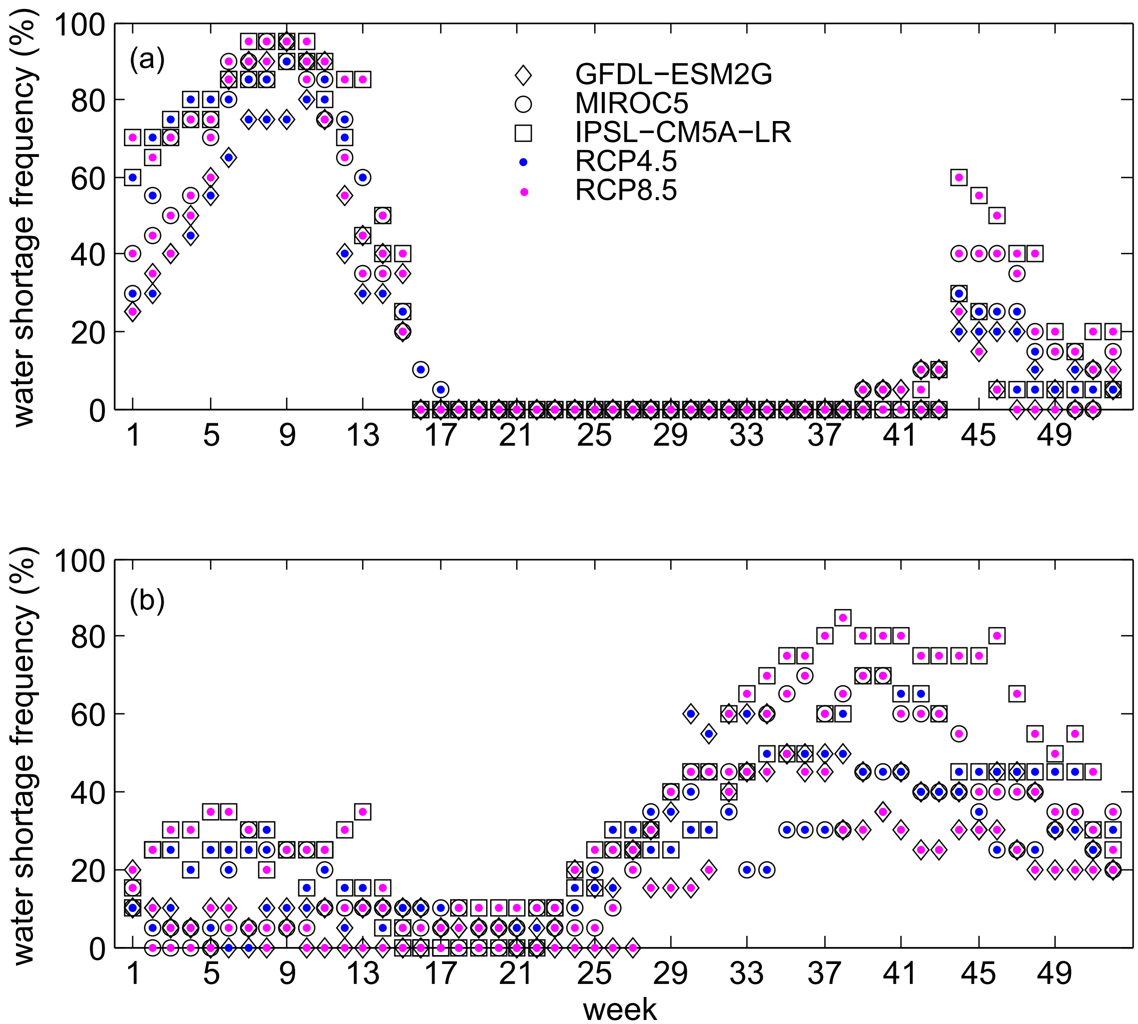

Figure 5.1: The percentage of time for each week of the year during mid-century (2041–2060) that river flow withdrawals cannot supply the full average industry withdrawal rate of 16 m^3/s for (a) the industry-first scenario and (b) the environment-first scenario.

Table 5.3: Example of the weekly water rules in the environment-first scenario for GFDL-ESM2G and RCP4.5. The water rule (R) defines the maximum permitted withdrawal rate when the weekly average river flow (F) meets the Q80 threshold (T) condition. Weeks are grouped here for brevity, but R is calculated separately for each week.

Week	R (m^3/s) If Flow in River F>T allow up to:	T(m^3/s)
1 - 15	15% of flow in river OR 29 m^3/s, whichever is lower	94 - 228
16 - 18		120 - 291
19 - 23		391 - 690
24 - 43		240 - 859
44 - 52		240 - 310

Application of the water rules of the environment-first scenario to mid-century streamflow shows that in the latter half of the year (from early July, or week 27, forward), river withdrawals cannot supply the high-growth average industry withdrawal rate of 16 m^3/s in any climate scenario (Figure 5.1b). Deficits in water availability also occur during weeks in January and February for all climate scenarios. The volume of water storage required to maintain an average industry withdrawal rate of 16 m^3/s is four to nine times greater than the largest volume required in the industry-first scenario (Table 5.2). Even at the 2010 average industry withdrawal rate of 6 m^3/s, the minimum storage capacity required would exceed that of the industry-first scenario by 110–140%.

5.4 Discussion

The withdrawal rules and rates, and the water storage requirements of the industry-first and environment-first scenarios, bookend a spectrum of future options for balancing water supply and demand in the Athabasca oil sands (Table 5.4). Restrictions on growth will limit the economic potential of the oil sands industry. If the focus is on the protection of industry, it is unlikely that policy makers will

Table 5.4: Matrix showing management options for a range of priorities based on the evaluation of the industry-first and environment-first scenarios.

	Industry protection	Environmental protection
Limited growth	Industry accepts economic losses and reduces water demand	$\sim 218 - 231$ days of storage required
High growth	$\sim 63 - 75$ days of storage required	Very high storage requirements, > 1 year

develop water management rules that limit the growth of operations (top left box, Table 5.4). Instead, it is more likely that storage volumes will be built to accommodate the increased demand for water that follows high-growth in oil sands production (bottom left box, Table 5.4). When environmental protection is a priority, permitting high-growth in oil sands production may encounter potential physical limitations of building sufficient storage volumes (bottom right box, Table 5.4), while reducing water demand will lead to more reasonable requirements for storage capacity (top right box, Table 5.4). The 2010 average industry withdrawal rate that was considered in the environment-first scenario is lower than the projected base-growth demand (based on announced or approved projects in 2006) of 11.3 m^3/s through 2030 [Golder Associates Ltd., 2009].

In both the industry-first and environment-first scenarios, the availability of water for oil sands operational use depends on several factors. First, water rules that define the EBF, low flow thresholds, and permitted withdrawals determine the rate and frequency of storage water use (when flow is below the threshold), as well as the frequency of storage filling (when flows are above the threshold). Second, the water intake capacity or water pipe diameter, determines the maximum rate of storage filling. Third, the average industry withdrawal rate determines both the rate of storage use (flow needed to meet the industry rate), and the rate of storage fill (available river flow in excess of the industry rate). Lastly, the maximum storage capacity limits the frequency and rate of storage filling and therefore determines the number of consecutive low flow periods that can be supplied with stored water (for example, in the IPSL-CM5A-LR-driven RCP4.5 simulation of the environment-first scenario, storage water is depleted over two consecutive years in which storage use exceeds storage fill opportunities). The presence of multiple controls on the availability of water for withdrawals make it challenging to design specific water rules and select water supply and demand thresholds that will be flexible enough to adapt to different future climate change scenarios.

Uncertainties in mid-century streamflow projections also complicate the design of specific water rules. This is demonstrated in the industry-first scenario, where the difference between the P2F committee and IBIS-THMB projections of climate change impacts suggest different storage capacity requirements, depending on the climate scenario. Understanding the range of future streamflow variability will also be important to future water use planning so that storage fill and use cycles can take full advantage of seasonal water availability. Water rules that are defined based on an incorrect assumption of higher available flows during certain seasons or weeks may miss opportunities for filling storage otherwise. For example, if minimum (winter flows) are projected to decline as generally simulated in the P2F committee climate change analysis, then water rules would be designed to limit withdrawals in the winter. However, if minimum flows generally increase as simulated by the IBIS-THMB climate change analysis, then water withdrawal rules may be relaxed to allow storage filling during these weeks, leading to more efficient use of storage capacity. The calculated storage requirements depend upon the specific sequence of climate variability in these simulations. The possibility of different climate realities than forecasted is therefore also an argument for the design of flexible water rules.

In order to maintain a specific industry average withdrawal rate in both the industry-first and environment-first scenarios, there must be a continuous and adequate water supply from river withdrawals and other water sources. The P2F committee considered several options for improving water access during periods of low flow, along with the associated capital costs, timing and feasibility issues, operating costs, footprint, and reliability of each option [Golder Associates Ltd., 2010]. Options included advancements in water treatment, off-site water storage (Lesser Slave Lake and McMillan Lake, other lakes and dams on tributaries), on-site water storage (constructed fresh water ponds, tailings pond treatment or delayed reclamation, delayed closure of pit lakes), and groundwater (Pleistocene aquifer via Wiau Channel). Of these, groundwater was the least likely to supply sufficient water, while water treatment was the least reliable and most costly ($40/m^3). Only two technologies were ultimately shortlisted as the preferred industry options based on risk, reliability, complexity, and timing issues: on-site fresh water ponds and on-site tailings ponds. Of these, on-site fresh water ponds were determined to be the more practical option, given that the ERCB Tailings Directive 074 requires that tailings ponds are decommissioned in a timely manner. These tailings ponds have a footprint that covers 22% of the total disturbed mining area, and contain the waste water and residue from oil sands bitumen extraction that can lead to the seepage of pollutants into surrounding soils and water, as well as pose a danger to migratory birds [Alberta Environment, 2009].

Oil sands operators will need to weigh the cost of building sufficient storage capacity (Table 5.5) against the cost of lost bitumen production during periods of water shortage. Although plant shutdowns do occur periodically, they are generally unplanned and any shutdown of water withdrawals may also lead to costs associated with equipment damage [Ohlson et al., 2010]. The P2F committee concluded that industry would be more likely to build additional storage capacity than to accept water supply shortfalls since the costs associated with a loss in production would exceed the cost of additional storage construction [Ohlson et al., 2010]. Given a 2012 WTI crude oil price of $95 US per barrel [CAPP, 2014] along with the P2F committee assumption of 3.5 million barrels of production per day by mid-century, a week of interrupted production would amount to $2.3 billion US in lost revenue, equivalent to the capital cost of building approximately 144 Mm^3 of on-site storage capacity. This storage volume would be sufficient to satisfy the industry-first scenario in each climate scenario (Table 5.5). In the environment-first scenario, however, constructing sufficient storage to prevent a single week of lost production during the mid-century time period could come at up to six times the cost of a week of lost revenue. In addition to capital costs, the annual operating costs and land area needed for storage will also influence decisions to build storage. Storage footprints in the industry-first scenario range from 44 to 52 km^2, while storage footprints in the environment-first scenario range from 212 to 470 km^2 and would exceed the mining area footprint of most oil sands operations (Table 5.5).

Table 5.5: Costs and footprint of freshwater pond storage per unit meter [Ohlson et al., 2010] and the calculated costs and footprint of storage requirements associated with the different management options considered.

Storage option	Capital cost ($\$/m^3$)	Annual operating cost ($\$/m^3$)	Footprint (km^2/Mm^3)	Water loss (Mm^3/Mm^3)
freshwater pond storage	16	0.88	0.5	0.04

Water scenario	Climate scenario	Withdrawal rate	Capital cost (M$)	Annual operating cost (M$)	Footprint (km^2)	Water loss (Mm^3)
industry-first	RCP4.5	16 m^3/s	1,392	76	44	3
industry-first	RCP8.5	16 m^3/s	1,648	90	52	4
environment-first	RCP4.5	16 m^3/s	6,784	371	212	16
environment-first	RCP8.5	16 m^3/s	15,024	822	470	35
environment-first	RCP4.5	6 m^3/s	1,920	105	60	5
environment-first	RCP8.5	6 m^3/s	1,808	99	57	4

The design and planning of future oil sands operations now include the construction of on-site freshwater storage facilities in anticipation of periods with low water availability that could interrupt bitumen production. The number of consecutive low flow periods that can be supplemented by stored water use is limited by the maximum built storage capacity. Imperial's Kearl mine site has a 30-day storage capacity intended to sustain production during winter months ($\sim$ 2.8 Mm^3 volume based on an estimated 1.07 m^3/s withdrawal rate from oil sands project data compiled in Chapter 3 [Imperial Oil Limited, 2013]), while Total E&P Canada's new Joslyn North Mine Project, scheduled to commence production in 2020, incorporates a 90-day water storage capacity ($\sim$ 2.9 Mm^3 volume based on an estimated 0.368 m^3/s withdrawal rate) [Total E&P Canada, 2014]. However, older operations without water storage capabilities, such as Suncor, have stated that implementing water storage facilities for their aging mining operations would produce a net negative impact on the environment due to additional land disturbance [Healing, 2010]. During the development process of the P2F, these companies have argued for a total 4.4 m^3/s exemption below the EBF due to plant designs that require continuous water withdrawals from the river and the absence of appropriate on-site water storage facilities. Using the per unit storage cost estimates, the construction of 30 days of storage capacity in order to supply Suncor's portion of the exemption withdrawal rate (2 m^3/s of the total 4.4 m^3/s) would require a $\sim$ 3 km^2 of freshwater pond storage area (Table 5.5), which is less than 2% of Suncor's mining footprint in 2010 [Suncor Energy Inc., 2011].

The environment-first scenario shows that water rules that provide maximum environmental protection cannot also supply a high-growth industry withdrawal rate of 16 m^3/s without prohibitively expensive storage volumes. If the current emissions trajectory is maintained (represented by RCP8.5), then maximum environmental protection will not be compatible with climate change and high industry growth due to the implausibly high storage requirements. To avoid high storage demands, limits could be placed on either bitumen production or the average industry withdrawal rate. A reduction in the average industry withdrawal rate without reducing production levels would require significant advancements in water mitigation technologies. In recent years, oil sands mining operations have taken successful measures to reduce their water consumption intensity; the amount of water needed to produce one barrel of oil. Suncor reports a current water consumption intensity of 2.06:1 (water:oil), a 10% reduction since 2007 [Suncor Energy Inc., 2013a]. Syncrude, in turn, reports a 60% reduction in water use since the 1980's [Syncrude Canada Ltd., 2012] Most oil sands mining operators have been exploring water use mitigation options both in retrofitting old operations and in the design and construction of future operations. For example, Suncors wastewater treatment plant, opening in 2014, is expected to reduce water consumption intensity by 65–75% relative to 2007 [Suncor Energy Inc., 2013b]. In 2012, 41.4% of water withdrawn for Suncor's operations was treated and returned to the Athabasca River, while for other operations such as Shell, no water from mining and extraction operations is currently returned to the Athabasca River [Shell Canada, 2014]. Canada's Oil Sands Innovation Alliance is also focused on accelerating the development and commercialization of water treatment technologies and managing salt accumulation in water streams on mine sites [Canada's Oil Sands Innovation Alliance, 2014].

Although the growth trajectory of oil sands mining operations is projected to continue rising, supply and demand forecasts don't generally extend into the mid-century time period considered in this study yet. There are a wide range of interacting factors that control future bitumen production, including energy prices, technology improvements, operational costs, crude oil demand, and remaining bitumen reserves [ERCB, 2013, Dobson et al., 2013]. Fluctuations in these conditions will control the pace of development of the oil sands industry and whether growth or decline in production and associated water use will occur.

5.5 Conclusions

A spectrum of future water management options for the Athabasca oil sands region was considered in this study. At one extreme, maintaining both maximum environmental protection and a high growth rate in water withdrawals is implausible, since the water storage requirements would not be cost-effective compared to the potential loss in production revenue and/or feasible with respect to available land area. At the opposite extreme, minimizing environmental protection and reducing current bitumen production output, is unlikely to find agreement with any stakeholders. Future water use in the Athabasca oil sands will require tradeoffs in both water supply and demand that consider the range of options in between these extremes. For example, water supply can be increased by relaxing the rules on seasonal water withdrawals and/or building greater water storage capacity, if environmental protection is reduced and/or additional capital and operating costs are incurred. Water demand for withdrawals, in turn, can be decreased by reducing bitumen production and/or increasing water use efficiency, but would result in lost revenue and/or increased research and development costs. The scale and costs of these actions will depend, in part, on the degree to which environmental protection and industry growth are each prioritized. In addition, there will be some risk associated with making these tradeoffs, since uncertainty (some of which is irreducible) in climate change projections introduces further uncertainties in estimating the future frequency and severity of low flow periods. The range of impacts and responses considered in this study can serve to inform future water management planning for the Lower Athabasca River, and also serve as a general example of the type of emerging tradeoffs between industrial water needs and in-stream flow needs in a changing climate.

Chapter 6

Conclusions

6.1 Key insights and findings

This dissertation describes the application of a land-surface model and a hydrologic model to the analysis of climate change and water use in the ecologically and economically important Athabasca River Basin. Collectively, the results of this research find that both climate change and industry growth will drive the future availability of freshwater, a critical resource for oil sands mining operations, as well as for people and ecosystems in the basin. In turn, the availability of freshwater to supply industry needs could influence the scale of future development in the Athabasca oil sands.

The key model results show that climate change is projected to be the primary driver of streamflow alterations that will directly affect seasonal water supply in the Athabasca River Basin by lowering summer flows and increasing winter flows (Chapter 4). Oil sands industry water withdrawals are projected to have a comparatively small impact on river flow (Chapter 3, Chapter 4). Since concern has conventionally focused on mitigating the environmental impact of oil sands water withdrawals on the Athabasca River, these findings suggest a new and additional motive for the careful management of water withdrawals - to mitigate the impacts of climate change-driven water shortages on bitumen production.

Calculations using a range of future water supply and demand trajectories indicate that sufficient water storage will be needed in all scenarios to prevent water shortages throughout the year (Chapter 5). The design of adaptive water rules should therefore optimize water storage by recognizing any seasonal shifts in the hydroclimatological regime. For example, the availability of flows is projected to increase during winter months, the historical low flow season when water withdrawals are typically minimized, and is projected to decrease during summer months, when water withdrawal restrictions are typically relaxed. Based on these projections, water rules should then be optimized to supply water during periods of low river flow by maximizing opportunities to fill water storage reservoirs during periods of high river flow.

The volume of storage needed to supplement river withdrawals depends not only on changes in the magnitude and timing of the freshwater river supply, but also on whether water demand for oil sands operations continues to rise, remains static, or declines. While the oil sands operators and the province of Alberta, although prominent contributors to greenhouse gas emissions, cannot alone mitigate the impacts of climate change on the Athabasca River Basin, there are options to address the water demand for bitumen production. Making decisions on the magnitude of water demand, and therefore the scale of bitumen production, will depend in part on how environmental protection versus industry growth is prioritized based on the tradeoffs between environmental and economic costs.

The management of future water resources for industry use is complex because it requires a scientific understanding of the regional water supply to inform management and policy options. For the Athabasca oil sands industry, this means that an understanding of the river basin hydroclimatology, the economics of bitumen projection, as well as the uncertainties in both future climate change and energy demand trajectories, is needed to inform tradeoff decisions.

6.2 Contribution

This research contributes a scientific basis for the future adaptive management of water resources in the Athabasca River Basin and develops a range of possible water management options for policy makers to consider. Although the results are specific to the Athabasca River Basin, the methods developed are also relevant to other river basins that face challenges in balancing energy and water demands under a changing climate.

Each chapter in this dissertation forms a part of the overall contribution. Existing large-scale, process-based models were adapted for application in the Athabasca River Basin and a historical baseline for streamflow was developed through the model parameterization and validation process (Chapter 2). This involved the collection and organization of climatic and hydrologic data to drive model simulations, and the results provide an essential reference point from which to evaluate future flow and projected impacts on water resources. This modelling framework has potential broader applicability to studies of the Mackenzie River Basin, as well as other northern Canadian river basins.

For the first time, a comprehensive set of oil sands water use estimates was synthesized from sparse data records and sources that are currently limited under the existing system of voluntary water use reporting (Chapter 3). This new data set provides a spatially explicit representation of water withdrawals in the Athabasca River Basin, which was used to construct a range of future water use scenarios. The application of these scenarios to simulate streamflow impacts is the first attempt to model oil sands water withdrawals within a process-based hydrological modelling framework.

This research is also the first attempt to quantify the range of climate change impacts on future streamflow in the Athabasca River Basin using the most recent global climate projections and scenarios (Chapter 4). The results of this climate change analysis constitute an assessment of the potential risks and vulnerabilities in future oil sands water supply, and highlight the dominant role of climate change in altering future streamflow availability. This discovery suggests that water managers, industry, and policy makers may wish to also consider the risks to future bitumen production, alongside the environmental risks of bitumen production.

Finally, the synthesis of climate change and water withdrawal impacts conducted in this study identifies a full range of water management options with different priorities and tradeoffs in environmental protection and industry growth, which can help to inform future water policy decisions (Chapter 5). This research expands on the body of knowledge that has been recently developed to draft a new regional water management framework. It considers different scenarios of industry growth and decline that have not been previously addressed. The methods for examining water storage options, while specific to the oil sands industry, is broadly relevant to any sector, such as agriculture, where freshwater withdrawals and storage is required.

The intersection of energy and water demands, along with the dependency of energy production on water, leads to increasingly common tradeoffs that are not unique to the oil sands industry [e.g., Richter et al., 2003, Chapagain and Orr, 2009, Döll et al., 2009, Harma et al., 2012]. The modelling approach of this study provides a tool to identify the science behind, and therefore inform the facilitation of, these tradeoffs that water managers may encounter in adapting a water management framework to future climatic and industry conditions.

6.3 Strengths and limitations of the research

The development of a scientific basis to inform water policy and management requires the integration of knowledge from different disciplines. These disciplines can include climate and hydrological science, ecology, and natural resource economics and management. Given the breadth of fields involved, the scope of this dissertation was necessarily focused on a subset of these topics. The approach for this research was to develop the specific linkages between hydrological science and water use management that quantify the timing of water supply and demand, in order to inform a framework for adaptation of future water use. The examination of water use is restricted to withdrawals by the oil sands mining industry; this is justified given that river water withdrawals for in situ oil sands projects and for other economic sectors in the Athabasca River Basin are negligible in comparison.

A large-scale process-based modelling approach was chosen for this study because it was important to simulate the hydrologic response of the entire river basin in order to capture future climate change impacts. Although the key water use issues in this study are primarily contained in the lower reaches of the basin, they reflect the upstream dynamics that drive downstream flow. A sacrifice in pursuing a large-scale approach is that small-scale processes, such as the river ice cycle and its impact on flow, are difficult to parameterize. However, there are inevitable tradeoffs between predictability and model complexity. For example, while alternative models, such as those calibrated to a river reach, may describe historical flows more accurately, a process-based model can be better able to capture the sensitivity of the model to changing drivers like climate.

Another challenge with large-scale, process-based models is the accurate simulation of all atmosphere, soil and vegetation exchanges across a large basin. The characterization of these physical processes requires a spatially and temporally extensive observational data set to validate each component of the modelled water balance, and such information was limited for the Athabasca River Basin. Although streamflow validation captured the timing of flows well, disagreements between the magnitude of observed and modelled discharge persisted, particularly in the winter months. An analysis of observed precipitation data also showed that the overprediction of streamflow in the last decade of the historical time period was likely due to inaccurately large reanalysis precipitation inputs to the model system. To control for these biases in the simulated streamflow, the common practice of studying the change in future projections relative to a baseline was adopted, rather than the use of raw future projection output. This approach still allows for a full range of water withdrawal and climate change impacts on streamflow to be captured. Due to the differences between global climate models, irreducible uncertainties between climate change projections, especially regional ones, will also occur.

6.4 Potential future research directions

Many avenues exist for future research that expands and draws on the work in this dissertation. Further development of the modelling system would improve the accounting of various hydrological processes important to the Athabasca oil sands region. For example, river and lake ice dynamics could be simulated by parameterizing the basic sensitivity of freeze/melt timing and ice thickness to temperature. Another example is the model parameterization of wetland environments that would have implications for flow storage and pathways that affect the downstream timing of flows. Modelling the spatial and temporal distribution of wetlands could involve a parameterization based on soil saturation and/or a parameterization based on inundated areas. Also of note is that the current oil sands mining landscape is not specifically captured in current model simulations. The parameterization of land-surface exchanges over the oil sands mining area may be important in determining whether the water demand for future land reclamation of mined sites can be satisfied.

Improvements to the modelling system would advance the accuracy of simulated seasonal streamflow, however, any new model developments must still be supported by adequate observational data in order to validate the physical processes that are represented. Continued development of a comprehensive network of observations in the Athabasca River Basin is needed to better validate model predictions of future water availability and therefore minimize the risk and uncertainty in management decisions. Observations are also needed to bridge the gap between experimental work at the river reach-scale, and the large-scale averages that are required for basin-scale climate modelling. In 2012, the provincial and federal governments announced a three-year Joint Canada-Alberta Implementation Plan for Oil Sands Monitoring which aims to increase monitoring efforts in the oil sands region. The plan will examine the long-term cumulative impacts of the oil sands industry using an expanded network of monitoring sites, including increased water quantity monitoring, and improved methodologies for data collection. Industry-funded initiatives such as the Regional Aquatics Monitoring

Program have also contributed to observations of discharge in the Athabasca River in recent years, although the majority of water quantity monitoring stations in this network are located along tributaries of the Athabasca River.

In addition to further model development, existing features of the modelling system can also be applied to expand the scope of this research. For example, the hydrological routing algorithm, THMB, has the capability to examine basin sediment flow and dissolved constituents [Donner et al., 2004, Donner and Kucharik, 2008]. These algorithms could potentially be applied to investigate water quality issues in the Athabasca oil sands, a key environmental concern.

Many other potential research directions exist beyond the scope of hydrological modelling and address the breadth of disciplines related to water management. One key example is the exploration of environmental risk. A direct evaluation of potential threats to river ecology and in-stream flow needs is needed to determine if environmental tradeoffs are legitimate, and whether water use allocations address environmental risk as intended. The vulnerabilities of multiple ecosystems need to be considered, in addition to the conventional focus on fish habitat and life cycles. Another dimension of environmental risk that can be examined is the contribution of greenhouse gas emissions from the oil sands industry to climate change, which in turn drives streamflow alterations that can interrupt bitumen production.

Water use beyond the scope of the oil sands industry, could also be considered in future research. For approximately the next decade, water use in other sectors is projected to remain small relative to water use for the oil sands mining industry. Climate warming by mid-century and beyond could, however, lead to an increase in competition for water resources in the Athabasca River Basin by transforming regions currently too cool and remote to sustain agriculture into viable sectors that require water for irrigation [Brklacich et al., 1997, Ramankutty et al., 2002]. While water withdrawal needs for oil sands operations are relatively constant throughout the year, water withdrawal needs for irrigated agriculture follow a more seasonal pattern. Different patterns of water use could further complicate the timing of available flows for either industry and make the design of water withdrawal rules across the basin more challenging.

While the research in this dissertation addresses hydrological and industry issues specific to the Athabasca River Basin, the scientific methods and concepts developed can also be applied more broadly in future work. The models used to analyze future water availability under climate change, for example, were adapted to the Athabasca River Basin, a cold, northern river basin, and can potentially be applied now to a study of the entire Mackenzie River Basin and other cold-region river basins. Water use concepts addressed in this study, such as adapting to freshwater supply and demand constraints, and tradeoffs between energy and water supply, have wide applicability for water resource management in other river basins as well. Some regions may face tradeoffs in future energy and water security with respect to different industries such as hydroelectricity and shale gas exploration [POLIS Project on Ecological Governance, 2012]. Studies of the evolving interaction between climate and human streamflow perturbations in any basin will help build an informed approach to the general climate change adaptation of future water use.

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