

**Climate Change Impact Analysis on Hydropower  
Operations in the Lower Nelson River Basin**

by  
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## **Abstract**

This thesis presents an assessment of the effects of climate change in reservoir inflow and hydropower generation potential across the Lower Nelson River Basin. A hydrologic-operations model coupling framework was developed and two coupled models, WATFLOOD-MODSIM and HEC-HMS-MODSIM, were set up to simulate both basin water balance and hydropower generation. The coupled models were driven by nineteen climate simulations from CMIP5 to compute historical (1981-2010) and future (2021-2070) reservoir inflow and hydropower generation potential. This work aimed to identify changes in the annual and seasonal reservoir inflow quantity and distribution and to evaluate the likelihood of future hydropower generation exceedance (relative to a historical threshold). Results show that it is *about as likely as not* or *unlikely* to be a statistically significant trend (neither increase nor decrease) in annual and seasonal reservoir inflow and hydropower generation potential over 30-year periods on Lower Nelson River. There is a large variability in projected changes in both annual and seasonal reservoir inflow and hydropower generation potential due to dry scenarios becoming drier and wet scenarios becoming wetter over the years. Winter is identified as the season with the greatest possible reduction in reservoir inflow and hydropower generation potential and the least possible increase in the 30-year mean over time. Increases in reservoir inflow did not always translate to an increase in hydropower generation potential on the Lower Nelson River due to limits on system generation capacity for storing water. Therefore, a reduction in inflow directly translated to a reduction in hydropower generation potential, while an increase in inflow only contributed to a limited increase in hydropower generation potential.

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## List of Acronyms

CMIP5	Coupled Model Inter-comparison Project Phase 5
CRD	Churchill River Diversion
CS	Control Structure
DSM	Down Scaling Method
GCM	Global Climate Models
GHGES	Greenhouse Gas Emissions Scenario
GRU	Group Response Unit
GS	Generating Station
HBDB	Hudson Bay Drainage Basin
IPCC	Intergovernmental Panel on Climate Change
KGE	Kling-Gupta Efficiency
LNR	Lower Nelson River
LNRB	Lower Nelson River Basin
LULC	Land Use/Land Cover
LWR	Lake Winnipeg Regulation
MH	Manitoba Hydro
NCRB	Nelson-Churchill River Basin
NSE	Nash-Sutcliffe Efficiency
RCP	Representative Concentration Pathway
ROR	Run-of-the-River
SIL	Southern Indian Lake
WSC	Water Survey of Canada

## **1.0 Introduction**

The Lower Nelson River Basin (LNRB) is an outlet basin of the Nelson-Churchill River Basin (NCRB) which drains water collected from the Rockies, Canadian Prairies, northern portions of North Dakota and Minnesota, Northwestern portions of Ontario into Hudson Bay. The massive amount of water coursing through the LNRB is used to generate hydroelectricity. Hydroelectricity is a major source of electricity in Manitoba for both domestic use and foreign exports. Almost 97% of electricity in Manitoba is generated through hydropower operations, the highest percentage nationally (Natural Resources Canada, 2017), and over 70% of provincial hydroelectric generation capacity lies in the LNRB (Manitoba Hydro, 2018). Nationally, hydropower is a major factor in the Canadian economy, accounting for 60% of national power generation in 2017. In 2016, Canada was the second-largest producer of hydroelectricity in the world (Natural Resources Canada, 2017) and the overall hydropower generation has been actively growing in the past decades (Cherry et al., 2017). The increase in hydropower generation potential and efficiency can help Canada transition away from fossil fuel.

Canada has observed a rapid increase in mean annual temperature of 1.7°C nationally (roughly double of global increase) and of 1.9°C in the Prairies (where the Nelson and Churchill River Basins are located) in the period of 1948-2016 (Natural Resources Canada, 2019). In the high emission scenario (RCP 8.5), the Prairies is expected to observe an increase in annual mean temperature of 2.3°C and 6.5°C in the period of 2031-2050 and 2081-2100 respectively relative to 1986-2005. This increase in mean annual temperature has and is expected to change the precipitation type, quantity and spatial distribution in the future (Buttle et al., 2016; DeBeer et al., 2016; Vincent et al., 2015), a major factor governing the amount of snowmelt freshet. Despite the high confidence in projected temperature increase and precipitation changes, their integrated

effects on streamflow are complex (DeBeer et al., 2016), leading to lower streamflow projection confidence. In particular, the Hudson Bay Complex, where the LNRB is located, is a highly climate-sensitive region with a low streamflow projection agreement (MacDonald et al., 2018), which warrants an investigation on the effects of climate change on hydropower operations in the LNRB.

In an attempt to assess the impact of climate change on hydropower systems, many studies have been devoted to evaluating the associated hydrological impacts (Ahn et al., 2016; Cristina and Desiree, 2017; Eum and Simonovic, 2010; Haguma Didier et al., 2015; MacDonald et al., 2018; Manitoba Hydro, 2015a; Minville et al., 2009, 2010; Park and Kim, 2014; Poitras et al., 2011; Stadnyk et al., 2019). These studies focused on generating flow ensembles using stand-alone hydrologic models with climate forcing generated from one or more global climate models (GCMs), greenhouse gas emissions scenarios (GHGES), and downscaling methods (DSMs). Amongst the studies evaluating operational impacts, most were focused on basins with independent upstream reservoir operations (Cristina and Desiree, 2017; Minville et al., 2009; Park and Kim, 2014) or on complex basins with simplified equations to represent reservoir operations (Carvajal et al., 2017; Patro et al., 2018). There is yet to be a study that examines a cascaded hydropower system or a combined system with Run-of-the-River (ROR) and storage hydropower generating stations or a study on the effects of climate change on hydropower operations in Northern Manitoba. This research was intended to contribute to these areas and to assess the effects of climate change on reservoir inflow and hydropower generation potential in the LNRB.

## 1.1 Objectives

The objectives of this research are to answer the following questions:

- 1) How will the annual and seasonal reservoir inflow quantity and distribution change across LNRB in the future (2021-2070) compared to the historical period (1980-2010)? Given the variability among climate projections, will there be a detectable, statistically significant change when examined as an ensemble and as individual projections?
- 2) How will changes in reservoir inflow in the LNRB affect hydropower generation potential of the Lower Nelson River? Will the current LNRB system be able to generate a similar amount of hydropower (as the historical period) in the future? When would generation from the existing LNRB system potentially be reduced as a result of changing inflows, requiring alternate supply or operations?

Objective 1 is achieved by developing a hydrologic-operations model coupling framework for LNRB to take both basin hydrology and Manitoba Hydro (MH) operations in flow simulations. Two hydrologic models, WATFLOOD and HEC-HMS, were chosen to evaluate streamflow uncertainty resulting from the choice of the model, model structure, and hydrologic process representation. An operations model, MODSIM-DSS, was chosen to simulate the reservoir operations and hydropower generation across LNRB and to be coupled with the hydrologic models. Nineteen climate simulations (from various global climate models, or GCMs, and representative concentration pathway, or RCP, combinations) were run through the coupled model framework, capturing approximately 90% of the variability in future climate projections across the entire Hudson Bay Complex (Stadnyk et al., 2019). The results were analyzed to examine changes in annual and seasonal inflow trends over time and distribution over 30-year periods.

Objective 2 is achieved by comparing the exceedance rate of historical annual and seasonal mean hydropower generation potential as a standardizing threshold and by quantifying the changes in the magnitude of hydropower generation potential between historical and projected simulation results.

## **1.2 Scope**

This study is one of the initial projects looking at hydrologic-operations coupling research under the Global Water Futures (GWF) IMPC (Integrated Modelling Program for Canada) project. This research produced a general hydrologic-operations coupling framework for WATFLOOD, HEC-HMS, and MODSIM-DSS. At this stage of research, dynamic feedback loops between atmosphere-terrestrial (GCM-hydrologic models) are not considered.

This study leverages data and results from prior BaySys projects and has used existing GCM outputs and models. The nineteen selected climate simulations represent approximately 90% of the variability in future climate projections across the Hudson Bay Drainage Basin (HBDB) area, not the LNRB specifically. The existing HYPE, WATFLOOD, HEC-HMS and MODSIM-DSS models of LNRB were used in this study. As the LNRB is located near the outlet of NCRB, the upstream NCRB flow contribution into LNRB at Jenpeg generating station (GS) and Notigi control structure (CS) relies on a regional HYPE simulation for the NCRB.

While the research considers uncertainty stemming from climate scenarios and hydrologic model selection, this research is limited to examining flow bounds and does not evaluate uncertainty apportionment. This study only evaluates the impacts of climate change on current hydropower system infrastructure and operations and hence assumes system, operation and demand stationarity. Furthermore, although the historical regulations were implemented in a step-wise

manner, the modelling assumes the present-day system and operation as overall historical representation.

## **2.0 Literature Review**

This chapter provides a brief summary of existing literature on climate change studies in a hydropower operations context. Over the last few decades, many studies focused on estimating the potential impacts of climate change in water resource operations. As there is much uncertainty in deducing “accurate future”, one of the main focuses of climate change impact analysis lies in selecting a good range of future scenarios and simulating various futures on a water resources system. In general, water resources system impact analysis examines the impact of climate change on basin hydrology or systems operation (e.g. reservoir operations) by analyzing the computed future streamflow. One of the newer methods of analysis is to couple hydrologic and operations models (also known as an integrated water resources management model) to assess the impact of climate change on both basin hydrology and operations infrastructure together.

### **2.1 Climate change and reservoir operation**

#### **2.1.1 Existing approaches to investigate the effects of climate change on hydropower operations**

Investigations on the effects of climate change on water resources operations as well as hydropower operations are not new. These studies aim to understand the changes in basin flow and to assess the robustness of historical anthropogenic systems and operations. However, many of these studies were limited to evaluating simulations of independent upstream reservoir operations (Cristina and Desiree, 2017; Minville et al., 2009; Park and Kim, 2014; Prudhomme et al., 2003) or using simplified equations to represent reservoir operations (Carvajal et al., 2017; Patro et al., 2018). In addition, there is yet to be a study that examined a system with a series of ROR and storage stations or a study on hydropower operations in Northern Manitoba.

There are two approaches to assess the effects of climate change on hydropower operations. The typical and conventional approach is the “top-down” approach (Whateley et al., 2014). The top-down approach aims to answer the question “What will the future climate and flow be? What are

the operational impacts of these future climates?” (Brown et al., 2012) and ultimately present results as multi-ensemble flow projections from discrete climate simulations. In the top-down approach, multiple GCMs driven by multiple GHGES form a set of plausible climate projections. The generated climate projections are then downscaled from global to regional resolution and bias-corrected to drive the hydrologic and operations models, which then generate a set of possible flow projections.

The “bottom-up” approach aims to answer the question “Is it the climate that favours decision A more or less likely than the climate that favours decision B?” and ultimately present results as a set of operational decisions with the associated extent of climatic state (Brown et al., 2012; Maier et al., 2016). The bottom-up approach examines the range of climate state, e.g. percent change in precipitation, rather than discrete climate simulations to evaluate system performance. Bottom-up decision scaling analyses uses historical data and stakeholder inputs to first identify performance threshold and operation decision, such as building a new reservoir. The associated climate range to each decision is identified through stochastic sensitivity analysis and are used to drive hydrologic and operations models to generate flow projections. Finally, GCM projections are evaluated to assign probabilities of occurrence of each climatic state.

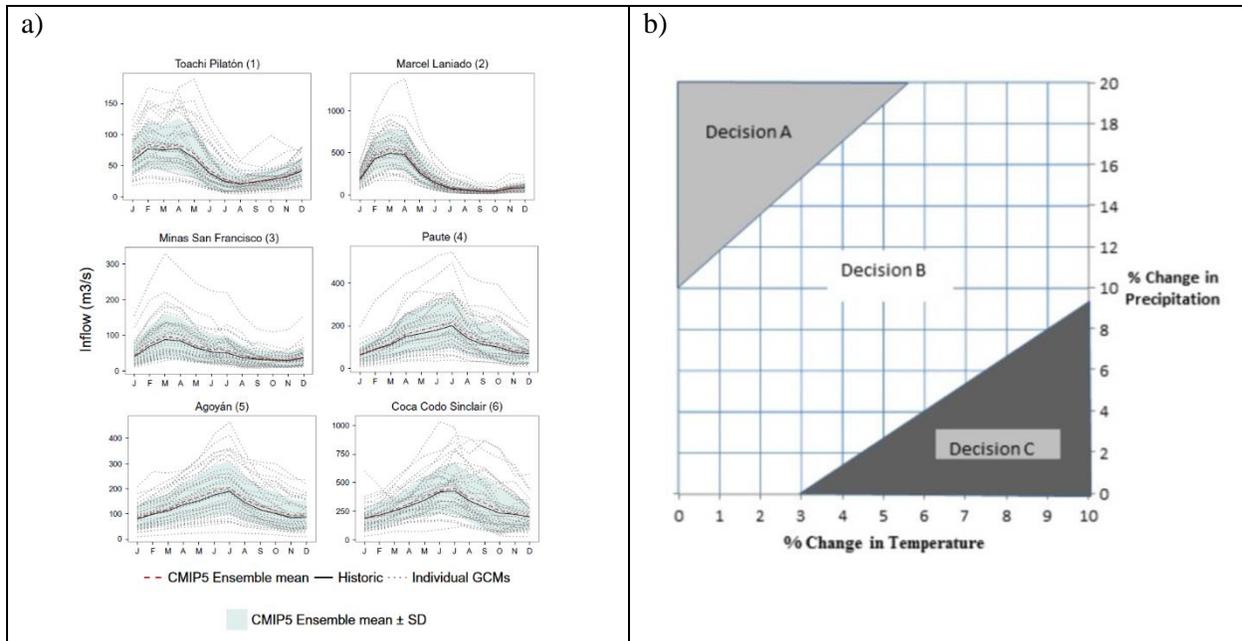


Figure 2-1: Final result representation of top-down (a) (Carvajal et al., 2017) and bottom-up (b) (Brown et al., 2012) approaches

### 2.1.2 Uncertainty in future flow projections

Water resources system performance is dependent on the system's streamflow supply and thus, an estimate of the future system flow is required. However, there are multiple sources of uncertainty associated with generating future flow projections. The five major sources of uncertainty are summarized in Table 2-1

Table 2-1: Summary of the main sources of uncertainty in future flow projections

Source of uncertainty	Definition
General Circulation Models (GCMs)	Uncertainty from lack of knowledge regarding certain governing climate principles and processes and responses of GCM to GHGES
Green House Gas Emission scenarios (GHGES)	Uncertainty from lack of knowledge regarding future GHGES
Downscaling Methods (DSMs)	Uncertainty from transforming global scale GCMs environmental phenomenon to local scale
Numerical models (model structure and process representation)	Uncertainty from a simplified and limited numerical representation of the physical environment
Model parameterization	Uncertainty in parameter assignment to simplified algorithms

The uncertainties from different sources are presented by the range of all flow simulations or a flow envelope. Currently, it is generally accepted that the largest uncertainty is contributed from GCMs and then to GHGES (Minville et al., 2010) for future projection studies and thus many studies focus on examining uncertainty stemming from climate simulations of different GCM and GHGES combinations (Cristina and Desiree, 2017; Eum and Simonovic, 2010; Her et al., 2019). Some studies argue that other sources of uncertainty, such as the downscaling method (DSN), are more or equally significant to uncertainty in climate simulations (Dibike and Coulibaly, 2005; Mandal and Simonovic, 2017). The contribution of uncertainty from GCMs, GHGES, hydrologic models and parameters may also vary depending on location and characteristics of the basin, and currently, there is limited literature in Canada which investigates all sources of uncertainty in streamflow projection under climate change (Mandal and Simonovic, 2017; Pokorny et al., in process).

Flow projections are results of underlying GCM, GHGES, model and parameter selection. Hence, the generated future climate simulations are only multiple *plausible* climate simulations, not multiple *probable* simulations (Maier et al., 2016). And even any probabilities associated with an ensemble of simulations do not represent the probability of any given climate, only a probability within the sampled ensemble itself (Beven, 2011). Therefore, there should be caution exercised in selecting climate simulations (GCMs and GHGES selection) that encompass a wide range of possible futures (Casajus et al., 2016).

### **2.1.3 Projected climate change in the Nelson-Churchill River Basin**

The Prairies, where the Nelson and Churchill River Basins are located, has observed a rapid increase in mean annual temperature of 1.9°C between 1948 and 2016 (Natural Resources Canada, 2019). In the high emission scenario (RCP 8.5), the Prairies are expected to observe an increase in

annual median temperature of 2.3°C and 6.5°C in the period of 2031-2050 and 2081-2100 respectively relative to 1986-2005. In terms of precipitation, the Prairies have observed an increase in normalized annual precipitation of 7% in the period of 1948-2012 (Natural Resources Canada, 2019); however, the changes in the seasonal precipitation are not uniform – with a decrease of 5.9% in winter but an increase of 13.6%, 8.4%, and 5.8% in spring, summer and fall precipitation, respectively. In the high emission scenario (RCP 8.5), the median annual precipitation is expected to increase 6.5% and 15.3% for 2031-2050 and 2081-2100, respectively relative to 1986- 2005 (Natural Resources Canada, 2019).

Rainfall and snowfall distributions have shifted significantly across Canada due to an increase in precipitation and temperature. Southern Canada (below 60° N latitude) has observed decreases in annual snowfall as well as seasonal (fall, winter, and spring) snowfall due to an increase in precipitation at above zero temperatures. In the Prairies, the shift in the precipitation type is more prominent in spring with a decrease in the snowfall ratio (ratio of total snow water equivalent divided over the total precipitation) mainly attributed to spring warming (Vincent et al., 2015). Jeong and Sushama (2018) projected a general increase in rain-on-snow events in 2041-2070 due to the increase in the rainfall frequency and air temperature based on Canadian regional climate models. The infiltration process is a function of soil ice conditions and snowmelt rate (Granger et al., 1984; van der Kamp et al., 2003; Stähli et al., 1999). The increase in temperature will reduce the degree and extent of permafrost and alter the amount of snowmelt freshet reaching streams.

Despite these more likely trends in temperature and precipitation, the agreement in discharge projections is weaker (MacDonald et al., 2018). Summer streamflow for many Prairie rivers with headwaters in western mountains is projected to decrease in association with decreasing snow and ice (Natural Resources Canada, 2019). However, the Western Hudson Bay region, including

NCRB, despite being a highly climate-sensitive region shows a low flow projection agreement with greater internal spatial variability than other regions of the Hudson Bay complex.

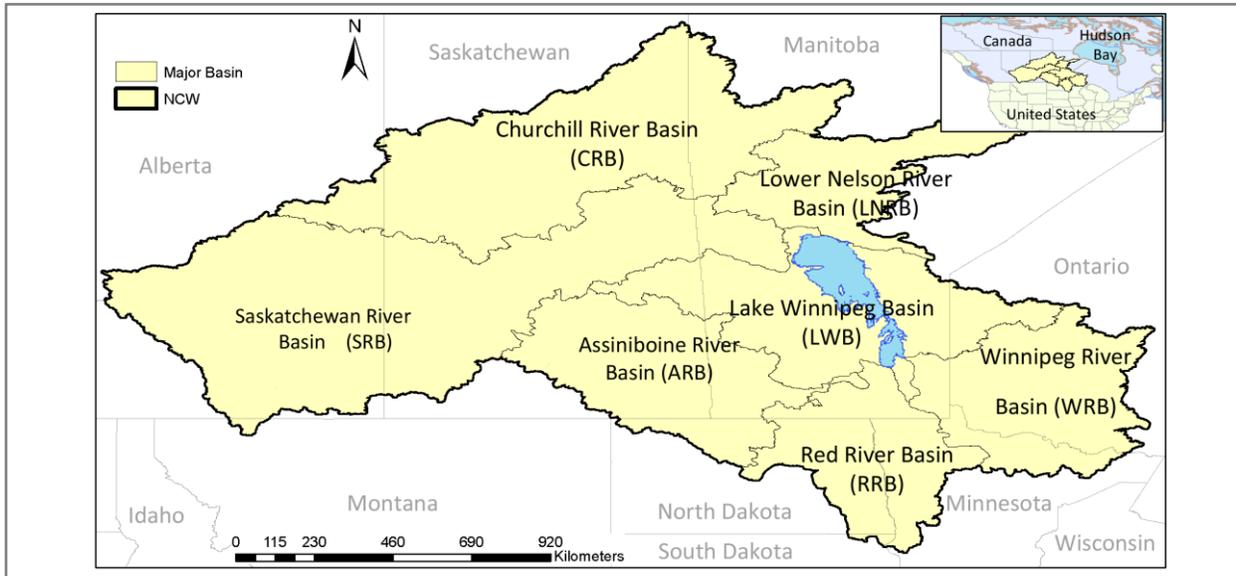


Figure 2-2: Map of Nelson-Churchill River Basin

An investigation on the effects of climate change on hydropower operations is needed given the projected changes and uncertainty in flow projections and the importance of the selected study area (LNRB) for both domestic and export needs.

## **2.2 Background on water resources model coupling**

### **2.2.1 Defining model coupling in water resources**

The definition of the word “couple” and the degree of “coupling” varies between studies and various models used. The scientific literature of water resources shows that the word “coupling” refers to using multiple models in tandem to supplement model limitations. Models supplement their limitations by exchanging simulated variables which cannot be calculated by themselves.

Model coupling gained popularity as it offers a better understanding of environment-human interaction (Belete et al., 2017; Laniak et al., 2013). The literature shows many studies that coupled models from different fields of research in order to bolster each model’s limitations. For example, Betrie et al. (2011) coupled SWAT (hydrologic) (Arnold et al., 1998) and SOBEK (hydrodynamic) (WL/Delft Hydraulics, 1995) in order to simulate the backwater effect that is not possible in SWAT alone. Morway et al. (2016) coupled MODFLOW (groundwater and surface water hydrologic) (Harbaugh, 2005) and MODSIM (water operation) (Labadie, 2006) model to represent limited groundwater supply in water allocation which is not possible in MODSIM alone. Vaghefi et al. (2017) coupled SWAT (hydrologic) and MODSIM (water operation) models to simulate crop water productivity while considering water allocation which would not be possible with the SWAT model alone. Anis et al. (2017) showed that by coupling MESH (hydrologic) and MODSIM (water operation) to capture physical hydrology and regulations, Nash-Sutcliffe efficiency (NSE) at the catchment outlet was improved from 0.28 to 0.98.

### **2.2.2 Types of model coupling**

There are many ways to categorize model coupling such as by coding methods or by data exchange methods. As the computation burden lies with data exchange methods, there is an interest in selecting appropriate data exchange method for hydrologic-operations model coupling. The model

coupling can be divided into three types based on data exchange methods – single feed, iterative, and dynamic coupling.

Single feed coupling is where two models are run to completion in a sequence. In hydrologic-operations model coupling, usually, a hydrologic model is run first to produce flow time series to be inputted into the operations model (Cristina and Desiree, 2017; Lanini et al., 2014) or optimization algorithm (Eum and Simonovic, 2010; Liu et al., 2018; Valeriano et al., 2009) to be optimized. Iterative coupling is similar to single feed coupling where two models are run to completion in a sequence. However, this model run sequence is iterated either by only running the models over smaller time intervals (e.g. each year) or by multiple feedbacks (i.e. run to completion each sequential run iteration). In single-feed or iterative model coupling, models are usually loosely coupled - meaning that the models are kept separate and data exchange between models is facilitated manually or via a script (Betrie et al., 2011; Rosenzweig and Hodges, 2011). This is a straightforward most common coupling approach in water resources coupling (Wu et al., 2017).

On the contrary, the dynamic coupling is where two models are run simultaneously and the input and output parameters in both models are updated in each time step to completion. In dynamic coupling, models are either interface coupled, also referred to as component-based coupling, where the models are kept independently and the data exchange between models are facilitated by API (Application Program Interface) such as OpenMI (Blind and Gregersen, 2005), or integrated, where one of the models is implemented inside another model. Both API coupled and integrated approaches require model source codes to enable the models to start and stop and to accept new simulated variables during the model run, which often requires application development skill above those of a typical scientific programmer (Sutherland et al., 2013).

### **2.2.3 Gaps in hydrologic – operations model coupling for hydropower operations**

A review of the literature indicates that hydrologic-operations model coupling, particularly for hydropower operations, has been approached in a limited way. The main interest of hydrologic-operation coupling is to assess “what if” scenarios of various climate, system and operation changes. Single-feed coupling is mainly used for this purpose (Ahn et al., 2016; Chhuon et al., 2016; Eum and Simonovic, 2010; Lanini et al., 2014; Li et al., 2010; Park and Kim, 2014; Sulis et al., 2009; VanRheenen et al., 2001). The limitations of these studies are that they only investigate “what if” scenarios for a single reservoir (Chhuon et al., 2016; Lanini et al., 2014; Li et al., 2010; Sulis et al., 2009) or multiple parallel reservoirs (Ahn et al., 2016; Eum and Simonovic, 2010) where the operation of a reservoir does not impact neighbouring reservoirs. These studies can use simple single-feed coupling because the reservoir operations of the study do not require feedback between upstream and downstream activities. There is a gap in the literature, however, in terms of applying these models to assess “what if” scenarios in basins with reservoirs in series (i.e. cascaded system).

The dynamic and iterative coupling approaches have rarely been used in the literature. Dynamic coupling is mainly limited to the simulation of groundwater-operations coupling (Brookfield et al., 2017; Morway et al., 2016; Winter et al., 2017) to reflect finite groundwater supply and the delays of groundwater response to surface water and groundwater management actions. Furthermore, groundwater models have advantages of having “stock variables” (e.g. groundwater head) as exchange outputs which lend itself for the simulation model to restart from the previous step (Khan et al., 2017). There are a few studies (Anis et al., 2017; Vaghefi et al., 2017) that used iterative coupling instead of dynamic coupling to incorporate water management operation into hydrologic modelling. This is because the main exchange output in hydrologic-operations model coupling is the reservoir release data (surface water) and operations models are able to balance it without

exchanging data to the hydrologic model at each time step. Reservoir operations in these previous studies were focused on agricultural demands, rather than hydropower generation.

### **3.0 Study area and models**

This chapter provides background on the study area and models used in this study. An understanding of the study area and models will provide an important context for the model coupling framework and model results.

### **3.1 Study area – Lower Nelson River Basin**

#### **3.1.1 Physiography of Lower Nelson River Basin**

The Lower Nelson River Basin (LNRB) is the main outlet basin of the larger Nelson-Churchill River Basin (NCRB) located in northern Manitoba. The LNRB is approximately 90,500 km<sup>2</sup> out of 1.4 million km<sup>2</sup> of NCRB that drains water from southern Alberta, Saskatchewan, and Manitoba, parts of northern Minnesota and North Dakota, and part of north-western Ontario into the Hudson Bay. This thesis is focused on hydropower operations in the LNRB and only includes parts of downstream of Nelson River West (Jenpeg GS) and East channel and Notigi CS. The Gunisao subbasin is excluded from the study domain as the subbasin contribution is included in the Nelson River East channel flow.

The majority of the basin lies in the Canadian Shield, underlain by shallow or exposed bedrock. The soil underlying the LNRB is shallow and predominantly lacustrine clay with poor drainage (Holmes, 2016; Smith et al., 2015). The basin is located in a sporadic permafrost region (10% - 50% permafrost), with the most downstream portion in extensive discontinuous permafrost (50-90%) (Smith et al., 2015). The LNRB is characterized by a low topographic gradient with an average basin slope of 0.037% due to Lake Agassiz glaciation. Surface depressions such as small lakes, channelized lakes, and wetlands are extensive throughout the basin (Holmes, 2016). Table 3-1 summarizes the percent distribution of land cover in the LNRB.

Table 3-1: Land cover of the LNRB (Holmes, 2016; Smith et al., 2015)

<b>Land type</b>	<b>Approximate basin percentage</b>
Coniferous forest	35%
Bogs, fens, and wetland	26%
Shrub	16%
Open water	14%
Mixed forest / treed rock / impervious area	9%

### 3.1.2 The climate of Lower Nelson River Basin

The LNRB lies in a sub-arctic continental climate region characterized by cool summers, cold winters and moderate precipitation and humidity (Holmes, 2016; Lihare et al., 2019). Table 3-2 summarizes the 1981-2010 temperature and precipitation normal for the LNRB (Environment and Climate Change Canada, 2019).

Table 3-2: 1981-2010 Climate normal summary for four climate stations in the LNRB

	<b>Gillam A</b>	<b>Thompson A</b>	<b>Cross Lake</b>	<b>Norway House</b>
<b>Average Daily Temperature [°C]</b>	-3.7	-2.9	-0.4	-0.7
<b>Annual Precipitation [mm]</b>	496.4	509.2	469.4	532.3
<b>Annual Rain [mm]</b>	315.3	340.2	349.9	375.8
<b>Annual Snow [mm]</b>	221.2	187.0	119.5	195.0

The basin average daily temperature varies North-South, with an average temperature of -3.7°C in Gillam and -0.4°C in Cross Lake. The coldest month is January with an average temperature of -22.7°C and the warmest month is July with an average temperature of 16.9°C. The snowfall-free period is short (June to September) and the average daily temperature remains subzero for the majority of a year (November to April) (Environment and Climate Change Canada, 2019).

The basin receives on average 500 mm of annual precipitation, with approximately 69% as rainfall and 31% as snowfall. The highest monthly precipitation occurs in July with approximately 16% of the annual precipitation, while the lowest monthly precipitation occurs between November and April. The annual evapotranspiration ranges from approximately 300 mm to 350 mm (Environment and Climate Change Canada, 2019; Smith et al., 2015).

### **3.1.3 Hydrology of Lower Nelson River Basin**

Nelson and Burntwood (carrying diverted Churchill River flow) Rivers are the major rivers running through the basin, merging at Split Lake. Nelson and diverted Churchill Rivers enter the LNRB through regulation points, Jenpeg GS and Notigi CS, respectively and a non-regulation point, Nelson River East channel, and contribute to approximately 57%, 23% and 10% respectively, of annual flow observed at the Long Spruce GS, which is the nearest Water Survey of Canada (WSC) gauge to Hudson Bay outlet. Only a small percentage, approximately 10%, of annual flow observed at the outlet is generated within the LNRB (Water Survey of Canada, 2019). Both Nelson and Churchill Rivers have relatively low seasonal variability in streamflow due to the regulation that is discussed in more detail in Section 3.1.4.

The LNRB has 17 active streamflow gauges sparsely distributed throughout the basin. The record period is relatively short (earliest continuous recording in the 1950s). Six of these 17 gauges are dedicated to recording regulated flows downstream of control structures and generating stations. The other 11 gauges measure local flow contributing to the LNRB.

Table 3-3: Hydrometric gauges within the LNRB (Water Survey of Canada, 2019). Brown denotes gauges downstream of diversions. Blue denotes gauges downstream of generating stations. Mean discharge flow values are provided on Water Survey of Canada (2019). Gauges on the main channel are denoted with NA for average % contribution to annual flow at Long Spruce GS.

Name	WSC gauge ID	Mean discharge [m <sup>3</sup> /s]	Average % contribution to annual flow at Long Spruce GS 1987-2017
<b>Tributary gauges (Local Flow)</b>			
Angling River near Bird	05UH001	11.3	NA
Burntwood River above Leaf Rapids	05TE002	56.3	≤1%
Burntwood River near Thompson	05TG001	874	NA
Footprint River above Footprint Lake	05TF002	6.51	≤1%
Grass River above Standing stone Falls	05TD001	118	1.6%
Kettle River near Gillam	05UF004	14.6	≤1%
Limestone River near Bird	05UG001	14.7	≤1%
Odei River near Thompson	05TG003	59.5	≤1%
Sapochi River near Nelson House	05TG006	2.68	≤1%
Taylor River near Thompson	05TG002	6.7	≤1%
Weir River above the Mouth	05UH002	21.5	NA
<b>Regulated gauges (Main channel)</b>			
Nelson River (East Channel) below Sea River Falls	05UB008	436	10%
Nelson River (West Channel) at Jenpeg	05UB009	1,620	57%
Notigi Forebay	05TF710	787	23%
Nelson River @ Kelsey GS	05UE005	2,010	NA
Nelson River @ Kettle GS	05UF006	3,220	NA
Nelson River at Long Spruce G.S.	05UF007	3,220	NA

### **3.1.4 Hydropower operations of Lower Nelson River Basin**

The LNRB is a highly regulated basin with two control structures (Jenpeg and Notigi) and six hydroelectric generating stations (Wuskwatim, Jenpeg, Kelsey, Kettle, Long Spruce, and Limestone). The 7<sup>th</sup> station, Keeyask, is expected to commence generating as early as 2020. A summary of the seven hydroelectric generating stations within the LNRB is listed in Table 3-4. Over 70% of Manitoba Hydro's total hydroelectric generating capacity (5, 228 MW (Manitoba Hydro, 2018)) is on the LNRB and three of Manitoba Hydro's largest generating stations (Kettle, Long Spruce, and Limestone) are located near the outlet of the LNRB (Manitoba Hydro, 2018).

A unique characteristic of the LNRB's hydropower system is that it mostly operates as a cascade ROR system with reservoirs of little storage capacity. For the purposes of this study, ROR is defined as hydropower stations that do not have immediate control of monthly or larger reservoir storage. The major system storages are Southern Indian Lake (SIL) and Lake Winnipeg located upstream of the generating stations, and their releases at Notigi (SIL) and Jenpeg (Lake Winnipeg) contribute approximately 25% and 65% respectively, of the annual flows at the Hudson Bay outlet. The release operations work together to optimize flow going downstream to major generating stations as there is a multi-week time delay between major system storage and generating stations (Manitoba Hydro, 2014).

Table 3-4: List of Manitoba Hydro generating stations (Manitoba Hydro, 2018). Top three GS denoted in bold.  
 \*\*Formally ROR (Run-of-the-River) generating station until 1977 (Manitoba Hydro, 2014).

Generating Station Name	River	Completion Year	Power Generation Capacity [MW]	Generating Station Type
Wuskwatim	Burntwood	2012	211	ROR
Jenpeg	Nelson	1979	115	CS
Kelsey	Nelson	1957	464	Storage ** (limited: ~ 1 month)
Keeyask	Nelson	Expected 2020	695	ROR
<b>Kettle</b>	<b>Nelson</b>	<b>1970</b>	<b>1, 220</b>	<b>ROR</b>
<b>Long Spruce</b>	<b>Nelson</b>	<b>1977</b>	<b>980</b>	<b>ROR</b>
<b>Limestone</b>	<b>Nelson</b>	<b>1990</b>	<b>1, 350</b>	<b>ROR</b>

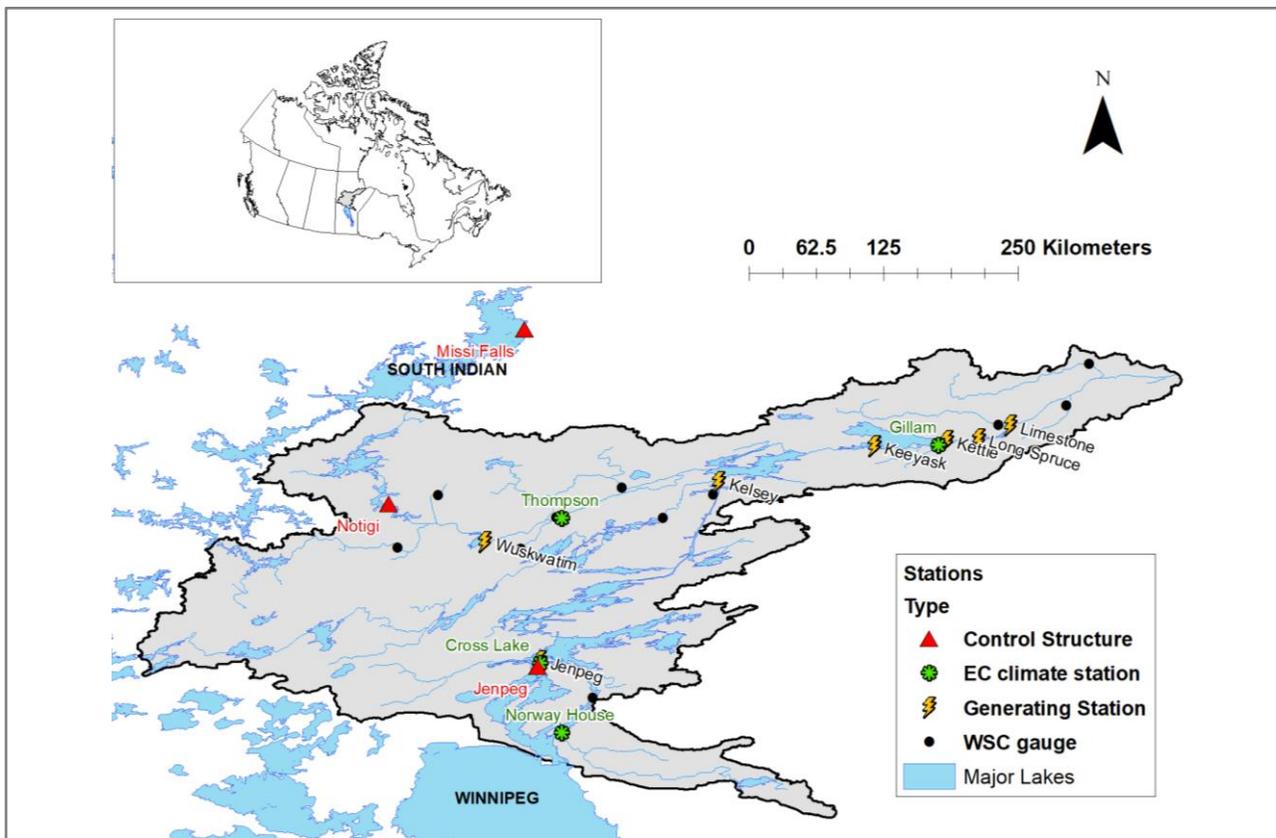


Figure 3-1: Map of major control points within the Lower Nelson River Basin

The release operations in the LNRB are controlled by two main regulations – Churchill River Diversion (CRD) and Lake Winnipeg Regulation (LWR). Both CRD and LWR work in tandem to ensure energy security for Manitoba Hydro’s customers and optimize the power generation while adhering to license constraints and considering impacts on the stakeholders and the environment. Operations of CRD and LWR significantly alter the natural flow regime within the LNRB (Manitoba Hydro, 2015a) in order to match the opposing natural flow pattern to energy demand, i.e. lower demand but higher water supply in summer, higher demand but lower water supply in winter.

Churchill River Diversion (CRD) refers to a set of regulations that utilize two control structures (Notigi CS and Missi Falls CS), the South Bay Diversion channel and the Southern Indian Lake in order to increase water supply to LNR to optimize power generation. CRD diverts approximately 60% (Province of Manitoba, 2017) of the Churchill River flow from Southern Indian Lake into the LNR through a 9.3 km channel. Through the regulation of two control structures, Southern Indian Lake can act as a storage reservoir and divert on average 25% more water into the LNR (Manitoba Hydro, 2014). Currently, MH is authorized to divert up to 990 m<sup>3</sup>/s of water at Notigi CS to supply the LNR.

Lake Winnipeg Regulation (LWR) refers to a set of regulations that control a series of natural and man-made channels and control structures (Jenpeg station and other smaller control structures) near the outlet of Lake Winnipeg in order to reduce flooding around the lake area and to optimize power generation in the LNR. LWR project created new channels, expanded the natural channels and developed control structures to increase the capacity of the Lake Winnipeg outflow by about 50% of its natural capacity into the Nelson River. Lake Winnipeg is operated as a reservoir that can supply water downstream to Lower Nelson River. However, its operational storage capacity

for power production purposes is limited within a 4 ft (1.22 m) range and the long routing time (several weeks) from Lake Winnipeg release to Lower Nelson River operations limits its usage for short-term operations (Manitoba Hydro, 2014, 2015a).

## **3.2 Models**

### **3.2.1 HYPE**

HYPE (HYdrological Predictions for the Environment) (Lindström et al., 2010) is a semi-distributed hydrological model for runoff and water quality simulation, developed by the Swedish Meteorological and Hydrological Institute (2017) with a focus on simulating large scale domains (e.g. Europe). Basins and sub-basins are discretized by land use/land cover (LULC), soil type and elevation. HYPE has various sub-processes well suited for cold regions hydrology, such as snow accumulation and melt, freezing and thawing of soil, and frozen soil infiltration. HYPE is open-source under the Lesser GNU Public License.

H-HYPE (Hudson Bay–HYPE) developed for the BaySys project by Tefs (2018) is used in this study. H-HYPE is a sub-basin model of the larger Arctic domain HYPE (A-HYPE), which includes the NCRB. H-HYPE uses a new generalized regulation routine developed by Tefs (2018), which divides reservoir water surface levels into seven stages to determine outflow, instead of three stages as in the original HYPE model. Each stage has customizable algorithms that can control reservoir release (1) by setting monthly operational stage bounds, (2) according to fixed regulation using a fixed equation, or (3) to ideal reservoir stage through transient gradient equations.

H-HYPE simulation over NCRB was validated for the period of 1981-2010. The new regulation routine improved seasonal NSE and percent bias improved compared to the original HYPE simulation. Particularly for Jenpeg GS and Notigi CS operations, seasonal NSE scores are above

0.67 with exception of fall (NSE: 0.33-0.67) for Jenpeg GS and spring (NSE: 0-0.33) and summer (NSE: 0.33-0.67) for Notigi CS. Please refer to Tefs (2018) for more information.

Table 3-5: Summary of HYPE setup. Please refer to the Swedish Meteorological and Hydrological Institute (2017) for more information on HYPE default settings.

<b>Hydrologic Processes</b>	<b>Selected methods</b>
Infiltration	HYPE default
Evapotranspiration	Priestly-Taylor
Snowmelt	Temperature and radiation index
Channel routing	HYPE default

### **3.2.2 WATFLOOD**

WATFLOOD is a partially physically-based, distributed hydrologic model that has been under development since 1972 (Kouwen and Stadnyk, 2017), with a focus on utilizing remotely sensed land cover data, DEMs and numerical weather data. The model uses the aforementioned gridded spatial products and calculates hydrological processes within a grid cell. WATFLOOD discretizes a basin into Grouped Response Units (GRUs) which is efficient for discretizing large basins like the LNRB. WATFLOOD's sublimation, wetland routine, and a dedicated wetland routing module make it well suited for the LNRB modelling. WATFLOOD no longer has a Graphic User Interface (GUI) and instead runs from the command line.

WATFLOOD version 10.1.54 is used in this study. WATFLOOD model of the LNRB was recently developed in part by Holmes (2016) and Pokorny (2019). The model uses  $0.167^\circ$  (longitude) x  $0.1^\circ$  (latitude) size grids (approximately 11 km by 11 km at the centroid of the LNRB). The WATFLOOD simulation of the LNRB was validated for the period of 1981-2010. The average KGE (Kling-Gupta Efficiency) value is 0.74 for 12 WSC gauges and 0.89 for MH reservoirs, as calculated from the model setup reported by Pokorny (2019).

Table 3-6: Summary of WATFLOOD setup (Pokorny, 2019)

<b>Hydrologic Processes</b>	<b>Selected methods</b>
Infiltration	Phillips formula
Evapotranspiration	Hargreaves
Snowmelt	Temperature Index
Channel routing	Kinematic routing

### 3.2.3 HEC-HMS

HEC-HMS (Hydrologic Modeling System developed by the Hydrologic Engineering Center) is a conceptual, semi-distributed hydrologic model developed by the United States Army Corps of Engineers (US Army Corps of Engineers, n.d.), with a focus on simulating the rain-runoff process of dendritic basins in a wide range of geographical locations. Several methods are available for each hydrological process, allowing flexibility in application to various basins. HEC-HMS can be run from a GUI and also using the command line.

HEC-HMS version 4.2.1 is used in this study. The HEC-HMS model of the LNRB was originally developed by Manitoba Hydro and further developed by Sagan (2017) for probable maximum flood study. The LNRB model was recently modified by Pokorny (2019) to be applicable across all seasons. HEC-HMS simulation of the LNRB was validated for the period of 1981-2010. The average KGE value is 0.71 for 12 WSC gauges and 0.86 for MH reservoirs for the period of 1981-2010, as calculated from the model setup reported by Pokorny (2019).

Table 3-7: Summary of HEC-HMS setup

<b>Hydrologic Processes</b>	<b>Selected methods</b>
Infiltration	Soil Moisture Accounting
Evapotranspiration	Priestly Taylor
Snowmelt	Temperature Index
Channel routing	Muskingum

### **3.2.4 MODSIM-DSS**

MODSIM-DSS (hereafter MODSIM) is a water resources operation model developed at the Colorado State University by Labadie (2006), capable of simulating complex surface water network systems and water allocation according to water demands and rights and governmental regulations. In particular, MODSIM has versatile options to simulate reservoir releases, from setting simple daily storage targets to customized functions. However, MODSIM is incapable of calculating basin streamflow and requires streamflow time-series data from the user. Given system water supply and user-specified constraints, MODSIM employs a network flow optimization to allocate (route) water by satisfying physical and institutional constraints. In the case where MODSIM is unable to satisfy all constraints, it outputs a summary of system shortfalls.

The MODSIM model of the LNRB was developed by Beiraghdar (2019). MODSIM version 8.5.0 was used for the study. MODSIM simulation of the LNRB was validated for the period of 1980-2018. The average KGE value is 0.97 for MH reservoirs and 0.96 for natural lakes.

## **4.0 Data and methodology**

This chapter describes the input creation, model coupling framework, and climate change assessment methodology. This study leverages from prior BaySys projects and has used an existing 19 climate ensemble and four hydrologic and operations models to assess the impact of climate change on the LNRB. A novel approach is developed to couple the existing hydrologic and operations models of the LNRB using the Python wrapper. A coupling framework of three model groupings was setup: (1) a continental-scale hydrologic model computing boundary inflow into the subbasin LNRB, (2) a basin-scale hydrologic model computing basin hydrology of the LNRB and providing reservoir inflow to the operations model, and (3) a basin-scale operations model computing reservoir operations and hydropower generation and providing reservoir release to the hydrologic model. The Python wrapper iteratively runs and transfers reservoir inflow and outflow data between the hydrologic and operations models by modifying model input files. The wrapper terminates the iterative model run when specified reservoir release from the operations model converges.

### **4.1 Climate and boundary flow data**

#### **4.1.1 Climate simulations creation**

An ensemble of plausible future climate simulations was chosen in previous studies as part of the BaySys project (MacDonald et al., 2018). The ensemble consists of 19 climate simulations generated from 14 GCMs and 2 RCPs selected from 150 simulations from CMIP5 ensemble (Stadnyk et al., 2019) through k-means clustering (Casajus et al., 2016) for the 2021-2070 period. Clustering, consequently selection, was based on changes in annual and seasonal mean temperature and precipitation spatially averaged over the HBDB domain. The resulting subsetted ensemble represents 90% of the variability in future climate projections over the HBDB, which includes variability over the LNRB although it does not specifically represent variability over the

LNRB. The clustering approach reduced the number of climate simulations (and thus computational cost) while maintaining adequate uncertainty representation of the entire ensemble. Please refer to Stadnyk et al. (2019) for more information.

The selected 19 climate simulations were bias-corrected using the quantile-mapping approach by Mpelasoka and Chiew (2009), using HydroGFD as a baseline (Berg et al., 2018). Bias-corrected climate data for HDBD was provided by Ouranos consortium. Precipitation and temperature data for four climate stations – Cross Lake, Gillam, Norway House, and Thompson – were extracted from the GCM dataset by selecting the closest grid to each station. Due to different GCM resolutions, each GCM had a different grid size and orientation, which led to some of the stations sharing the same precipitation and temperature time series. The grid size and station overlap of each climate simulation can be found in Appendix A: Climate station overlap.

The HEC-HMS model required two additional climate stations, Grass and Burntwood stations, and dew point temperature data. Precipitation and temperature for Grass and Burntwood stations were interpolated using Thiessen weighted average method. Thiessen weights from Pokorny (2019) were used. Dew point temperature data is required for HEC-HMS for the Priestly-Taylor method. The dew point temperature was estimated using equation Equation 4-1 by Hubbard et al. (2003) where:

$T_d = \alpha(T_n) + \beta(T_x - T_n) + \gamma(P_{daily}) + \lambda$	Equation 4-1
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$T_d$  is the dew point temperature;  $T_n$  is the daily minimum temperature;  $T_x$  is the daily maximum temperature;  $P_{daily}$  is the daily precipitation; and  $\alpha$ ,  $\beta$ ,  $\gamma$ , and  $\lambda$  are regression constants. The regression constants were calculated in a previous study by Pokorny (2019).

### **4.1.2 HYPE system inflow**

Upstream Nelson and Churchill River contributions to the LNRB system under 19 climate simulations were generated previously by Tefs (2018) using H-HYPE. H-HYPE simulates Jenpeg GS and Notigi CS operations and therefore streamflow contributions from Nelson and Churchill Rivers are applied downstream of Jenpeg GS and Notigi CS in the hydrologic models of the LNRB.

## **4.2 Model coupling methodology**

### **4.2.1 Selected coupling type: Iterative coupling**

Hydrologic and operations models were iteratively coupled using a Python script. Iterative coupling has advantages in terms of ease of setup and model flexibility because data formatting and exchange are facilitated externally through a script and the models are not required to be open-sourced for source code manipulation. Hydrologic and operations model each ran and exchanged data upon model run completion. This setup has the disadvantage of longer computation run time compared to dynamic coupling as data exchange occurs via shared memory during a model run rather than external I/O format conversion after a model run. As dynamic coupling requires model source code and longer setup time, iterative coupling provides an efficient way of testing concepts prior to undertaking more complex and time-consuming coupling methods like dynamic coupling (Rosenzweig and Hodges, 2011).

### **4.2.2 Coupling structure**

#### **4.2.2.1 Model layers in coupling framework**

There are three model groups in the coupling framework – (1) continental-scale hydrologic model (HYPE), (2) basin-scale hydrologic model (WATFLOOD and HEC-HMS) and (3) operations model (MODSIM). As the LNRB is located downstream of NCRB, a continental-scale hydrologic model such as HYPE was required to provide the upstream contribution of NCRB coming into Jenpeg GS and Notigi CS, the upstream boundary condition of the LNRB, to basin-scale hydrologic models. The two basin-scale hydrologic models – WATFLOOD and HEC-HMS,

simulated the water balance within the LNRB and provided reservoir inflow to the operations model MODSIM. Furthermore, the comparison of WATFLOOD and HEC-HMS simulations provided a means to evaluate uncertainty introduced by the choice of model and model structure. Operations model, MODSIM, simulated the reservoir operations according to operational constraints and targets and provided reservoir releases back to basin-scaled hydrologic models. As seen in Figure 4-1, the reservoir inflow and release data were exchanged and updated between the basin-scaled hydrologic models and operations models at the end of each model run.

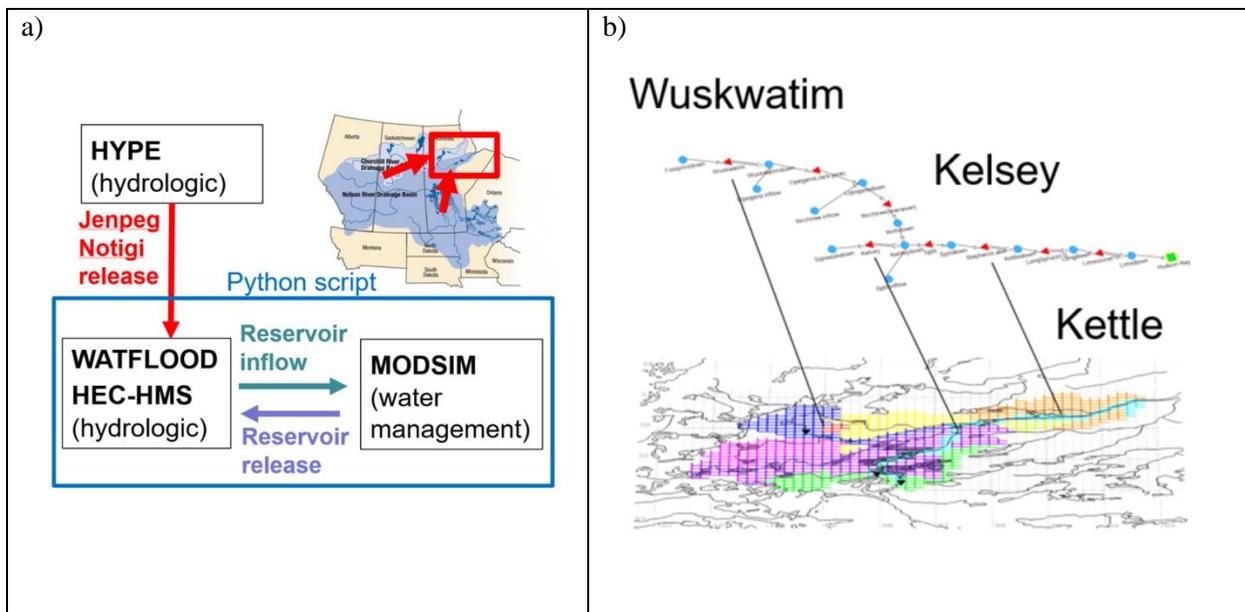


Figure 4-1: Model hierarchy (left) and data exchange locations (right)

Table 4-1: Summary of model type and purpose in the coupling framework

<b>Name</b>	<b>Type</b>	<b>Purpose</b>
<b>HYPE</b>	Continental-scale hydrologic model (Nelson-Churchill River Basin)	<ul style="list-style-type: none"> <li>• Provide upstream boundary flow from NCRB into LNRB</li> </ul>
<b>WATFLOOD</b>	Basin-scale hydrologic model (Lower Nelson River Basin)	<ul style="list-style-type: none"> <li>• Simulate basin water balance</li> <li>• Provide flow comparison stemming from the model structure with HEC-HMS</li> </ul>
<b>HEC-HMS</b>	Basin-scale hydrologic model (Lower Nelson River Basin)	<ul style="list-style-type: none"> <li>• Simulate basin water balance</li> <li>• Provide flow comparison stemming from the model structure with WATFLOOD</li> </ul>
<b>MODSIM</b>	Operations model (Lower Nelson River Basin)	<ul style="list-style-type: none"> <li>• Simulate reservoir operations and power generation</li> </ul>

#### 4.2.2.2 Exchanged variable, location, and time step

The purpose of iterative model coupling in this research is to leverage a hydrologic model capability to calculate net basin water balance and reservoir inflow and an operations model's ability to simulate the operation of reservoirs that can be too complex for a hydrologic model to simulate. Hence, the exchanged variables were reservoir inflows and releases between the two models.

Daily reservoir flow data were exchanged at three locations within the LNRB – Kelsey GS, Wuskwatim GS, and Kettle GS, as shown in Figure 4-1. These stations were chosen for:

- 1) Representation of the Churchill and Nelson River contributions (Wuskwatim GS downstream of Notigi CS and Kelsey GS downstream of Jenpeg GS)
- 2) Storage capacity (~1 month in the case of Kelsey GS) to warrant reservoir operation
- 3) Influence on downstream stations (release from Kelsey and Wuskwatim GS impacting inflow at Kettle GS; release from Kettle GS governing inflow to Limestone and Long spruce GS)

Daily reservoir flow data were exchanged at the completion of each model runs, e.g. completion of WATFLOOD simulation. This is because both hydrologic and operations models are capable of computing basin water balance without exchanging with one another at each time step.

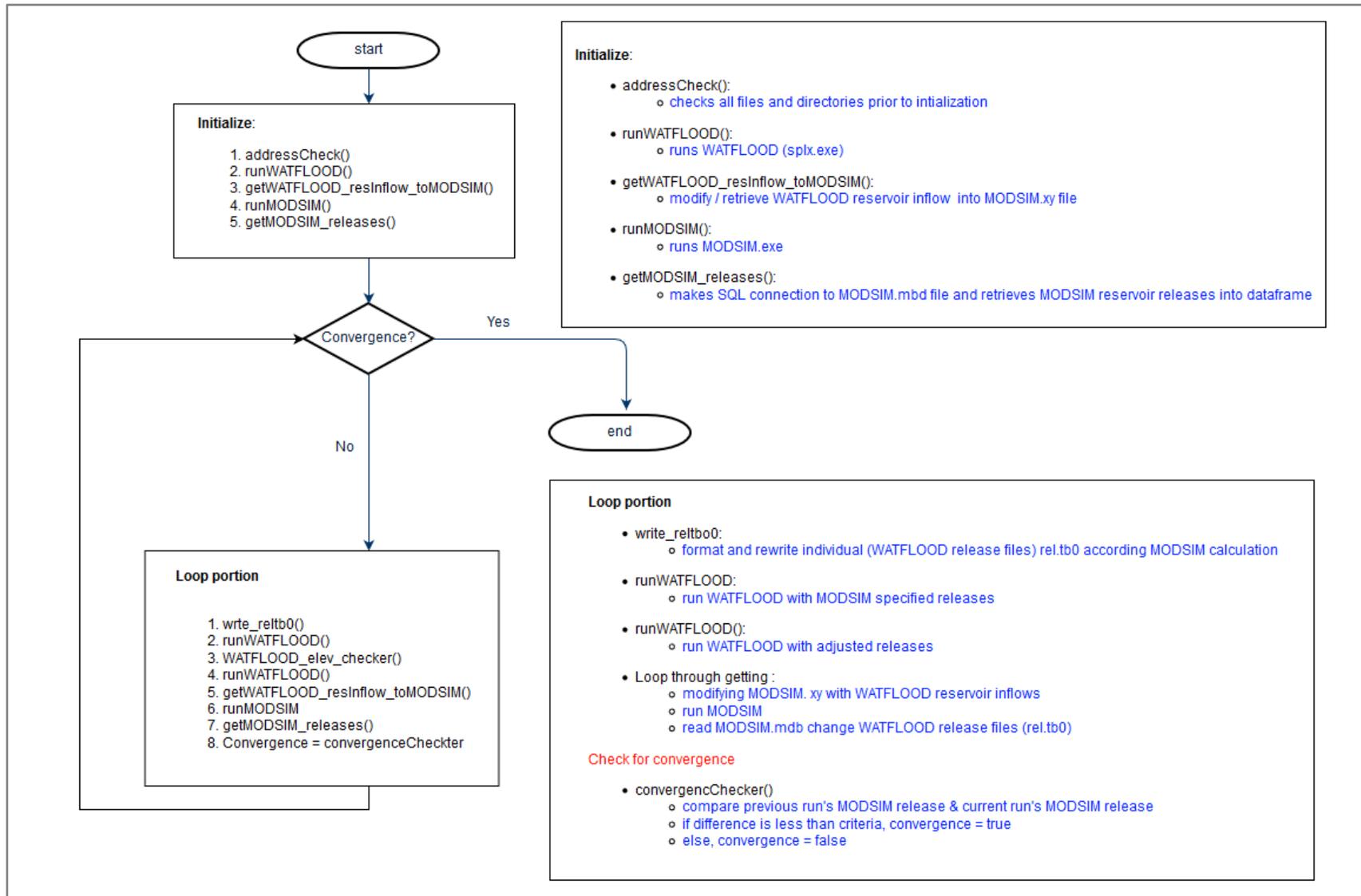


Figure 4-2: Hydrologic-operations model coupling flow chart

### 4.2.2.3 Overcoming model inconsistencies

One of the main challenges of model coupling is resolving the inconsistencies between the coupling models (Belete et al., 2017). At the simplest, the input and output file type differed between hydrologic and operations models of the LNRB. Multiple modules in Python script were coded to access and update reservoir inflow and output data into correct file type and format to ensure proper reading and execution of models.

Table 4-2: Name and type of model input and output files

	<b>WATFLOOD</b>	<b>HEC-HMS</b>	<b>MODSIM</b>
<b>Input file</b>	rel.tb0 (ascii)	HecDSS-Vue.dss	Basin.xy (ascii)
<b>Output file</b>	Lake_sd.csv (ascii)	(Java compiled)	MS Access.mdb (mdb)

Furthermore, both hydrologic and operations models had different spatial and temporal representations of the basin, reservoir settings, and computational methods. Yet, the coupling framework requires a way to make models comparable with one another in order to compute physically feasible and operationally optimized reservoir releases. Three features enforced model consistency:

- 1) Modification to original MODSIM configuration

An additional sink node had to be added and demand and non-storage inflow nodes upstream of Kettle GS reservoir node were adjusted from the original MODSIM configuration by Beiraghdar (2019) to account for the inconsistency of water balance between hydrologic models and operations model. In order to take advantage of the model's flexible reservoir operations, the hydrologic and operations models both must have equal flow quantity. Additional features were placed to adjust the reservoir inflow inequality between the models in a general manner.

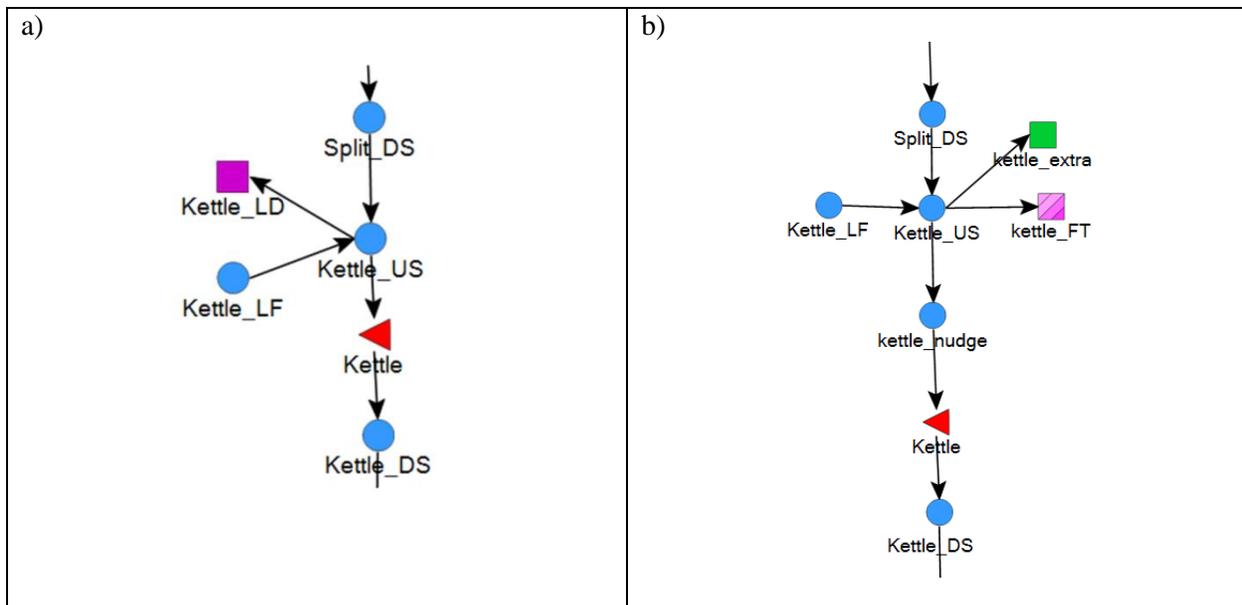


Figure 4-3: Original MODSIM setup of Kettle GS (a) and adjusted MODSIM setup of Kettle GS (b)

In order to enforce a consistent reservoir inflow into Kettle GS, maximum channel capacity was set to WATFLOOD reservoir inflow quantity with an extra  $1 \text{ m}^3/\text{s}$  capacity. Extra channel capacity is a buffer to ensure model stability stemming from rounding errors.

## 2) Nudged reservoir release feature of WATFLOOD and HEC-HMS

Reservoir release in both WATFLOOD and HEC-HMS can be user-specified by choosing the “specified release” option and providing a release time-series input file. Using this feature, hydrologic models were forced to release the numerically equal flow specified by MODSIM.

## 3) MODSIM internal storage and elevation check

The feasibility of MODSIM releases is automatically checked by MODSIM’s internal calculation. The reasons for checking release feasibility in MODSIM are 1) due to it having the most extensive reservoir module and most representative MH reservoir setting compared to hydrologic models and 2) because of inconsistencies in reservoir settings described in Table 4-3 making inter-model comparisons infeasible.

Table 4-3: Summary of inconsistencies between models

<b>Inconsistency</b>	<b>Inconsistencies between models</b>	<b>Issue &amp; mitigation</b>
<p>Physical reservoir representation (reservoir number, surface area, depth)</p>	<p><b>WATFLOOD</b>, being a gridded model, only identified lakes and reservoirs which are represented on the LULC map. All or part of a grid (0.167° longitude by 0.1° latitude or approximately 11 km by 11 km at the centroid of the LNRB) can be represented as a lake. There are 19 lakes in the WATFLOOD model of LNRB.</p> <p>Lake/reservoir volume is simply surface area times depth (<math>V = SA * h</math>).</p>	<p>The inconsistency in model representation of lake made reservoir storage comparison impractical. Despite the different number of lakes and reservoirs represented in each model, major reservoirs, including reservoirs used for data exchange, exists in all three models.</p>
	<p><b>HEC-HMS</b>, being a conceptual model, requires user specification to “identify” lakes and reservoirs. There are 9 lakes in HEC-HMS models of LNRB.</p> <p>Lake/reservoir volume is also defined by a user-specified elevation-area relationship.</p>	
	<p>Similar to HEC-HMS, <b>MODSIM</b> requires the user specification to identify lakes and reservoirs. MODSIM setup was based on Manitoba Hydro’s in-house model (QSIM) and therefore had a different number of reservoirs than the existing hydrologic models. There are 10 lakes in the MODSIM model of LNRB.</p> <p>Lake/reservoir volume is defined by a user-specified elevation-area-storage relationship.</p>	

Inconstancy	Inconsistencies between models	Issue & mitigation
Reservoir evaporation representation	As <b>WATFLOOD</b> identifies lakes by grid area, the entire lake is considered as reservoirs. Open water evaporation is computed as lakes in the LNRB can be as larger than 1000 km <sup>2</sup> .	The inconsistency in model representation of lake processes stems from the model configuration. The effects of model differences are assessed in the results and discussion section.
	<b>HEC-HMS</b> simulates forebay operation and therefore considers the only forebay as reservoirs. For example, HEC-HMS's Wuskwatim reservoir (forebay) is < 4% of the actual lake, i.e. 4% of <b>WATFLOOD</b> 's representation of Wuskwatim reservoir (entire lake). Open water evaporation is not considered in the HEC-HMS model of the LNRB.	No mitigation is required as the difference will highlight uncertainty stemming from model choice.
	Similar to HEC-HMS, <b>MODSIM-DSS</b> is configured to only consider forebay as the reservoir and does not account for open water evaporation.	
Local flow (basin generated inflow) calculation	<b>WATFLOOD</b> being a gridded model generated local flow from each grid	
	<b>HEC-HMS</b> being a conceptual model had user-specified modular subbasins contributing local flows	
	<b>MODSIM</b> being an operations model requires all network inflows to be specified (does not calculate local flow)	
Routing time step	<b>WATFLOOD</b> : Minimum routing step is set to 15 minutes	Discussed in Section 4.2.2.4. No significant improvement can be made using an external wrapper script.
	<b>HEC-HMS</b> : Routing in daily time-step (Muskingum K > 24 hr)	
	<b>MODSIM</b> : No routing set	No mitigation in this phase of research

#### 4.2.2.4 Unresolved inconsistency in time step resolution

As mentioned in Section 4.2.2.3, WATFLOOD, HEC-HMS, and MODSIM all have different reservoir representations. Reservoir operation feasibility is checked by the internal storage and elevation checks in MODSIM. Ideally, a secondary coupled model feasibility check would verify the storage feasibility in hydrologic models, as well as in the operations model. Despite the differences in reservoir representation, theoretically, as long as all models compute the same reservoir inflow and outflow, the change in storage should be the same in all models based on mass conservation principles. The consistency in storage computation across models, however, also requires consistent internal model computation time-step resolution and numerical precision, which cannot be enforced using an external wrapper.

As mentioned in Section 3.1.1, the LNRB is a very flat region and the minimum internal routing time-step of WATFLOOD is set to 15 minutes to satisfy routing stability criteria. With this setting, WATFLOOD routing is computed between every 15 minutes to 1 hour and requires the user-specified release time-series to match this time-step variation. While MODSIM is capable of routing at the minimum 15 minutes interval, the current LNRB model of MODSIM routes at a daily interval and is unable to produce time-scale varying reservoir release time-series. With a daily simulation time-step (the chosen time-step for the coupled model run), WATFLOOD uses a single, average daily outflow value with multiple 15–60 minute inflow values to compute storage, resulting in incorrect and inconsistent storage computations. There is a high computational burden for MODSIM to run at the sub-hourly interval for a multi-year simulation. At daily time-step, a 30-year simulation requires 2-3 minutes, while even at hourly time step, a 3-year simulation requires ~20 minutes run time.

Another challenge is the numerical precision of internal model computation. Users can define decimal precision when creating time series data in HEC-DSSVue. However, regardless of the

chosen decimal place precision, HEC-DSSVue creates an 11<sup>th</sup> placed decimal number, which is only precise to the specified decimal accuracy. The added trailing decimal precision to specified reservoir release time series causes inconsistency in internal HEC-HMS storage computation precision and leads to small offset in storage magnitude (i.e. storage mass balance) ( $\Delta S < 2\%$  over 30-year simulation) between HEC-HMS and MODSIM.

#### **4.2.2.5 Convergence criteria**

Coupled model convergence is based on the convergence of reservoir release between the hydrologic and operations models, which is indicated by the convergence of two consecutive MODSIM releases. The convergence of two consecutive MODSIM releases signifies that the optimal release has been reached. Theoretically, the convergence of two consecutive releases may imply converged storage balance (water budget); however as explained in 4.2.2.4, the inconsistencies in time step resolution between models lead to different storage balances between the two models. The feasibility of the storage balance is checked by internal MODSIM computation.

In a similar study, Morway et al. (2016) used  $L^2$  Norm shown in Equation 4-2 as the convergence criterion. However,  $L^2$  Norm is a subjective metric, dependent on flow magnitude, and the quantification of a good  $L^2$  Norm was not specified. A similar but objective metric would be RMSE-observation standard deviation ratio (RSR) shown in Equation 4-3. Moriasi et al. (2007) defined RSR equal or below 0.5 as very good when comparing observed and simulated flow time series. In comparing two consecutive simulated time series, a stricter criterion of  $RSR = 0.05$  was used to enforce convergence.

$L^2 = \sqrt{\sum_t (Q_{t,k} - Q_{t,k-1})^2} < \delta$	Equation 4-2
$RSR = \frac{RMSE}{STDEV_{i,k-1}} = \frac{\sqrt{\sum_{t=1}^n (Q_{t,k} - Q_{t,k-1})^2}}{\sqrt{\sum_{t=1}^n (Q_{t,k-1} - Q_{\mu,k-1})^2}} \quad \text{where } RSR \leq 0.05$	Equation 4-3
Where: $Q_{t,k}$ is MODSIM simulated flow at time step $t$ and iteration $k$ .	

### 4.3 Climate change assessment methodology

#### 4.3.1 Selected analysis approach: Top-down approach

The impact of climate change on hydropower operations in the LNRB was analyzed using the “top-down” approach. This study leverages previous BaySys studies that have already identified the uncertainty range of climate variables from 150 possible simulations and identified 19 climate simulations (GCM and RCP pairs) ensemble which represent 90% of the variability in future climate projections, reducing the computation burden for the analysis.

#### 4.3.2 Climate and model inter-comparison methodology

##### 4.3.2.1 Comparison categories

To accomplish the main objectives of this study, four categories of comparison were performed to assess changes in streamflow and power generation in the LNRB, and are shown in Table 4-4.

These comparisons are:

- 1) WSC observed flow and HydroGFD-forced HYPE simulated outflow at Jenpeg GS and Notigi CS to identify biases in HYPE
- 2) HydroGFD-forced and climate ensemble-forced HYPE outflow at Jenpeg and Notigi CS to identify biases in the selected climate ensemble
- 3) Inter-period (historical, near and mid-future) simulated reservoir inflow and power generation to identify changes in reservoir inflow and generation potential at LNRB generating stations. The inter-period comparison negates the climate ensemble and model bias identified in comparison (1) and (2) as the same bias exists in climate ensemble-forced simulations.

- 4) Coupled model results (inflow and generation potential) to identify uncertainty in streamflow and power generation stemming from model choice and structure.

Table 4-4: Schematic of inter-comparison of periods and models

Period	WATFLOOD	HecHMS
Historical	1981-2010 (WSC)	1981-2010 (WSC)
Historical	1981-2010 (HydroGFD)	1981-2010 (HydroGFD)
Historical	1981-2010 (GCM)	1981-2010 (GCM)
Near future	2021-2050 (GCM)	2021-2050 (GCM)
Mid future	2041-2070 (GCM)	2041-2070 (GCM)

#### 4.3.2.2 Statistical tests

Two non-parametric statistical tests were conducted to quantify changes in trend and distribution of reservoir inflow and power generation. The Mann-Kendall (MK test) statistical test (Kendall, 1975; Mann, 1945) was performed to identify the existence and direction of statistically significant trends. The assumptions of the MK test are: the data are independent and identically distributed and the data collection is unbiased. However, hydrological time series such as annual mean may show serial correlation (Yue et al., 2002). The Trend-Free Pre-Whitening (TFPW) technique by Yue et al. (2002) was used to eliminate autocorrelation. TFPW was used in recent literature in the analysis of annual streamflow volume trends by Déry et al. (2016) and Déry and Wood (2005). Moreover, Yue et al. (2002) demonstrate that the TFPW technique was able to estimate slope and significance more accurately compared to other classical methods such as the pre-whitening method (Von Storch, 1995), and the variance correction method (VCA) (Hamed and Rao, 1998). The Mann-Whitney-Wilcoxon U (MWW) test (Mann and Whitney, 1947) was conducted to quantify statistically significant changes in annual and seasonal inflow volume distributions between 30-year periods. The assumptions of the MWW test are: the data are independent and the data collection is unbiased. In the case of identical distribution between two data sets, MWW tests

for changes in distribution median while in case of different distribution, MWW tests for changes in distribution shape (Hart, 2001). TFPW was not done for the MWW test as seasonal inflow volume distribution was assumed to be independent. Both MK and MWW tests were conducted two-sided and with a 5% significance level (95% confidence interval).

#### **4.3.2.3 Terminology convention**

The seasonal convention (Spring: MAM, Summer: JJA, Fall: SON, Winter: DJF) was adopted by that used in previous HYPE and Hudson Bay domain studies (Tefs, 2018). To discern the degree of the climate simulation agreement, IPCC (2013) likelihood terminology was used where: *virtually certain*:  $\geq 99\%$ , *very likely*:  $\geq 90\%$ , *likely*:  $\geq 66\%$ , *about as likely as not*: 33-66%, and *unlikely*:  $< 33\%$  simulation agreement.

#### **4.3.2.4 Reservoir inflow comparison**

Annual and seasonal inflow volumes were computed for each of the model runs. The MK test was conducted for three 30-year periods: historical (1981-2010), near future (2021-2070), and mid future (2041-2070), for each of 19 climate simulations to detect trends in annual and seasonal inflow at Kelsey, Wuskwatim and Kettle GS. These three locations were chosen as they represent the individual and combined contribution of the Nelson and Churchill Rivers. Sen's slope is an estimate of a linear trend line. The magnitude and signs of Sen's slope (Sen, 1968) were calculated to note changes in 30-year reservoir inflow trends. As the majority of hydropower generation occurs downstream of Kettle GS, changes in the inter-period inflow distribution were calculated using the MWW test. The mean inflow volumes of each period were computed and compared to analyze changes in magnitude.

The selected 19 climate simulations represent a wide range of climatic variability over NCRB. Therefore, statistically significant changes and percent changes in reservoir inflow were analyzed

individually for each climate simulation. IPCC “likelihood” categories were used to determine the “likelihood” of statistically significant change.

#### 4.3.2.5 Power generation comparison

The MK test was used to quantify trends in annual and seasonal generation potential. The mean hydropower generation potential of each climate scenario and period were computed and compared to analyze changes in magnitude. IPCC “likelihood” categories were used to determine the “likelihood” of statistically significant change. In addition, the “robustness” of the system was assessed. Robustness is defined as “insensitivity of system performance to various conditions” (Maier et al., 2016; McPhail et al., 2018) and is quantified as a probability of system satisfaction over plausible future scenarios. The mathematical forms are summarized in equations Equation 4-4 and Equation 4-5 (Whateley et al., 2014), where  $\Lambda(x_j)$  is binary performance function, returning 1 for satisfied performance,  $Y_T$  is a predefined satisfaction threshold,  $Y_j$  is a performance variable and RI (Robustness Index) is a ratio of system satisfaction.

$\Lambda(x_j) = 1 \quad \text{if } Y_j \geq Y_T$ $\Lambda(x_j) = 0 \quad \text{if } Y_j < Y_T$	Equation 4-4
$RI = \frac{\int_{x_0}^{x_j} \Lambda(x_j) dx}{\int_{x_0}^{x_j} dx}$	Equation 4-5

In assessing future system performance where no single time-series is representative, the performance metric must include a measure of the probability of multiple plausible future time series. As indicated by the integral, the merit of the Robustness Index strengthens by the range of considered future climate space.

The current configuration of MODSIM is set up to compute potential power generation rather than actual power generation. This means that all the water coming into the generating stations is used,

regardless of the need. This was because MODSIM requires power generation targets in order to meet the given generation target and redirect the remaining flow down through the spillway. Since estimating future power demand was outside of the scope of this study, potential power generation was computed instead. In this study,  $Y$  was set to be the historical annual and seasonal ensemble mean hydropower generation potential to quantify whether the current LNRB system will be able to generate similar power compared to the historical period.

## 5.0 Results and discussion

This chapter provides the results of the coupled model framework and climate change assessment on LNRB hydropower operations. The coupled models were tested to ensure input data consistency between the hydrologic and operations models. Biases in HYPE forcing and climate simulations used in future projections were briefly summarized. All data used for bias analysis were obtained from Tefs (2018) and no additional work on HYPE was done in this study. The coupled models ran under the selected 19 climate simulations and the trends and changes in future reservoir supply and potential power generations were analyzed.

### 5.1 Model validation

#### 5.1.1 Coupled model convergence

Iterative coupling was chosen for this study as it provides an efficient way to test concepts without extensive source code manipulation. A concern of iterative coupling was possible long run time from models waiting on each other for completion. The tests show that the coupled WATFLOOD and HEC-HMS models, at daily time step, are able to complete multiple 30-year simulations with the daily time step within a 30-minute time frame (Table 5-1). The coupled models converge after the first iteration. Iterative coupling (MODSIM) made only a small release modification ( $RSR < 0.01$ ) as the hydrologic models were already calibrated to match historical reservoir release data. The coupled model demonstrated that the specified input time series data from each model was read correctly using the coupling script as illustrated in Figure 5-1.

Table 5-1: Summary of the coupled model computational budget for 30-year simulation at daily time step. Tested on a personal computer (PC) with an Intel i5-7300U Processor and 8 GB Random Access Memory (RAM).

<b>Model</b>	<b>Couple model runtime</b>
WATFLOOD - MODSIM	20 minutes
HEC-HMS - MODSIM	10 minutes

Table 5-2: Comparison of WATFLOOD, HEC-HMS and coupled model Kling-Gupta Efficiency (KGE) values on WSC gauges below major regulation points for the reference period (1981-2010)

	<b>WATFLOOD</b>	<b>Coupled WATFLOOD</b>	<b>HEC-HMS</b>	<b>Coupled HEC-HMS</b>
<b>05UE005 (Kelsey)</b>	0.92	0.95	0.86	0.94
<b>05TG001 (Wuskwatim)</b>	0.87	0.87	0.94	0.86
<b>05UF006 (Kettle)</b>	0.86	0.82	0.81	0.82
<b>05UF007 (Long Spruce)</b>	0.86	0.83	0.82	0.82

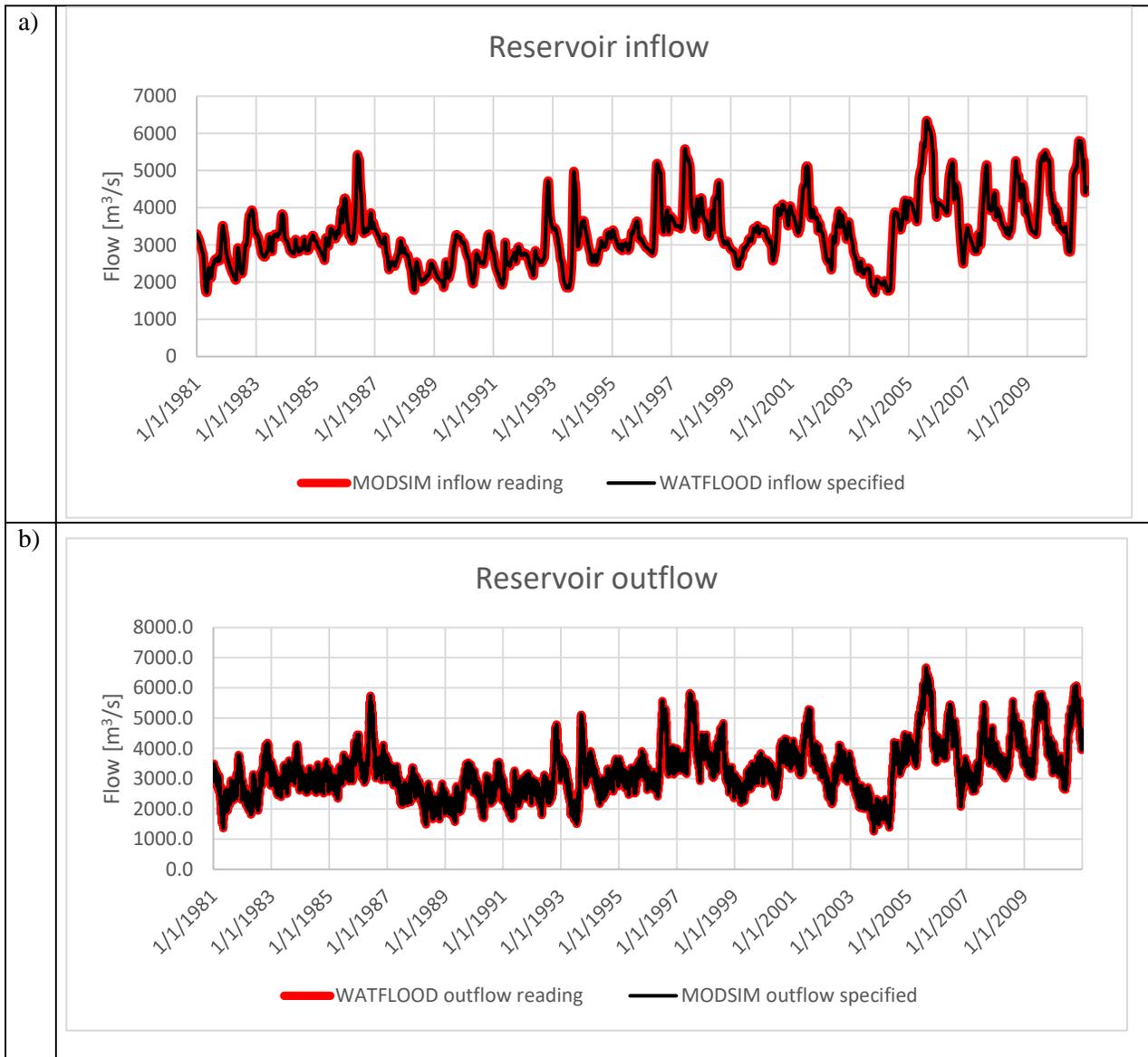


Figure 5-1: Model time series reading for the reference period (1981-2010). Black (red) indicating specified (read) time-series data; (a) showing reservoir inflow time series and (b) showing release time series

### 5.1.2 Bias in HYPE

Historically, approximately 90% of streamflow going through the LNRB is generated upstream of the LNRB. Therefore, in order to assess coupled model results, an understanding of the underlying bias in Nelson and Churchill River boundary contributions is required. The results presented in this section were generated using data from Tefs (2018), which leverages simulated HYPE output. Figure 5-2 shows a comparison of daily flow at Jenpeg GS and Notigi CS to WSC observations, HydroGFD-forced HYPE (HYPE simulation under HydroGFD forcing) and WSC-nudged HYPE (HYPE simulation nudged with WSC observed inflow at Jenpeg GS and Notigi CS) simulations. Table 5-3 summarizes the overall HYPE and LNRB regulation scheme performance.

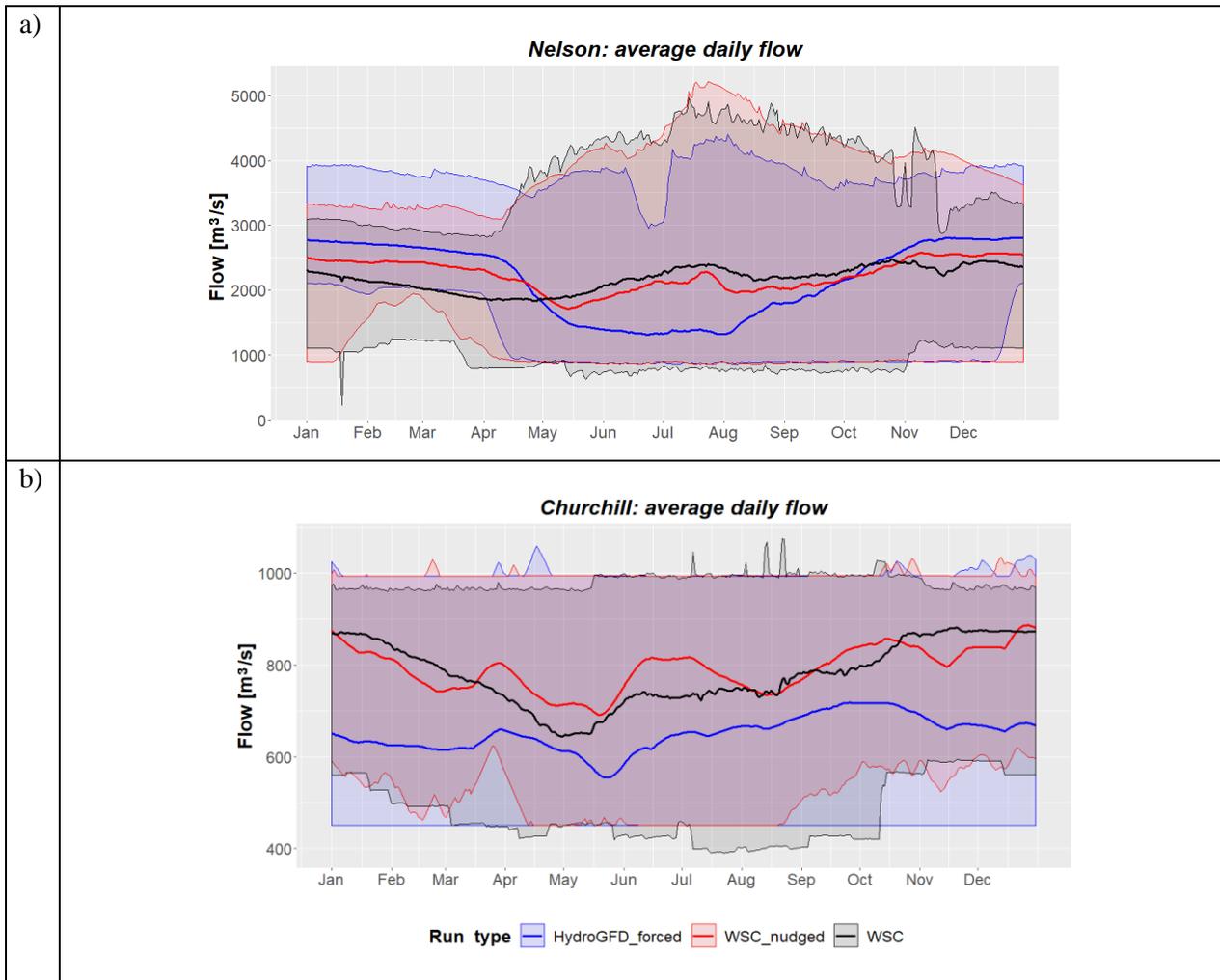


Figure 5-2: Average daily flow distribution at Jenpeg GS (a) and Notigi CS (b). Solid lines denote average daily flow while bounds indicate the minimum and maximum flow bounds.

Table 5-3: Summary of the performance metric of overall HYPE and LNRB control structures (Jenpeg GS and Notigi CS) for the 1981-2010 period

	Season	HydroGFD-forced HYPE vs WSC observation				WSC-nudged HYPE vs WSC observation			
		NSE	KGE	R <sup>2</sup>	% Bias	NSE	KGE	R <sup>2</sup>	% Bias
Jenpeg	<b>Overall</b>	-0.53	0.30	0.09	-0.70	0.57	0.78	0.67	2.60
	<b>Winter (DJF)</b>	-1.07	0.35	0.16	22.10	0.52	0.83	0.75	10.50
	<b>Spring (MAM)</b>	-0.46	0.38	0.17	11.80	0.57	0.77	0.73	10.20
	<b>Summer (JJA)</b>	-0.65	0.11	0.07	-36.10	0.68	0.83	0.74	-8.30
	<b>Fall (SON)</b>	-0.36	0.42	0.22	1.90	0.26	0.59	0.59	-0.40
Notigi	<b>Overall</b>	-1.30	0.27	0.11	-16.70	0.27	0.59	0.36	1.30
	<b>Winter (DJF)</b>	-3.66	0.11	0.29	-24.70	0.32	0.69	0.47	-3.40
	<b>Spring (MAM)</b>	-0.73	0.35	0.15	-12.70	0.33	0.66	0.45	5.10
	<b>Summer (JJA)</b>	-1.16	0.08	0.01	-12.30	-0.14	0.40	0.17	5.20
	<b>Fall (SON)</b>	-2.00	0.17	0.12	-16.10	0.28	0.59	0.37	-0.70

Both Figure 5-2 and Table 5-3 demonstrate some annual and seasonal bias in the HYPE simulation compared to WSC observed flow. HYPE overestimates fall and winter Jenpeg GS flows compared to WSC observed data, leading to an inverse flow trend compared to the observed flow trend. HYPE consistently underestimates Notigi CS flow throughout the year, producing an overall -16.7% volumetric error. HYPE simulation bounds show greater variability but firm, fixed lower bounds as shown in Figure 5-2. The low-flow limits shown for HydroGFD-forced and WSC-nudged hydrographs are due to the minimum flow set in HYPE. In HYPE, the minimum flows at Jenpeg GS and Notigi CS were set to 840 and 450 [m<sup>3</sup>/s], respectively, in order to avoid being less than the 1% historic percentile discharge.

Relatively satisfactory (NSE > 0.5, PBIAS < ±15%) performance (Moriassi et al., 2007, 2015) at Jenpeg GS, and improved performance at Notigi CS of WSC-nudged HYPE simulation indicates that the error and bias in simulated flow downstream of Jenpeg GS and Notigi CS come mainly from error and bias in simulated upstream contribution rather than reservoir operation simulation.

### 5.1.3 Bias in selected climate simulations

A comparison of average daily flow between 19 climate simulations and HydroGFD-forced HYPE flow is shown in Figure 5-3. Theoretically, the hindcast climate simulations should follow closely to the HYPE simulation forced by HydroGFD. As shown in Figure 5-3, the climate ensemble encapsulates a much wider range around HydroGFD-forced flows (that are representative of observed historical climate). This shows that while the climate ensemble bound includes historic climate, the range encompasses both dry and wet bias relative to historic flow scenarios that will propagate to seasonal bias in HYPE.

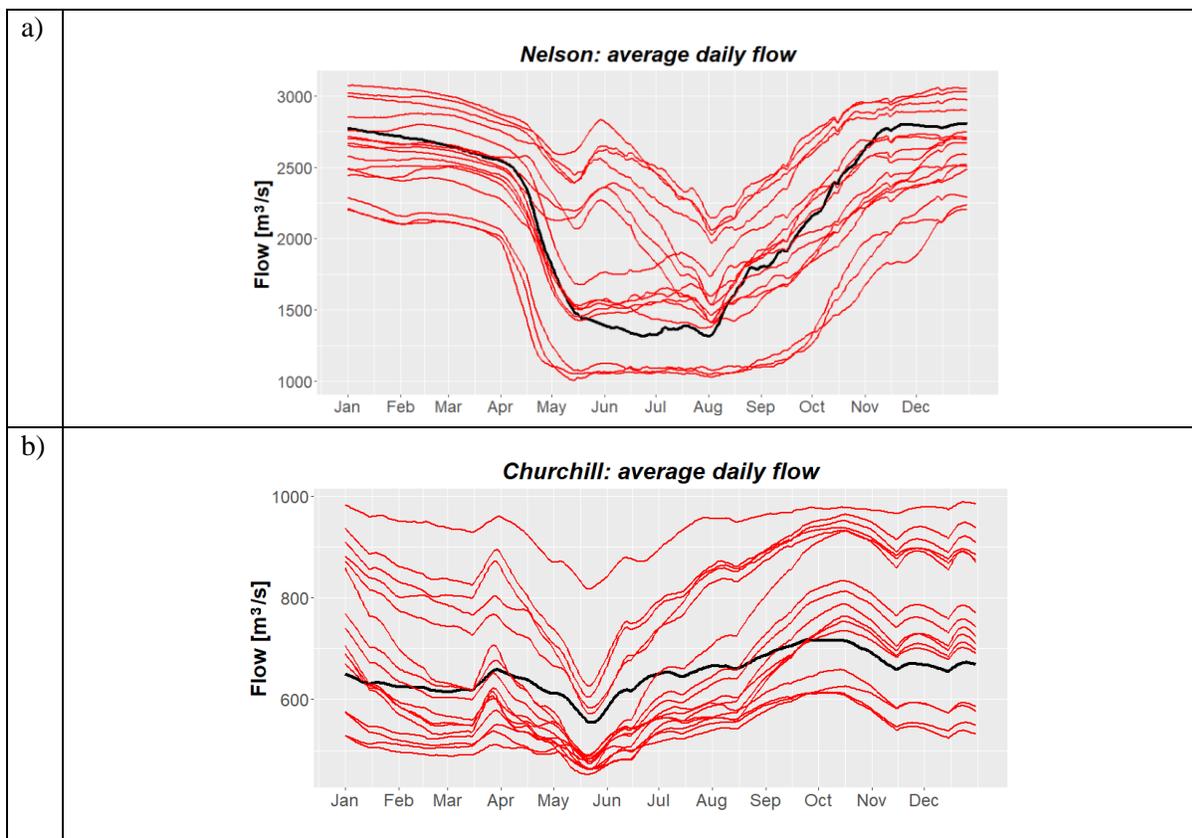


Figure 5-3: Comparison of average daily flow distribution at Jenpeg GS (a) and Notigi CS (a) between GCM ensemble (red) and HydroGFD forcing (black)

## 5.2 Impacts of climate change on LNRB

### 5.2.1 Impacts on streamflow under climate change

The following sections present and discuss the impacts of climate change on streamflow and power generation in the LNRB based on coupled model results. Results are derived from running coupled WATFLOOD-MODSIM (denoted as coupled WATFLOOD) and coupled HEC-HMS-MODSIM (denoted as coupled HEC-HMS) models.

#### 5.2.1.1 Annual and seasonal trends

The trends in annual and seasonal flow were analyzed using the MK test. Figure 5-4 compares the historic and future annual inflow volume time series at Kelsey and Wuskwatim GS using the coupled WATFLOOD model. Similar results were seen in using the coupled HEC-HMS model (not shown). The MK test shows it is *about as likely as not* or *unlikely* that there are statistically significant trends in historic and future annual volumes. Low agreement in projected Nelson and Churchill flow was recognized by MacDonald et al. (2018). The low trend agreement is not unreasonable given the selected 19 climate simulations represent the outer extreme of climatic variability over a large domain, from extremely wet to dry and various degrees of warming.

In considering the extreme trends (Table 5-4), the magnitudes of maximum positive and negative Sen's slopes generally decrease from 1981-2010 to 2021-2050 and increases to 2041-2070 across all seasons at Kelsey GS (Nelson contribution); while remaining relatively constant at Wuskwatim GS (Churchill contribution). The magnitudes of statistically significant positive slopes are generally noted to be greater than negative slopes. Given over 60% of flow at Kettle GS is contributed from Jenpeg operation (Nelson contribution), inflow at Kettle GS shows a similar trend as Kelsey GS (not shown).

Table 5-4: Summary of maximum positive and negative Sen's slopes computed of annual and seasonal inflow volume. Coupled WATFLOOD model results were used. Sen's slope is denoted in units of [km<sup>3</sup>/year].

		<b>Kelsey GS</b>		<b>Wuskwatim GS</b>	
	<b>Season</b>	<b>Max positive</b>	<b>Max negative</b>	<b>Max positive</b>	<b>Max negative</b>
Historic 1981- 2010	Annual	2.22	-1.48	0.29	-0.24
	Winter	0.54	-0.24	0.09	-0.05
	Spring	0.44	-0.26	0.05	-0.11
	Summer	0.75	-0.41	0.10	-0.04
	Fall	0.58	-0.46	0.11	-0.07
Future 2021- 2050	Annual	1.27	-1.04	0.37	-0.27
	Winter	0.18	-0.24	0.07	-0.08
	Spring	0.25	-0.17	0.12	-0.05
	Summer	0.69	-0.29	0.13	-0.05
	Fall	0.33	-0.27	0.09	-0.07
Future 2041- 2070	Annual	2.05	-1.44	0.35	-0.08
	Winter	0.32	-0.28	0.09	-0.02
	Spring	0.41	-0.26	0.07	-0.01
	Summer	0.56	-0.23	0.10	-0.02
	Fall	0.61	-0.38	0.10	-0.03

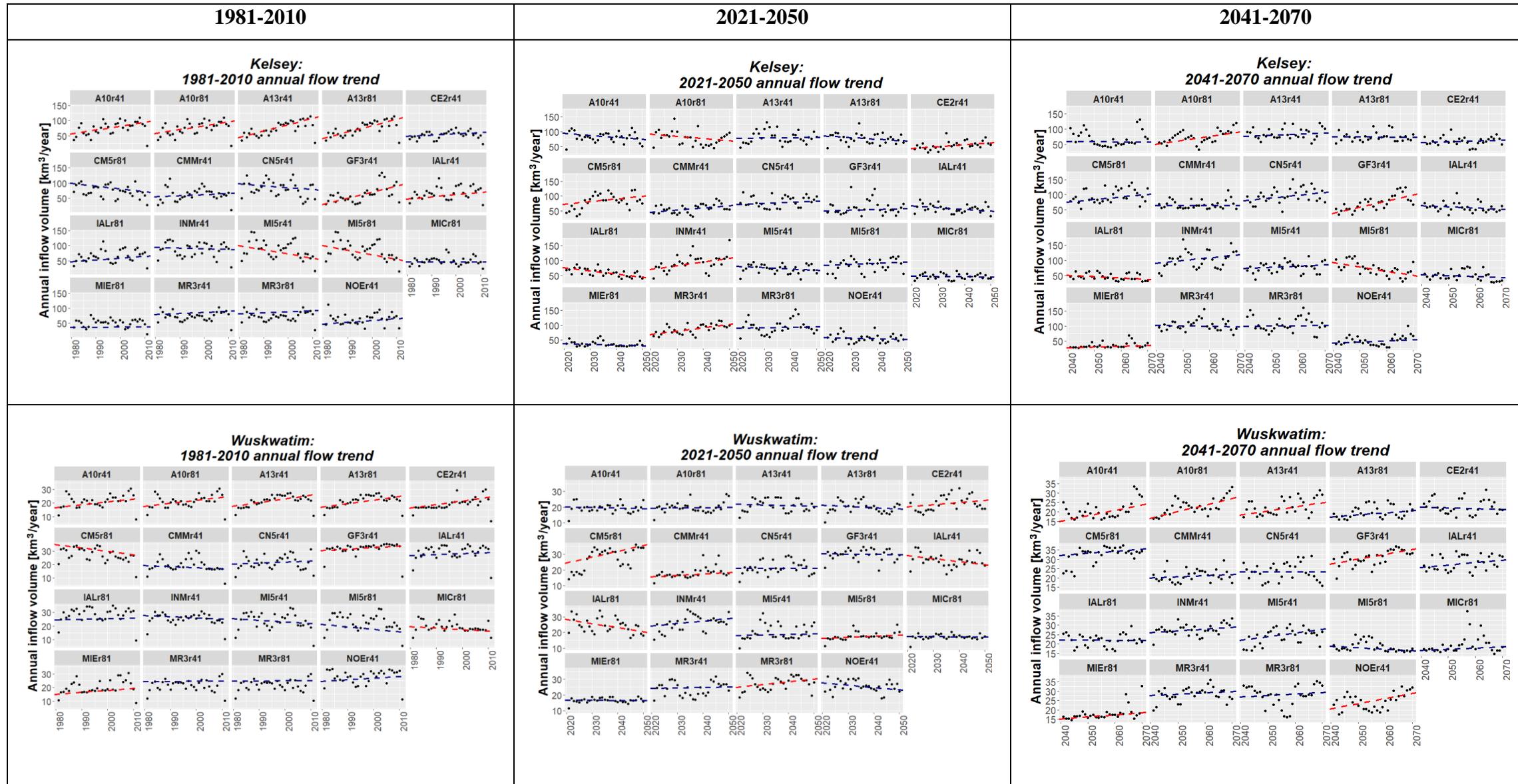


Figure 5-4: Annual inflow volume trends for 1981-2010, 2021-2050 and 2041-2070. Significance of the trend is indicated by the colour of Sen's slope (red for significance at 95%, navy for insignificant trend).

### 5.2.1.2 The shifts in the annual and seasonal distributions

As the majority of LNRB generation occurs on Lower Nelson River (LNR), downstream of Split Lake where the two rivers converge, shifts in the annual and seasonal inflow volume distribution at Kettle GS were analyzed. MWW test shows it is *about as likely as not* or *unlikely* that there are statistically significant changes in seasonal inflow volume distribution for all seasons. This is not to say that the median nor the shape of the seasonal inflow volume distributions remain constant over time. To illustrate this, Figure 5-5 shows an inter-period comparison of 19 winter inflow distribution simulations. Each inflow distribution of 19 climate simulations in 1981-2010 starts off near the historic ensemble mean, but over time, each simulation shift toward either lower or higher flows. Similar divergence, or polarization, of seasonal inflow distribution away from the ensemble mean can be seen in other seasons as well and can be found in Appendix B: Seasonal reservoir inflow distribution at Kettle GS.

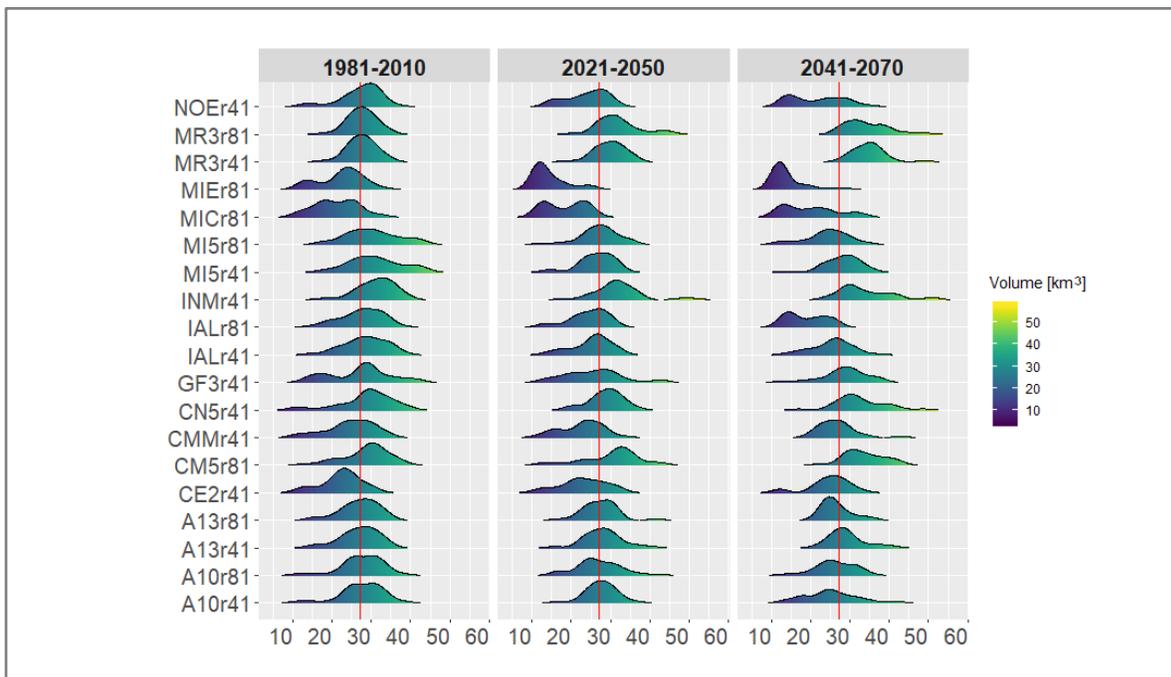


Figure 5-5: Inter-climate and inter-period comparison of Winter (DJF) volume at Kettle GS. Red lines indicate the 1981-2010 ensemble mean, as a reference point.

Figure 5-6 shows the seasonal distribution of the 30-year mean among the 19 climate simulations per analysis period. The magnitudes of the ensemble annual and seasonal mean of means, with exception of spring and summer, reduce in 2021-2050 relative to the historical period and increases again for the 2041-2070 period. The ensemble mean of means for spring and summer are shown to increase over time. The range of 30-year means is also shown to increase over time. The cause of the continued increase in the ensemble mean of means for spring and summer, as well as an increasing range for the 30-year means over time, are driven by increasing polarization within the ensemble (Figure 5-5). IALr81, MICr81, and MIEr81 (dry scenarios) flow simulations shift to lower flow over time, whereas INRr41, MR3r41, and MR3r81 (wetter projections) result in increasing flow. These simulations represent the extreme ends of box-whisker-plots from Figure 5-6. Greater volume increases from the wetter simulations (relative to drier) contribute to an overall increasing trend in the ensemble mean. The minimum, mean and maximum percent changes in 30-year seasonal ensemble inflow means in respect to 1981-2010 is summarized in Table 5-5. In general, an equal number of climate simulations indicated either increase or decrease in 30-year means with the exception of spring and fall, in which more simulations agreed in an increase or decrease, respectively.

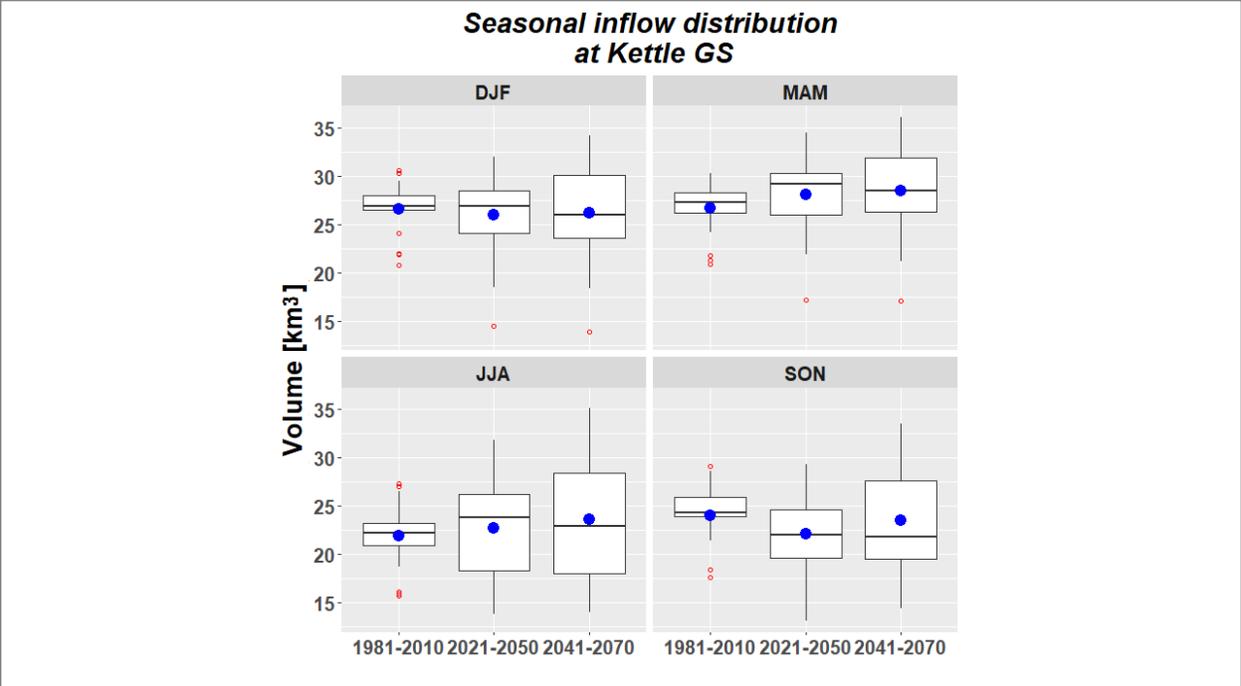


Figure 5-6: Box-whisker-plot for mean seasonal inflow derived by the 19 climate simulations at Kettle GS. Blue dots indicate distribution mean. Red dots indicate outliers.

Table 5-5: Summary of minimum, mean and maximum percent changes in 30-year seasonal ensemble inflow means compared to 1981-2010. Bold indicates percent change in ensemble mean of means.

	<b>2021-2050</b>	<b>2041-2070</b>
<b>Annual</b>	(-24.6 %, <b>-0.6%</b> , +26.7%)	(-28.5%, <b>2.4%</b> , +36.2%)
<b>Winter (DJF)</b>	(-34.1%, <b>-2.5%</b> , +17.8%)	(-36.7%, <b>-1.7%</b> , +26.3%)
<b>Spring (MAM)</b>	(-19.0%, <b>5.2%</b> , +26.7%)	(-22.7%, <b>6.9%</b> , +32.0%)
<b>Summer (JJA)</b>	(-23.8%, <b>3.0%</b> , +45.0%)	(-27.6%, <b>7.2%</b> , +57.7%)
<b>Fall (SON)</b>	(-28.8%, <b>-8.3%</b> , +20.4%)	(-31.7%, <b>-2.6%</b> , +36.3%)

The increase in inflow range variability can also be seen on the monthly time series in Figure 5-7, by the expansion of maximum and quantile flow bounds from the historic to future period. The magnitude of minimum and maximum average monthly flow increases from historical to future periods. The third quantile bound is shown to stay relatively constant in winter, increase in spring and summer and reduce in fall over time. The first quantile bound is shown to stay relatively constant with the exception of slight increases in late spring and reduction in fall over time.

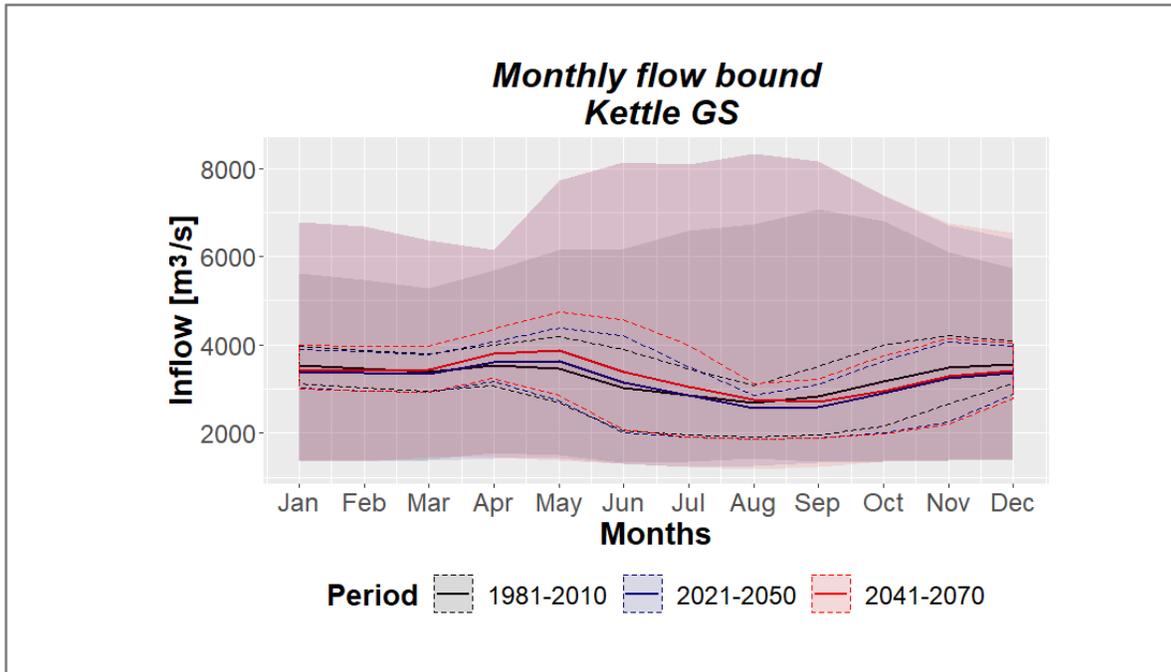


Figure 5-7: Monthly flow bounds for Kettle GS over periods of analysis. Solid lines denote 30-year ensemble average, dashed lines denote first and third quantile bounds, and filled bounds denote minimum and maximum ensemble-averaged monthly flow.

Figure 5-8 compares annual peak flow frequency between time periods using 30 years of peak flow data from all 19 climate simulations for Kelsey, Wuskwatim and Kettle GS. The month of greatest daily peak flow frequency remains consistent throughout all time periods for all three stations, but the frequency of peak flow increases moving further into the future. In general, the peak flow frequency in fall and winter diminish, while spring peak frequency increases further into the future for the Nelson, diverted Churchill and Lower Nelson flows.

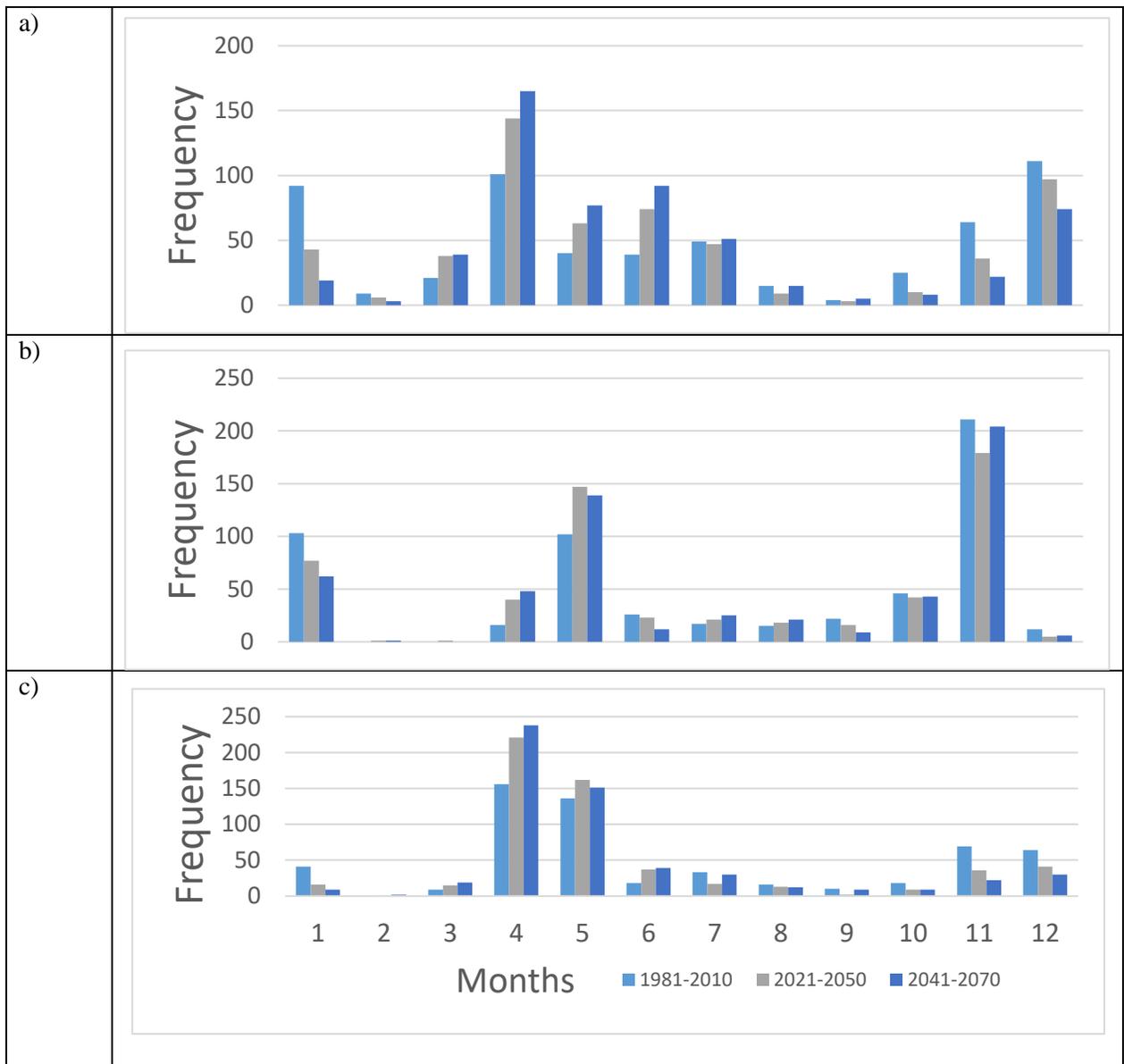


Figure 5-8: Frequency distribution of annual peak flow occurrence over all time periods at (a): Kelsey GS (b): Wuskwatim GS (c): Kettle GS

### 5.2.1.3 Summary and discussion on changes in reservoir inflow

One of the main objectives of this research was to examine the changes in seasonal and annual reservoir inflow quantity and distribution of the future compared to the historical period. The following findings were outlined in Section 5.2.1.1 and 5.2.1.2:

- 1) It is *about as likely as not* or *unlikely* to have a statistically significant trend in streamflow over any of the 30-year periods at Kelsey, Wuskwatim GS and consequently Kettle GS.
- 2) It is *about as likely as not* or *unlikely* to have a statistically significant shift in the distribution of annual and seasonal inflow volume from the historic to future periods at Kettle GS.
- 3) In considering the percent increase or decrease in flow with respect to the historical 30-year mean, the 19 climate simulations were evenly split in direction of change, with exception of spring and fall seasons where more simulations agreed in an increase and decrease, respectively.
- 4) The projected shift among climate simulations becomes more polarized over time as dry projections become drier and wet projections become wetter.

In this study, both the projected changes in quantity and distribution of reservoir inflow were analyzed as an ensemble and individually to examine both general and extreme changes. Overall, projected ensemble changes generally agreed with the projections reported in Tefs (2018). It should be noted that there are some differences in methodology, which may have contributed to disagreement in discharge projections:

- a) Study region: The discharge reported in Tefs (2018) encompassed the entire NCRB region, which included additional outlets such as Churchill River through Missi Falls CS. This work only examined NCRB discharge exiting through Lower Nelson River.

- b) Data discretization: Tefs (2018) examined changes in discharge by using the ensemble of 19 climate simulations. The work here distinguishes the discharge from each climate simulation individually to examine (dis)agreement within the ensemble.
- c) Data aggregation: Tefs (2018) averaged daily flow into a monthly average flow. In this study, daily flows were aggregated to seasonal or annual volumes.

In this study, due to low projection agreement, no particular statistically significant trend in reservoir inflow at Kelsey GS and Wuskwatim GS can be concluded with confidence. Maximum positive and negative Sen's slope magnitudes for annual and seasonal inflow volume stay generally constant on diverted Churchill flow (Wuskwatim GS) over time, indicating that the rate of extreme increase or decrease will stay constant in each 30-year assessment period. In contrast, the magnitude of both positive and negative Sen's slopes reduce in 2021-2050 compared to 1981-2010 and 2041-2010 on Nelson flow (Kelsey GS), indicating a reduced rate of extreme change over 2021-2050 comparatively.

Similarly, there is a low projection agreement on both the existence and direction of a statistically significant shift when comparing annual and seasonal inflow volume distribution of each climate simulations independently at Kettle GS. Given the range of wet and dry bias in reference (1981-2010) period, illustrated in Section 5.1.3, the polarization among climate (flow) projections, with drier scenarios becoming drier, and wet becoming wetter (Figure 5-5) resulted in low ensemble agreement.

On examining the ensemble 30-year mean annual and seasonal inflow volumes at Kettle GS, the near-future (2021-2050) is projected to be drier compared to historical and mid-future periods. Considering over 60% of flow contribution from Nelson (Kelsey GS), the lower rate of change at

Kelsey GS in 2021-2050 and projected reduction in ensemble 30-year mean may lead to consistently drier 2021-2050.

The possible reasons for reduced reservoir inflow in 2021-2050 can be seen in Figure 5-9 where the changes in the ensemble mean climatic variables and discharge for the NCRB (derived from Table 3-6 in Tefs (2018)) is summarized. The increase in mean annual actual evapotranspiration (AET) outpaces the increase in precipitation in 2021-2050 compared to the historic period. This likely results in reducing mean annual discharge for the 2021-2050 period. The changes in mean annual precipitation and AET for 2041-2070 are relatively equal, and runoff is shown to increase slightly (~2%), which agrees with findings from Figure 5-6. Figure 5-9 shows the greatest precipitation increases in NCRB occur in spring, which coupled with spring melt events, likely contributes to projected increases in spring inflow volume. Despite increases in AET outpacing increases in precipitation in summer, the summer ensemble mean is projected to increase over time, which is likely due to increases in extreme summer events contributing to increases in the 30-year ensemble mean and the wet scenarios getting even wetter. Reported increases in precipitation in winter and fall periods may not directly contribute to an increase in discharge, depending on the precipitation type and instream ice cover at the time of precipitation.

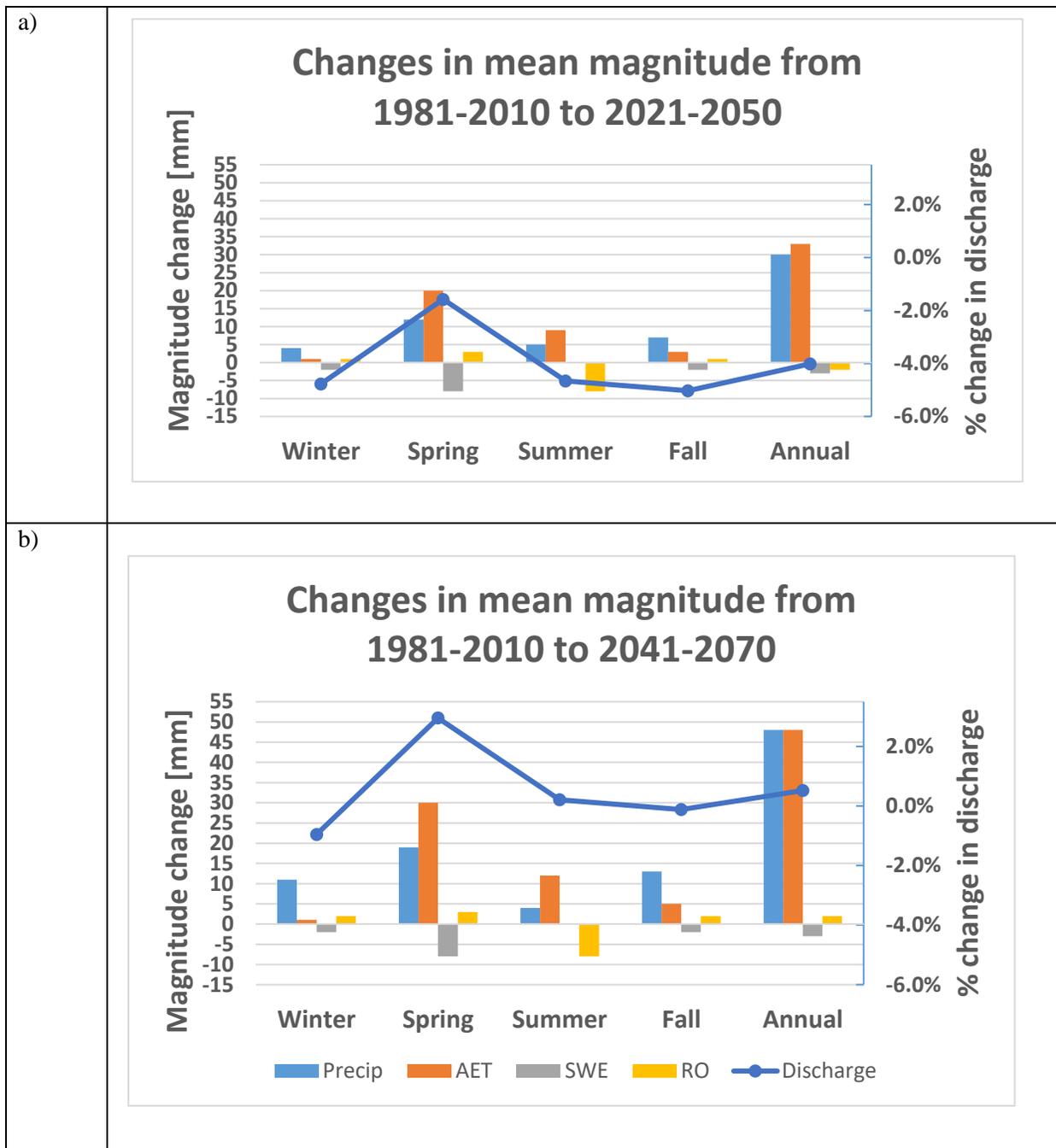


Figure 5-9: Changes in mean precipitation, AET and SWE in [mm] and runoff in [%] compared to historic period. Values derived from Tefs (2018) Table 3-6.

In extreme cases, the 30-year mean discharge of driest (wettest) simulations continue to decrease (increase) on annual and seasonal bases. On an annual scale, the changes from historic to near future can be as great as -24.6% to + 26.7%, and -28.5% to +36.2% for the mid-future. The largest range in the 30-year mean is found in summer (near future: -23.8% to +45.0%, far future: -27.6%

to +57.7%), indicating that the greatest uncertainty in inflow will occur in the summer. Individually, the greatest percent decrease and lowest percent increase (from the historic mean) are found in winter, for both future periods. Whereas the lowest percent decrease occurs in spring, but the greatest percent increase occurs in summer, for both future periods. It is noted that the magnitudes of the maximum percent increases in annual and seasonal 30-year means are greater than the maximum percent decreases. Similarly, the magnitudes of maximum positive Sen's slopes are noted to be greater than the maximum negative slope, indicating that wetter projections become wetter at a greater rate relative to drying simulations.

It is important to note that while it was found that there is *about as likely as not* or *unlikely* agreement to have a statistically significant trend or changes in annual and seasonal inflow volume, this does not mean that there will actually be insignificant changes in inflow volume in the future. As Beven (2011) mentioned, simulation agreement in trend or shift does not represent the probability of any given climate simulation occurring; only the probability of model projections having a trend within the ensemble sample. Furthermore, it is noted that the projected absence of particular statistically significant trend and greatest decrease and least increase in winter inflow compare to historical period is unique to this study. Tefs (2018) and Stadnyk et al. (2019) indicated an increasing trend in winter discharge in NCRB and HBDB respectively over 2021-2070 period. This may be due to the aforementioned differences in the study region, data discretization, and aggregation.

## 5.2.2 Impacts on potential hydropower production

### 5.2.2.1 Annual and seasonal generation trend

Similar to inflow volume results, there is *about as likely as not* or *unlikely* agreement on the existence of significant trends in hydropower production over the three 30-year periods. Table 5-6 summarizes the maximum positive and negative slope magnitudes using the coupled WATFLOOD model. Similar results were seen in using coupled HEC-HMS (not shown).

Table 5-6: Summary of maximum and minimum Sen's slopes computed for annual and seasonal potential power generation in Lower Nelson River. Coupled WATFLOOD results are presented in this table. Sen's slope is denoted in units of [TWh/year].

		<b>Lower Nelson River GS</b>	
	<b>Season</b>	<b>Max positive</b>	<b>Max negative</b>
Historic 1981-2010	Annual	19.85	-10.15
	Winter	3.18	-1.30
	Spring	3.81	-1.83
	Summer	6.39	-3.38
	Fall	2.31	-2.36
Future 2021-2050	Annual	8.36	-11.21
	Winter	1.88	-3.14
	Spring	2.39	-2.08
	Summer	3.43	-2.57
	Fall	3.00	-3.38
Future 2041-2070	Annual	15.90	-14.03
	Winter	2.81	-2.96
	Spring	2.11	-1.81
	Summer	4.92	-3.68
	Fall	5.77	-4.33

Unlike the inflow volume slope, the magnitudes of maximum negative slopes for the future periods are generally found to be *greater than* or *equal to* the maximum positive slopes. This indicates that an increasing trend in inflow volume may not directly translate into an increase in potential power generation.

In order to quantify whether LNR power generation potential remains similar to the historic period, the total number of years (summation of 19 climate simulations over 30-year periods) exceeding a threshold value was calculated. The threshold value was set to be the ensemble average historical annual (or seasonal) hydropower generation potential. The percentage of years exceeding the threshold value among time periods is summarized in Table 5-7. On an annual scale, the number of years exceeding the threshold in 2021-2050 decreases compared to the historic and mid-future periods, which coincides with 2021-2050 being a comparatively drier period. Winter hydropower generation potential exceedance decreases in 2021-2050 and remains low in 2041-2070. Spring and summer hydropower generation potential exceedances increase, while fall exceedance decreases over time. This follows the seasonal inflow volume shift (Figure 5-6), which is not surprising given there is limited storage capacity within the LNRB and hydropower generating stations are Run-of-the-River (ROR).

Table 5-7: Percent of total year exceeding historical annual and seasonal mean hydropower generation potential, based on 19 climate simulations

<b>Periods</b>	<b>1981-2010</b>	<b>2021-2050</b>	<b>2041-2070</b>
<b>Annual</b>	56.1%	52.1%	56.6%
<b>Winter</b>	65.3%	59.1%	60.4%
<b>Spring</b>	60.4%	64.5%	70.2%
<b>Summer</b>	46.5%	45.6%	50.0%
<b>Fall</b>	53.3%	45.8%	44.9%

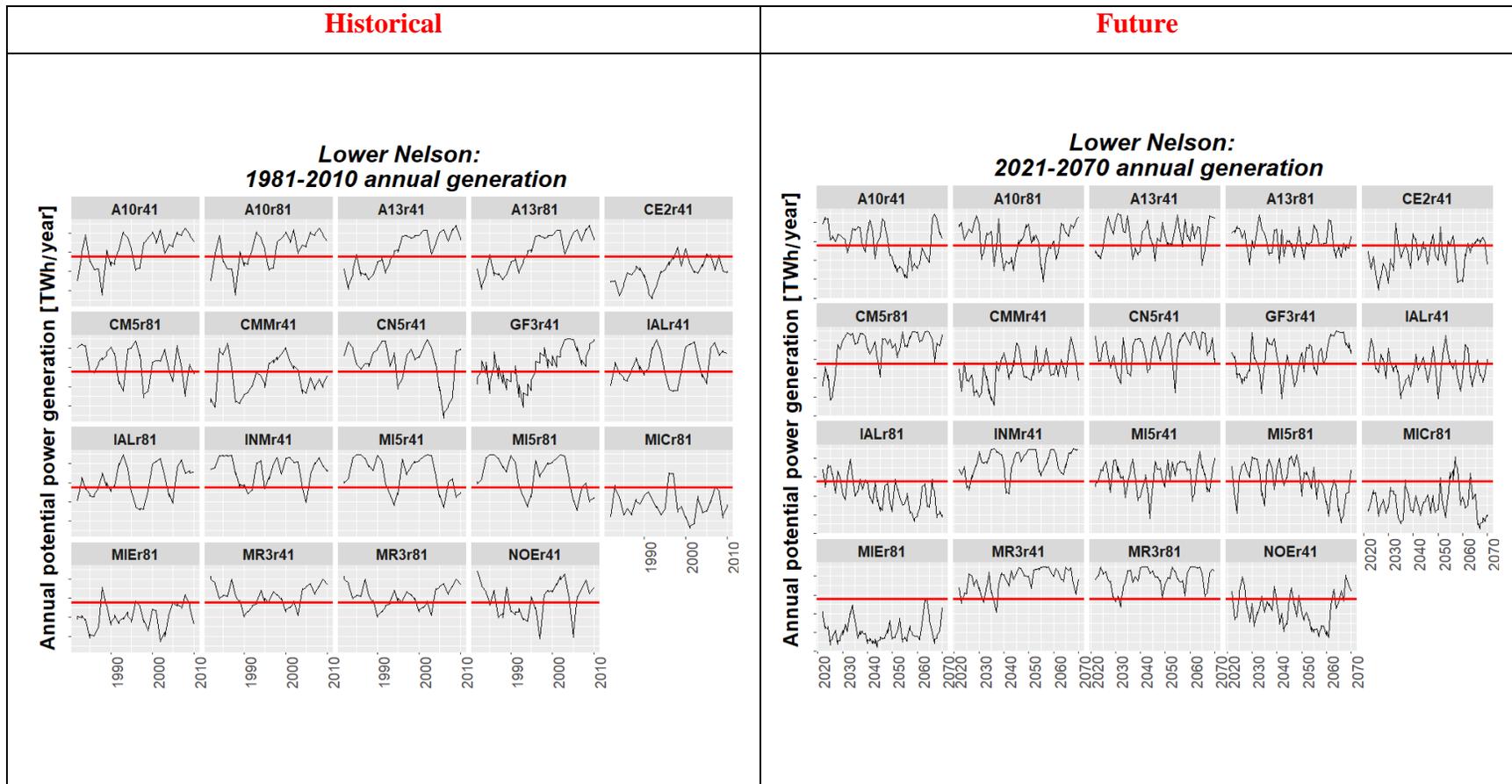


Figure 5-10: Comparison of annual power generation in LNR over historical and future periods. Red line denotes the historical ensemble annual average potential generation threshold.

The shift in percent exceedance, however, does not necessarily agree with the simulation shift summarized in Table 5-8. Table 5-8 shows that the number of simulations with “*likely*” exceedance of historic ensemble mean does not change from period to period, with the exception of winter and summer seasons. While the total number of years (19 simulations x 30 years, per time period) exceeding the historical threshold may shift from time period to time period, this does not necessarily signify that climate simulations independently identify a similar shift in threshold exceedance. The percent exceedance of total years and climate scenarios agrees for the winter period, which is unsurprising given both the MWW test and mean winter inflow volume indicate reductions relative to the historic period. The apparent disagreement between Table 5-7 and Table 5-8 for the summer trend is due to 5 of 19 climate simulations having 19 out of 30 years of exceedance ( $\geq 63\%$ ) and consequently being excluded in the statics in Table 5-8. If the “*likely*” category is extended to include simulations with 63% exceedance, the number of climate simulations with “*likely*” exceedance will remain constant throughout all time periods.

Table 5-8: Number of simulations with 20 or more years (“*likely*”:  $\geq 66\%$ ) exceeding the historical mean

<b>Periods</b>	<b>1981-2010</b>	<b>2021-2050</b>	<b>2041-2070</b>
<b>Annual</b>	7 / 19	8 / 19	7 / 19
<b>Winter</b>	15 / 19	7 / 19	8 / 19
<b>Spring</b>	11 / 19	11 / 19	12 / 19
<b>Summer</b>	1 / 19	6 / 19	7 / 19
<b>Fall</b>	5 / 19	6 / 19	5 / 19

### 5.2.2.2 Changes in the mean magnitude of hydropower generation potential

The percent change in annual and seasonal mean hydropower generation potential follows similar patterns shown in percent change in inflow at Kettle GS (Table 5-9). The ensemble mean annual hydropower generation potential decreases slightly (< 1%) in the future in comparison to the historical period; although percent change can be as great as -25% to +20 % under individual climate simulations. The greatest reduction in the ensemble mean seasonal potential decrease occurs in fall, although the greatest reduction in percent difference under an individual climate simulation occurs in winter. Spring and summer ensemble mean hydropower generation potentials are increasing through time.

Table 5-9: Summary of the ensemble mean, the minimum and maximum percent difference in hydropower generation potential and reservoir inflow at Kettle GS. Mean is denoted in bold, minimum and maximum are denoted in parenthesis. Only coupled WATFLOOD results are shown.

Period	Hydropower generation potential		Reservoir inflow	
	2021-2050	2041-2070	2021-2050	2041-2070
<b>Annual</b>	<b>- 0.8 %</b> [-24.1 %, 15.3 %]	<b>-0.5 %</b> [-25.5 %, 20.1 %]	<b>- 0.6 %</b> [-24.6 %, 26.7 %]	<b>+2.4 %</b> [-28.5 %, 36.2 %]
<b>Winter (DJF)</b>	<b>-2.1 %</b> [-33.4 %, 9.8 %]	<b>-3.1 %</b> [-36.2 %, 13.6 %]	<b>-2.5 %</b> [-34.1 %, 17.8 %]	<b>-1.7 %</b> [-36.7 %, 26.3 %]
<b>Spring (MAM)</b>	<b>+ 3.8 %</b> [-18.7 %, 14.2 %]	<b>+ 2.5 %</b> [-19.9 %, 15.9 %]	<b>+ 5.2 %</b> [-19.0 %, 26.7 %]	<b>+ 6.9 %</b> [-22.7 %, 32.0 %]
<b>Summer (JJA)</b>	<b>+ 2.1 %</b> [-14.7 %, 26.9 %]	<b>+ 2.5 %</b> [-24.5 %, 30.3 %]	<b>+ 3.0 %</b> [-23.8 %, 45.0 %]	<b>+ 7.2 %</b> [-27.6 %, 57.7 %]
<b>Fall (SON)</b>	<b>- 7.0 %</b> [-27.9 %, 12.4 %]	<b>- 3.4 %</b> [-28.3 %, 24.0 %]	<b>- 8.3 %</b> [-28.8 %, 20.4 %]	<b>- 2.6 %</b> [-31.7 %, 36.3 %]

Hydropower generation in LNR operates as a ROR system, meaning that the reservoir inflow is directly related to hydropower generation potential. However, Table 5-9 shows while the magnitude of the maximum reduction in the 30-year mean hydropower generation potential is proportionate to the maximum reduction in reservoir inflow, the magnitude of maximum increase in reservoir inflow is not proportionate to the increase in hydropower generation potential. The

cause of this disproportionate response for the maximum increase in hydropower generation potential can be seen in Figure 5-11 via the relationship between the measured LNR power generation and streamflow at Kettle GS from 2000-2017. At a certain flow,  $Q_0$ , the rate of increase in power generation with flow decreases and plateaus, indicating that generation is at maximum capacity and any additional inflow will not contribute to increased hydropower generation potential. The limited extent of the increase in hydropower generation potential contributes to a decrease in the ensemble mean hydropower generation potential, as a decrease in inflow is still directly proportional to a decrease in the hydropower generation potential for this system.

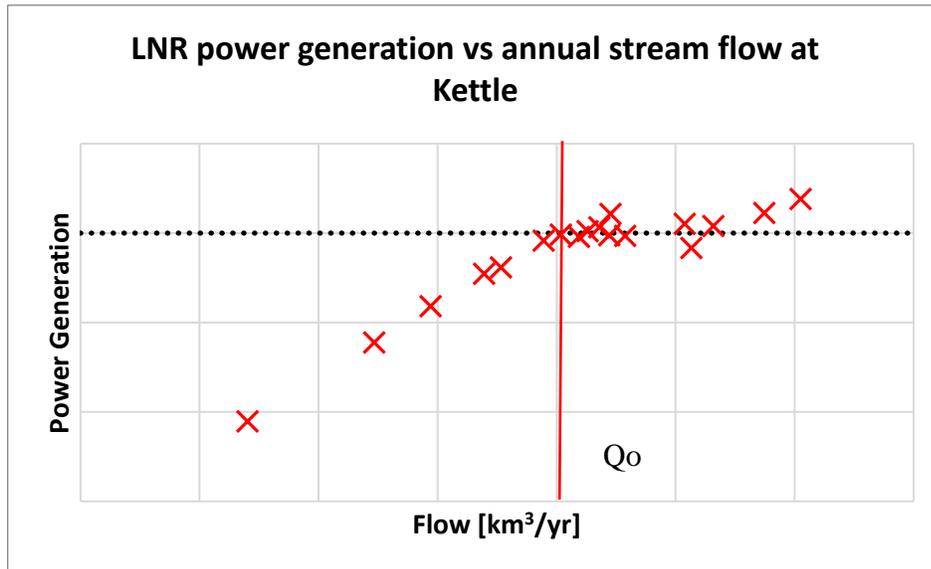


Figure 5-11: Scatter plot of LNR power generation with respect to streamflow at Kettle GS (2000-2017). Threshold  $Q_0$  indicated by the vertical red line.

### 5.2.2.3 Summary and discussion on changes in hydropower generation potential

One of the main objectives of this research was to examine whether the LNRB system will be able to deliver similar potential power generation in the future compared to the historical period. The following findings were outlined in Sections 5.2.2.1 and 5.2.2.2:

- 1) It is *about as likely as not* or *unlikely* to have a particular statistically significant trend in LNR hydropower generation potential. The statistically significant trends identified in hydropower generation potential are similar to significant trends found in reservoir inflow for Kettle GS.
- 2) The number of climate simulations “*likely*” to exceed the historical mean are projected to stay constant over time, with the exception of winter.
- 3) The percent of the total number of years exceeding historical mean is found to decrease in 2021-2050 and increase again in 2041-2070 on an annual scale. The percent exceedance for winter and fall seasons are projected to reduce in 2021-2050 and remain low.
- 4) Increases in reservoir inflow did not directly translate to increases in hydropower generation potential, although a decrease in inflow directly translates to a decrease in hydropower generation potential.

Similar to reservoir inflow, there is low agreement on hydropower generation potential projections. MK test results show similar trends as reservoir inflow at Kettle GS as the LNR system operates as a ROR system and is directly influenced by inflow supply. The magnitudes of maximum negative slopes, however, were equal or greater than the magnitudes of the maximum positive slopes, which is the opposite of reservoir inflow. This indicates that a general increasing trend in inflow volume may not directly translate into a general increase in potential power generation.

The number of climate scenarios “*likely*” ( $\geq 66\%$  of 30 years) to exceed the threshold value of the historic mean stay relatively constant, with exception of winter. The percent of years exceeding the threshold, however, decreases for 2021-2050 and increases for 2041-2070 on annual scale following a similar ensemble trend as inflow. Winter and fall seasons are projected to see reduced

percent exceedances in the future. These different signals in percent exceedance between individual climate simulations (number of climate scenarios “likely” to exceed) and ensemble (number of total years exceeding the threshold) highlight the importance of examining climate change scenarios both as individual simulations and as an ensemble.

The winter period is identified to see a decrease in the percent exceedance both as individual simulations and as an ensemble. The scenarios identified as “likely” to exceed threshold potential ( $\geq 66\%$  of 30 years) in 1981-2010 winter had a reduced number of years ( $< 66\%$  of 30 years) exceeding the threshold in the future periods. These were climate simulations projected to experience a reduction in the 30-year mean in 2021-2050 and 2041-2050 relative to the 1981-2010 historic period. This implies that the climate scenarios which were “likely” to exceed the threshold in 1981-2010 are “unlikely” to exceed the threshold in the future periods due to projected reduction in inflow compared to the historical period.

It is projected that hydropower generation potential can either increase or decrease over time, although the percentage increases are not proportionate to the increases in reservoir inflow. As illustrated in Figure 5-10, under historical infrastructure and operating rules, generation reaches maximum capacity at certain flow,  $Q_0$ , and any additional inflow does not contribute to an increase in hydropower generation potential. In Figure 5-12, the seasonal ensemble inflow distribution for Kettle is compared with LNR hydropower generation potential and illustrates that, although inflow volume increases over time for spring and summer; the increase does not translate to increasing hydropower generation potential given the reservoirs are already at maximum capacity. Although spilling was not modelled in the current setup of the coupled model, this would translate to spilling in reality (wasted potential). A decrease in inflow, however, directly translates to a reduction in

hydropower generation potential, as shown by a lower percentage increase in the ensemble mean potential compared to the percent increase in reservoir inflow.

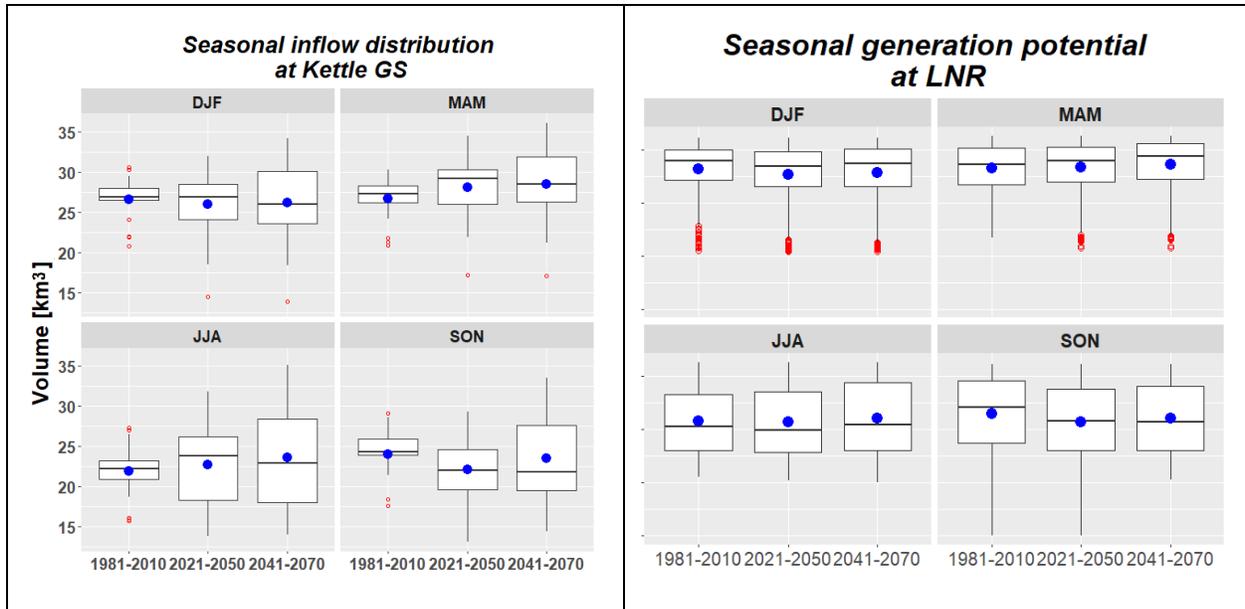


Figure 5-12: Comparison of seasonal inflow at Kettle and hydropower generation potential from the Lower Nelson River. Blue dots denote ensemble mean and red dots denote outliers.

### Possible impact on LNRB operations

In general Lake Winnipeg Regulation (LWR) and Churchill River Diversion (CRD) operate to meet high winter demand and to avoid flooding in Lake Winnipeg and along the Lower Nelson River region (Manitoba Hydro, 2015b). Historically, LWR and CRD outflows are utilized to meet higher winter demands, drawing down major system reservoirs (Lake Winnipeg and South Indian Lake). The outflow is reduced in spring to avoid overloading the system when demand is lower and spring runoff is higher; spring runoff from snowmelt is used to refill some of the reservoirs (Manitoba Hydro, 2015b). Maximum outflow may be continued in summer, via spilling, should inflows be high in a particular year to avoid flooding within the system.

Results indicate the hydropower generation potential in spring and summer is expected to increase (as an overall ensemble), and experience the least reduction among the four seasons relative to the

historical period. Despite the projected increase in hydropower generation potential, these seasons are not peak demand seasons historically, and increased power generation may not be required and may result in increased spilling in reality under historic infrastructure and operations. Furthermore, annual peak flow frequencies in spring are expected to increase into the future, with a general reduction across all other months. The increased frequency in annual spring peak flow, coupled with an increase in spring volume magnitude, in the future might suggest a possible reduction in system efficiency for retaining increased spring and summer flows for reservoir refilling and the avoidance of flooding along with the Lower Nelson. Winter is typically the highest system demand period in Manitoba due to heating and lighting requirements in the winter months. Winter may be impacted the most in the future as inflows are projected to experience the greatest reduction and the least increase in hydropower generation potential under historic infrastructure and operations, including freeze-up programs. Under warmer temperature, the ice restriction at the outlet of Lake Winnipeg may be less severe which may improve MH's ability to use Lake Winnipeg storage to offset the reduction in winter inflows.

### 5.2.3 Impacts of uncertainty stemming from model choice

In this study, two hydrologic models, WATFLOOD (distributed) and HEC-HMS (semi-distributed), were chosen to examine the impact of uncertainty in streamflow and power generation stemming from model choice and structural uncertainty. Figure 5-1 shows a comparison of monthly reservoir inflow to Kettle between WATFLOOD and HEC-HMS.

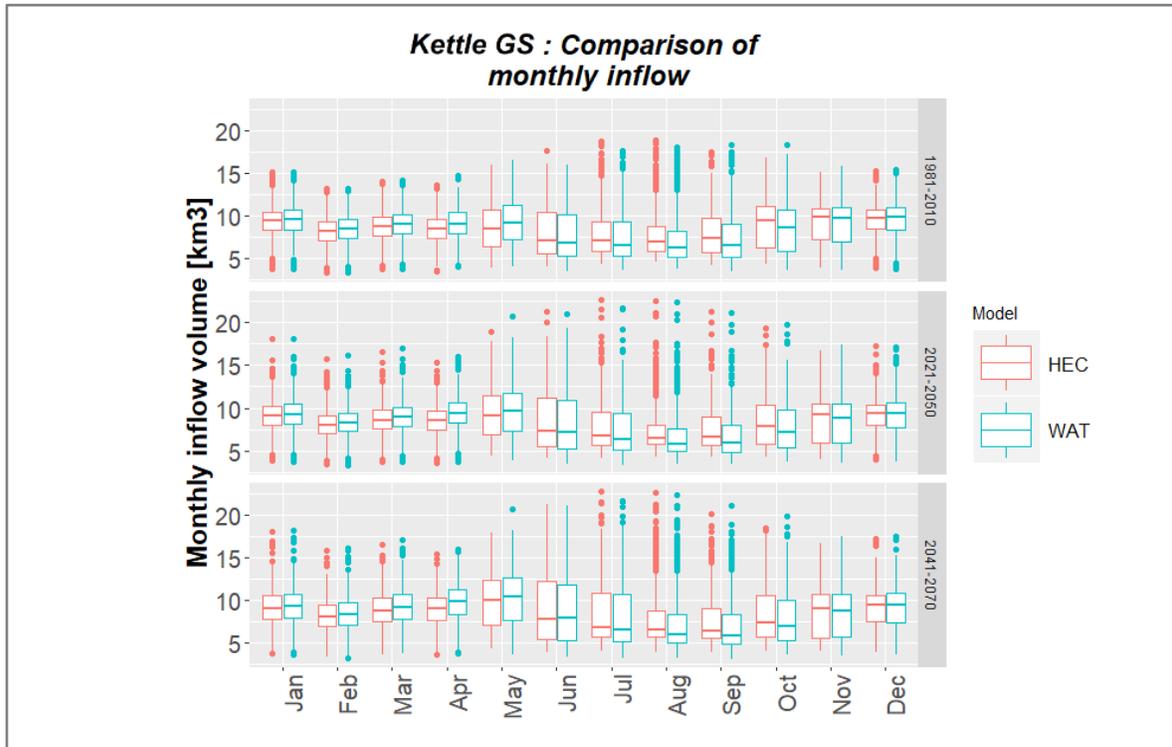


Figure 5-13. Comparison of monthly reservoir inflow at Kettle GS from WATFLOOD and HEC-HMS

Differences between WATFLOOD and HEC-HMS simulated flows fluctuate from season to season. WATFLOOD tends to compute higher winter and spring flows, and lower summer and fall flows relative to HEC-HMS. Potential factors driving this difference (or uncertainty) in model results are the individual model representations of reservoir and reservoir processes. As a gridded model, WATFLOOD determines the lake area from the gridded land class map. Hence, WATFLOOD considers the entire water body that feeds the forebay of the generating station as a lake. In contrast, all of the lake settings in HEC-HMS are user-specified. The current HEC-HMS

model setup only considered the forebay as the reservoir, which is only 1% to 4% of the actual lakes (Table 5-10). While both models include an evaporation module, given the significant difference in lake surface area, WATFLOOD computes higher evaporation, or water loss, than HEC-HMS. WATFLOOD internally subtracts evaporation loss from upstream inflow into the reservoir, leading to reduced reservoir inflow for the summer and fall periods compared to HEC-HMS.

Table 5-10: Reservoir size specified in WATFLOOD and HEC-HMS for Wuskwtim, Kelsey and Kettle GS

	<b>WATFLOOD</b>	<b>HEC HMS</b>
<b>Wuskwtim</b>	~ 78 km <sup>2</sup>	~ 3 km <sup>2</sup>
<b>Kelsey</b>	~ 31 km <sup>2</sup>	~ 0.3 km <sup>2</sup>
<b>Kettle</b>	~ 400 km <sup>2</sup>	~ 13 km <sup>2</sup>

Furthermore, WATFLOOD computes open water evaporation only when there is no snow cover (Kouwen and Stadnyk, 2017). Historically, the snow-free period in the LRNB is relatively short, generally between May and October (Environment and Climate Change Canada, 2019), and there are significantly more sunlight hours in summer than winter due to its high latitude. The snow-free period coincides with the reduced inflow estimation period for WATFLOOD.

Table 5-11: Average percent difference between HEC-HMS and WATFLOOD for three 30-year periods

	Annual	Winter (DJF)	Spring (MAM)	Summer (JJA)	Fall (SON)
LNR Inflow	0.2 %	- 2.1 %	- 6.2 %	+ 5.5 %	+ 4.5 %
LNR Power	0.7 %	- 1.4 %	- 4.3 %	+ 5.3 %	+ 4.8 %

As seen in Table 5-11, the average percent difference in inflow and power generation are reflective of one another as power generation in the LNR is operated as ROR. Overall, although there were some model differences in streamflow and power generation computation, the magnitude of the difference is only a fraction of the uncertainty stemming from that introduced by the climate

simulation. A detailed uncertainty partitioning analysis is outside the scope of this study; however, by comparing the percent difference between model, time period and climate simulations, a crude estimate of the magnitude of uncertainty attributed to each source can be made. As seen in Table 5-11, model difference contributes to a small percent difference (less than 1%) in annual inflow and generation potential estimation. Considering the magnitude of the percent difference in inflow or generation potential among climate simulations stemming from the time period ( $\pm 20\%$ ) and GCM/RCP selection ( $\pm 25\%$ ), the uncertainty stemming from model difference is inconsequential. This is not surprising given it is generally accepted that the largest uncertainty contributions stem from uncertainty in climate (Minville et al., 2010). Furthermore, as discussed in Section 3.1.2, approximately 90% of the flow into the LNRB is generated upstream of the LNRB. Both WATFLOOD and HEC-HMS received the same upstream contribution from HYPE simulation. Therefore, the selection of the hydrologic model for the LNRB made little difference in the overall inflow and hydropower generation potential estimate due to the LNRB location within greater NCRB. Despite the small percent difference for the LNRB, the model inter-comparison does highlight the importance of uncertainty stemming from model selection, or combined uncertainty of model structure and parameters, perhaps more so for headwater basins. Bohrn (2012) investigated the model uncertainty using three hydrologic models in the upstream portion of the Churchill River Basin. His work demonstrated the flow volume uncertainty stemming from the model choice was greatest during the open-water period (lower flow period) and was driven by the difference in evaporation computation between the models. Considering modelling uncertainty, particularly due to the structure of ET computation, will be important for future time periods within NCRB. ET was found to increase through time with a statistically significant trend, especially in summer where ET outpaces increasing precipitation (Tefs, 2018).

## **6.0 Conclusion and future works**

This chapter provides a summary of the major findings and possible future work to further expand on the study limitations. In this study, a coupled hydrologic-operations model framework was presented to analyze the impact of climate change on basin streamflow distribution and hydropower generation potential. Two coupled models were established using existing hydrologic models for the LNRB (WATFLOOD-MODSIM and HEC-HMS-MODSIM) to evaluate streamflow uncertainty resulting from model choice and model structure. The coupled models were run under 19 climate simulations to evaluate changes in reservoir inflow and potential generation.

### **6.1 Summary of major findings**

#### **6.1.1 Implementation of the coupled hydrologic-operations model framework**

The purpose of establishing a coupled model framework was to leverage the unique computational ability of each model: to take advantage of hydrological processes by hydrologic models, and the flexible simulation of reservoir operation and power generation by the operations model. Despite iterative coupling being a more computationally expensive coupling method compared to the dynamic coupling method, the coupled models were able to complete a 30-year simulation in 20 minutes (coupled WATFLOOD) and 10 minutes (coupled HEC-HMS). The coupled model demonstrated that specified input time series data from each model was transferred correctly to ensure model reservoir flow consistency using the wrapper script. The coupled models reached model convergence (MODSIM specified release has reached its optimized release) after the first iteration. Overall, iterative coupling only made a small release modification ( $RSR < 0.01$ ) as the hydrologic models were already calibrated to match historical reservoir release.

### 6.1.2 Effects of climate change on reservoir inflow in Lower Nelson River Basin

The effects of climate change on reservoir inflow were assessed through a series of inter-period (1981-2010, 2021-2050 and 2041-2070) comparisons. The statistical significances of trend and changes in inflow distribution were assessed using Mann-Kendall and Mann-Whitney-Wilcoxon U tests, and comparison of the ensemble mean inflow magnitude. There was low agreement between the selected 19 climate simulations; using IPCC likelihood categories, it was shown that under historical infrastructure and operations:

- It is *about as likely as not* or *unlikely* to have a statistically significant trend in annual and seasonal inflow volume over any of the 30-year periods at Kelsey, Wuskwatim and Kettle GS.
- It is *about as likely as not* or *unlikely* to have a statistically significant shift in the distribution of annual and seasonal inflow volume between historic and future periods at the Kettle GS.

On examining the mean 30-year inflow volume among the 19 climate simulations, it was found that:

- There is low agreement in direction of percent change between historic and future reservoir inflow at Kettle GS. In considering the percent increase or decrease with respect to the historical 30-year mean, the 19 climate simulations were evenly split in their direction of change projected; with the exception of spring and fall, where more simulations indicated more increase and decrease, respectively.
- The range of projected changes in reservoir inflows to Kettle GS will increase with time as dry scenarios become drier and wet scenarios become wetter. On an annual scale, projected changes from the historic mean may range from -24.6% to 26.7% in 2021-2050 and -28.5% to 36.2% in 2041-2070. The largest range in the 30-year mean is found in summer, indicating the greatest uncertainty. Winter is projected to see greatest reductions (-34.1% and -36.7% in 2021-2050 and 2041-2070 respectively) and least increase (17.8% and 26.3%) among the four seasons.

- Both the seasonal volume distribution and ensemble mean of volumes for spring and summer are predicted to increase in the future. The frequency of annual peak flow in the spring period is predicted to increase over time. Coupled with the projected increase in spring inflow magnitude, this may lead to increases in spilling.

### **6.1.3 Effects of climate change on potential power generation on Lower Nelson River Basin**

The effects of climate change on potential power generation were assessed by inter-period (1981-2010, 2021-2050 and 2041-2070) comparisons. There was low agreement between the 19 climate simulations; using IPCC likelihood categories, it was shown that under historical infrastructure and operations:

- It is *about as likely as not* or *unlikely* to have a statistically significant trend in annual and seasonal hydropower generation potential over the 30-year periods on the Lower Nelson River. Generally, the climate simulations identified with a statistically significant trend in reservoir inflow showed statistically significant trends in hydropower generation potential.
- In contrast to inflow volume slopes, the magnitude of maximum negative Sen's slopes for the future periods are found to be *greater than* or *equal to* the positive slopes, indicating that a general increasing trend in inflow volume may not always translate into a general increase in potential power generation.

Using the historical ensemble mean generation potential as a threshold value, the number of total ensemble years exceeding the threshold and the number of climate scenarios that will “*likely*” ( $\geq 66\%$  of 30 years) exceed the threshold was evaluated. It was found that:

- Annually, the percent of the total number of years exceeding the historic mean decreased in 2021-2050 and increased in 2041-2070. Winter and fall percent exceedances are projected to reduce in the future.
- While the total number of years exceeding the threshold may shift from time period to time period, the number of climate simulations “*likely*” to exceed the historical mean is projected to stay constant over time, with the exception of winter. This highlighted the

importance of examining the climate change scenarios both as individual simulations and as an ensemble.

- The winter period was identified to decrease in exceedance rates both as individual simulations and as an ensemble. This was due to climate scenarios, which “*likely*” exceed the historic mean in 1981-2010 experienced a reduction in inflow in the future and were unable to exceed threshold hydropower generation potential.
- Increases in reservoir inflow did not translate 1:1 to increase in hydropower generation potential. Under historical infrastructure and operations, any additional inflow past a certain flow,  $Q_o$ , did not contribute to increased hydropower generation potential and in reality, will add to increased spilling. While projected reductions in inflow directly translate to reduced hydropower generation potential, only a limited degree of the projected increase in inflow can be leveraged in the future to increase hydropower generation potential.
- Similar to reservoir inflow, winter is projected to see the greatest reductions in hydropower generation potential (-33.4% and -36.2% in 2021-2050 and 2041-2070 respectively), and least increases (9.8% and 13.6%) among the four seasons.
- The greatest reduction in the ensemble mean generation potential is projected to occur in fall in the future, while spring and summer ensemble mean generation potentials are projected to increase over time.

#### **6.1.4 Uncertainty stemming from model choice**

Uncertainty stemming from model choice was examined by comparing results of coupled WATFLOOD and HEC-HMS models. Overall, the average percent difference in reservoir inflow and hydropower generation potential was found to be less than 7%. The small percent difference is likely attributed to the majority of streamflow being generated from upstream of the LNRB. Both WATFLOOD and HEC-HMS models were forced with the same upstream flows generated from HYPE. Seasonal oscillation of percent differences between WATFLOOD and HEC-HMS was identified, with WATFLOOD estimating higher inflow volume in winter and spring, and lower volume in summer and fall periods. Possible causes of this oscillating difference are due to

differences in model lake representation and ET modules, with WATFLOOD simulating greater reservoir extent and higher reservoir evaporative loss. Despite the small percent difference contribution in the LNRB, the model comparison does highlight the importance of uncertainty stemming from model selection, or combined uncertainty of model structure and parameters, perhaps more so for headwater basins.

## **6.2 Study limitation and future work**

### **6.2.1 Specification of demand time series in MODSIM**

The configuration of MODSIM used in this study was set up to compute potential power generation, generating maximum power generation possible regardless of the need. This was because MODSIM requires power generation targets in order to optimize to meet the given generation targets and redirect remaining flow down through the spillway. In this sense, the optimization capability of MODSIM was not utilized in this study due to a lack of demand estimation and generating station priority ranking. Estimating future power demand was outside of the scope of this study and therefore potential power generation was computed instead of what ‘actual’ generation might have been.

Possible future work would be to estimate a set or sets of demand scenarios in order to examine whether the LNRB will be able to meet future needs. This can be done by comparing estimated future demand to the computed potential generation reported in this study. If possible, it would be more beneficial to implement the estimated future in the ‘mass-balance’ configuration of MODSIM (Beiraghdar, 2019). By specifying the generation targets, optimization can be implemented should there be a shortage and water supply partitioning can be identified. Furthermore, with specified generation targets, wasted hydropower generation potential can be computed by quantifying water through the spillway. This analysis will be useful with identified changes in seasonal flow quantity (e.g. winter flow reduction and spring flow increase) and

extreme flows (elongation of distribution tails). Due to the flat geography of the LNRB, the head difference which drives power generation is the hydraulic head created by the difference between head and tailwater level. Wasted ‘spills’ will unnecessarily reduce the head difference and hence, generation efficiency.

Also, in this study, each of the generating stations in MODSIM was set up with a single operating rule. It is questionable whether the same operating rule applies for all flow conditions (low, normal and high flow periods). As mentioned in Beiraghdar (2019), different operating rules can be specified for flow conditions (dry, normal and wet), which can add to more closely represent actual operations to meet given demand targets.

### **6.2.2 Stationary system and operation under future conditions**

This study aimed to answer the question ‘Will the current LNRB system be able to deliver similar power generation to the historical period in the future?’ Therefore, one of the assumptions of this study was that the historical reservoir operation and infrastructures will hold constant through 1981 to 2070. In reality, this assumption is untrue, especially with the newly constructed generating station Keeyask (omitted in this study) expected to commence generating as early as 2020 and a new 500 kV transmission line to the United States expected to be in service in 2020. The historical operating rule curves at Jenpeg GS and Notigi CS, major control structures regulating approximately 90% of inflow into the LNRB, as well as the historic storage targets of generating stations within the LNRB were assumed to be representative in future scenarios.

In the light of the possible reduction in annual, winter and fall hydropower generation potential, it would be useful to further examine the following points along with MODSIM implementations suggested in Section 6.2.1:

- 1) Whether the inclusion of Keeyask GS in the future periods (2020-2070) will increase LNR generation to meet future demand
- 2) Whether different operating rule curves at Jenpeg and Notigi CS will reduce potential generation loss from increased spring and summer flow
- 3) The extent climate change will impact ice restrictions at the outlet of Lake Winnipeg, and therefore Manitoba Hydro's ability to draw water from Lake Winnipeg through the winter

In this study, a subset of the full LNRB MODSIM model, which started from Kelsey and Wuskwatim GS, was used and HYPE simulated upstream forcing for LNRB models. An extended LNRB model is available from Beiraghdar (2019)'s work, which includes Lake Winnipeg and Southern Indian Lake, and can be used for examination of the second point. In this setup, Jenpeg GS and Notigi CS will be added as additional data exchange location between hydrologic and operations models. Furthermore, in this study, the LNRB models were forced with HYPE-simulated upstream NCRB flows. Future work could utilize different upstream forcing models (e.g. in-house MH models) to force the LNRB models to compare projections.

### **6.2.3 Climate change simulation targeted for HBDB instead of LNRB**

This study leveraged from prior BaySys projects and used available 19 climate simulations selected from CMIP5 ensemble representing variability in flow signatures across the Hudson Bay Drainage Basin, which encompasses the LRNB region but does not represent the LNRB specifically. With the release of CMIP6 (Eyring et al., 2016), a possible future work is running the coupled model under a different set of climate simulations selected from CMIP6 that represent the LNRB specifically and to examine any differences in predicted conditions.

### **6.2.4 Inconsistency in internal computation time step**

The coupled model framework could not eliminate all inherent discrepancies between the models using a wrapper script. Both coupled models were able to write and read specified inflow and

outflow time series between one another however, the models showed discrepancies in reservoir storage computations due to internal computation modules inherent to each hydrologic model. For WATFLOOD the discrepancy was due to mismatch between internal routing time step of WATFLOOD (minimum time step set to 15 minutes) and MODSIM (set to daily). Transition to sub-hourly or hourly routing time step for the coupled model proved to be too computationally expensive (~20-minute computation budget for 3 years at hourly time step) and deemed infeasible for the purposes of this study. For HEC-HMS, it was due to HEC-HMS's internal decimal precision. Regardless of the specified decimal place precision, HEC-DSSVue creates 11<sup>th</sup> placed decimal number, which is only precise to the specified decimal accuracy. The added trailing decimal precision causes inconsistency in internal model precision leads to small offset in storage magnitude. The storage discrepancy did not ultimately affect the results of the coupled model runs as reservoir storage computations were checked by MODSIM. MODSIM as an operations model acted as reservoir modules of the hydrologic models in the coupled framework. HEC-HMS storage discrepancy cannot be resolved using an external wrapper script. An alternative method for WATFLOOD-MODSIM is described in Appendix C: WATFLOOD-MODSIM hourly computation.

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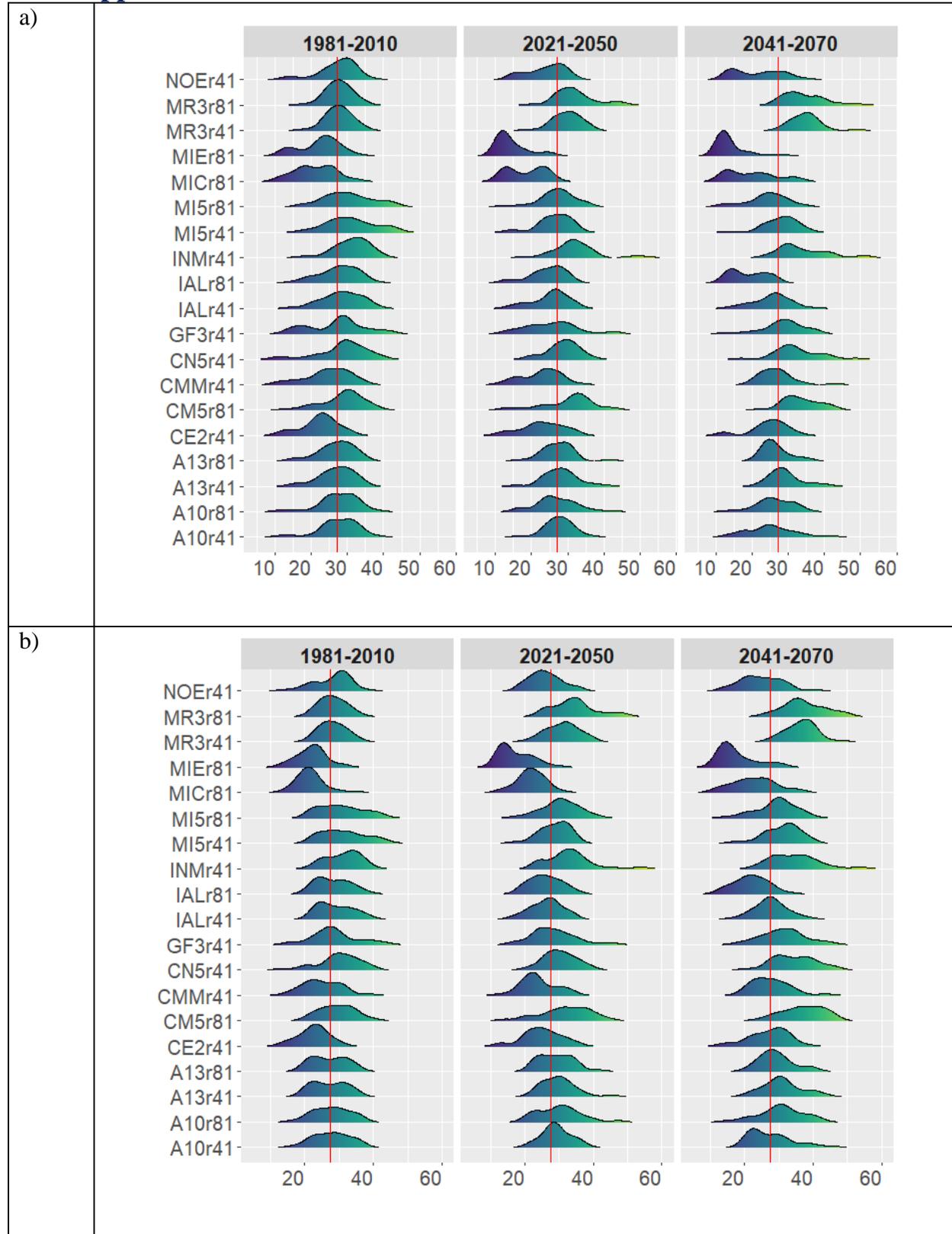
## 8.0 Appendix

### 8.1 Appendix A: Climate station overlap

Table 8-1: Summary of station overlap and grid size of 19 climate simulations. NA denote no grid overlap between stations.

<b>Name</b>	<b>Climate station overlap</b>	<b>X grid size [decimal degree]</b>	<b>Y grid size [decimal degree]</b>
A10r41	N/A	1.2500	1.8750
A10r81	N/A	1.2500	1.8750
A13r41	N/A	1.2500	1.8750
A13r81	N/A	1.2500	1.87500
CE2r41	Thompson, Cross Lake, Norway House	2.7905	2.8125
CM5r81	Thompson, Cross Lake	1.8650	1.875
CMMr41	N/A	0.7484	0.7500
CN5r41	Cross Lake, Norway House	1.4008	0.4063
GF3r41	Thompson, Cross Lake	2.0000	2.5000
IALr41	Cross Lake, Norway House	1.8947	3.7500
IALr81	Cross Lake, Norway House	1.8947	3.7500
INMr41	N/A	1.5000	2.000
MI5r41	Cross Lake, Norway House	1.4008	1.4063
MI5r81	Cross Lake, Norway House	1.4008	1.4063
MICr81	Thompson, Cross Lake, Norway House	2.7905	2.8125
MIEr81	Thompson, Cross Lake, Norway House	2.7905	2.8125
MR3r41	Cross Lake, Norway House	1.1215	1.1250
MR3r81	Cross Lake, Norway House	1.1215	1.1250
NOEr41	Cross Lake, Norway House	1.8947	2.5000

## 8.2 Appendix B: Seasonal reservoir inflow distribution at Kettle GS



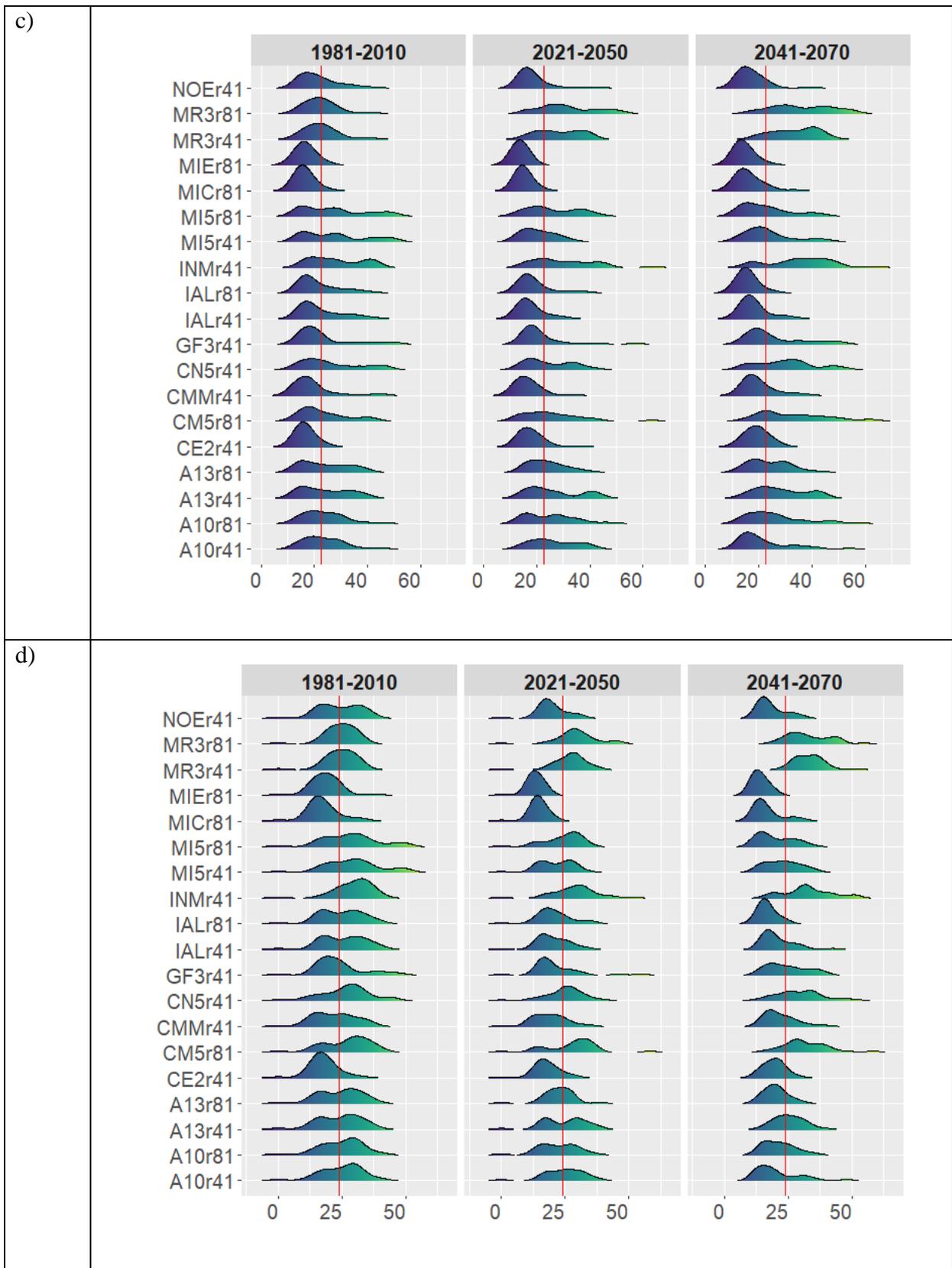


Figure 8-1: Seasonal reservoir inflow distribution at Kettle GS – a) Winter (DJF), b) Spring (MAM), c) Summer (JJA) and d) Fall (SON). Red line denotes historical ensemble mean.

### 8.3 Appendix C: WATFLOOD-MODSIM hourly computation

The coupled model framework could not eliminate all inherent discrepancy between the models using a wrapper script. Despite reading the same inflow and outflow time series as MODSIM, WATFLOOD storage computation was shown to either increase or decrease constantly over time whereas storage should have remained constant, as seen in MODSIM. This inconsistency did not affect coupled model results as storage and release computation were done within MODSIM. However, it did pose a question as the storage should have remained constant using WATFLOOD's internal storage equation (Equation 8-1).

$S_2 = S_1 + \frac{(Q_{inflow,1} + Q_{inflow,2} - qo1 - qo2)}{2}$	Equation 8-1
---	--------------

The cause of inconsistency in storage computation between WATFLOOD and MODSIM was the inconsistent internal model routing computation time step. In WATFLOOD the minimum routing time step is set to 15 minutes while MODSIM routes on the daily time step. In order to run WATFLOOD at hourly time step with MODSIM specified outflow time series, MODSIM specified time series must also be in an hourly time step. Transition to hourly routing time step for the coupled model proved to be too computationally expensive (~20-minute computation budget for 3 years) and deemed infeasible. An alternative method was tested by running WATFLOOD at an hourly time step and running MODSIM at a daily time step to avoid the computational burden. The methodology as follows:

1. Run WATFLOOD at an hourly routing time scale
2. Generated reservoir inflow time series on a daily time scale using computed hourly time series to be inputted into MODSIM. Daily inflows were calculated by taking an average of 24 hour periods.
3. Run MODSIM on the daily time scale

4. Extract MODSIM daily outflow
5. Compute modification factor by dividing MODSIM daily outflow by WATFLOOD daily outflow
6. Generate MODSIM specified hourly outflow time series by multiplying WATFLOOD hourly outflow time series by the modification factor (i.e. daily modification factor will be applied to 24-hour series each)

Using this method it was shown that:

- a) WATFLOOD storage computation no longer increases or decreases with finer specified outflow time step. WATFLOOD internal storage computed matched storage computation using specified inflow and outflow time series as shown in Figure 8-3
- b) Coupled WATFLOOD storage computation reflects both independent MODSIM and WATFLOOD storage computation as shown in Figure 8-2

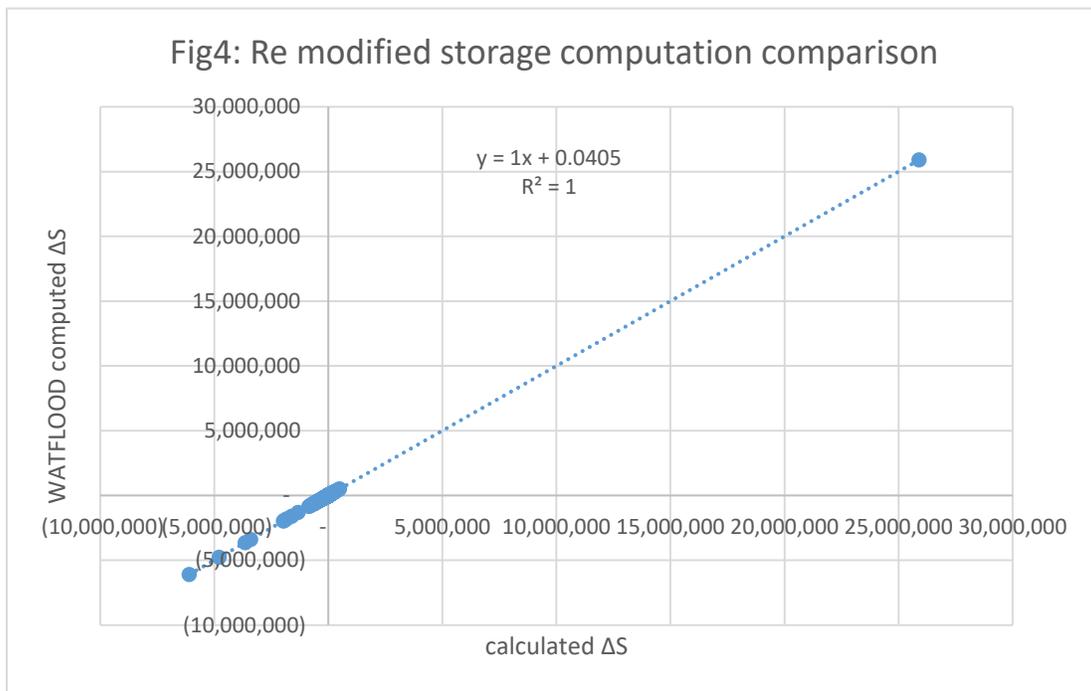


Figure 8-2: Comparison of change in storage between WATFLOOD internal computation and using specified inflow and outflow

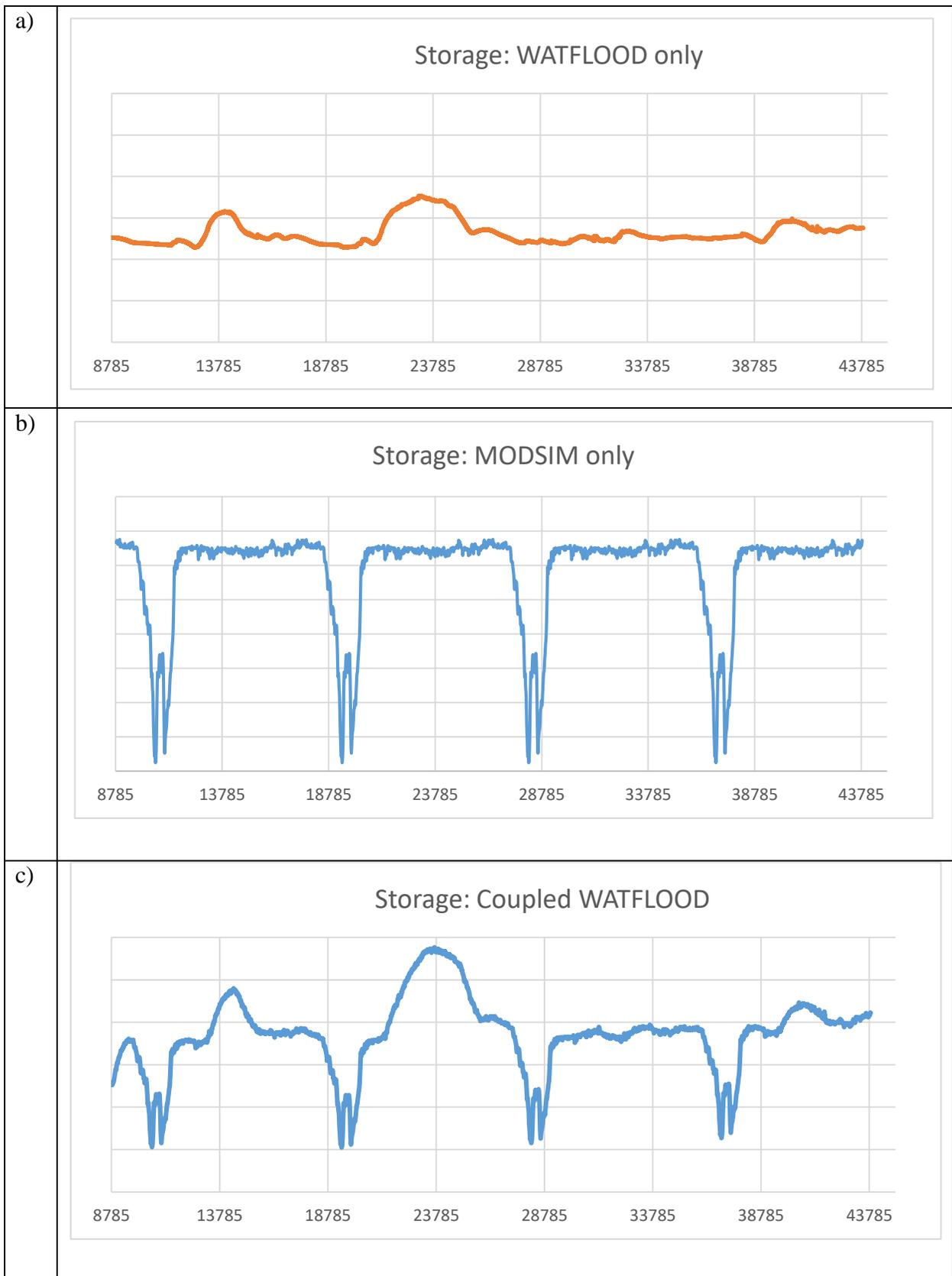


Figure 8-3: Storage comparison between a) WATFLOOD only, b) MODSIM only and c) Coupled WATFLOOD

## 8.4 Appendix D: WATFLOOD-MODSIM script

```
# Master script for coupled WATFLOOD-MODSIM framework
# Written by SJ Kim
# Contact at: kims3411@myumanitoba.ca
#
# Updated 2019.10.24
# repaced getWATFLOOD_resInflow_toMODSIM() to go with infite.xy version
# MH local flow calculation eliminated: obsolete just combined in resIn_toMODSIM()
# WATFLOOD final re-run eliminated: no point if reservoir back-calculation is off

# Purpose of this script is to:
# 1) Run WATFLOOD
# 2) Access WATFLOOD reservoir inflows
# 3) Input reservoir inflows into MODSIM .xy file
# 4) Run MODSIM.exe
# 5) Access MODSIM output.mdb file and retrieve reservoir releases
# 6) Input reservoir releases as controlled releases (WATFLOOD rel.tb0 files)
# 7) Loop until convergence criteria
#
# Ran on Python 2.7
#
# import required Python libraries
import os
import sys
import subprocess
import datetime as dt
import re
import pandas as pd
import pyodbc
import shutil
from calendar import isleap

# Loop within main()

def main():
    # set main folder address
    mainFldr_Adrss = r"C:\Users\kims3411\Desktop\LNRB_copyPast"
    os.chdir(mainFldr_Adrss)

    # On initialization, check all folder/file addresses
    addressCheck(mainFldr_Adrss)

#####          specify          address          on          main()          call:
#####
# main folder files
headerCsv_Adrss = os.getcwd() + "\\reltb0.csv"

# WATFLOOD folder
lnrb_Adrss = os.getcwd() + "\\lnrb"
resrl_Adrss = lnrb_Adrss + "\\resrl"
spl_Adrss = lnrb_Adrss + "\\results\\spl.csv"
lakeSDcsv_Adrss = lnrb_Adrss + "\\results\\lake_sd.csv"

# MODSIM folder
modsimFldr_Adrss = os.getcwd() + "\\lnrb_MODSIM_simplified"
modsimXY_name = "MODSIMMODEL_OperationaltoSJ_modSimp"
```

```

MODSIMxy_Addrss = modsimFldr_Addrss + "\\MODSIMMODEL_OperationaltoSJ_modSimp.xy"
MODSIM_Exe_Addrss = modsimFldr_Addrss + "\\MODSIMMODEL_OperationaltoSJ_modSimp Custom
Run\OperationaltoSJ.exe"
MODSIMmdb_Addrss = modsimFldr_Addrss + "\\\" + modsimXY_name + "OUTPUT.mdb;"
mdbDriver_addrss = r'Driver={Microsoft Access Driver (*.mdb, *.accdb)};DBQ= ' + MODSIMmdb_Addrss
#####
#####

# set simulation years; Exclude spin-up period
startYear = 1981
endYear = 2010
simYrs = range(startYear, endYear+1)

# looping criteria
# on initialization: convergence = False, iteration count = 0
criteriaSatisfy = False
iter_count = 0

# initialize coupled run
startT = dt.datetime.now()
print ("Coupled run starting :" + str(startT))
print "WATFLOOD run starting for iteration :" + str(iter_count)
runWATFLOOD(Inrb_Addrss, iter_count) # run WATFLOOD
getWATFLOOD_resInflow_toMODSIM(startYear, endYear, lakeSDcsv_Addrss, MODSIMxy_Addrss,
iter_count) # update reservoir inflow in MODSIM.xy

print "MODSIM run starting for iteration :" + str(iter_count)
runMODSIM(modsimFldr_Addrss, modsimXY_name, MODSIMxy_Addrss, MODSIM_Exe_Addrss, iter_count)
# runs MODSIM
[MODSIM_resOutDF, resConvDF] = getMODSIM_releases(mdbDriver_addrss, iter_count) # get MODSIM
release TS

# loop until convergence
while not criteriaSatisfy:
    iter_count += 1
    print "\nnumber of iteration : " + str(iter_count)
    print "time : " + str(dt.datetime.now())

    resConvDF_old = resConvDF*1 # make a copy

    write_reltb0(startYear, endYear, resrl_Addrss, headerCsv_Addrss, MODSIM_resOutDF, simYrs) # prep reltb0
for WATFLOOD
    print "WATFLOOD run starting for iteration :" + str(iter_count)
    runWATFLOOD(Inrb_Addrss, iter_count)
    getWATFLOOD_resInflow_toMODSIM(startYear, endYear, lakeSDcsv_Addrss, MODSIMxy_Addrss,
iter_count) # update MODSIM.xy

    print "MODSIM run starting for iteration :" + str(iter_count)
    runMODSIM(modsimFldr_Addrss, modsimXY_name, MODSIMxy_Addrss, MODSIM_Exe_Addrss,
iter_count) # runs MODSIM
    [MODSIM_resOutDF, resConvDF] = getMODSIM_releases(mdbDriver_addrss, iter_count) # get MODSIM
release TS
    criteriaSatisfy = convergenceChecker(resConvDF, resConvDF_old)

print "\n*****"

```

```

print "\nnumber of iteration : " + str(iter_count)
print "Star time:  " + str(startT)
print "Finish time:  " + str(dt.datetime.now())
print "Run Duration: " + str(dt.datetime.now()-startT)
print "Run Complete"

return

def addressCheck(mainFldr):
    # Purpose :
    # a) checks all folder and file locations prior to the main code
    # b) flags if wrong/missing address - error message popup
    #
    # Required variable: Main directory with WATFLOOD and MODSIM files
    #

    # set main folder address as main directory
    os.chdir(mainFldr)

    # main folder files
    headerCsv_Addrss = os.getcwd() + "\\reldb0.csv"

    # WATFLOOD folder
    lnrb_Addrss = os.getcwd() + "\\lnrb"
    reslr_Addrss = lnrb_Addrss + "\\reslr"
    spl_Addrss = lnrb_Addrss + "\\results\\spl.csv"
    lakeSDcsv_Addrss = lnrb_Addrss + "\\results\\lake_sd.csv"

    # MODSIM folder
    modsimFldr_Addrss = os.getcwd() + "\\lnrb_MODSIM_simplified"
    MODSIMxy_Addrss = modsimFldr_Addrss + "\\MODSIMMODEL_OperationaltoSJ_modSimp.xy"
    MODSIM_Exec_Addrss = modsimFldr_Addrss + "\\MODSIMMODEL_OperationaltoSJ_modSimp Custom
Run\\OperationaltoSJ.exe"

#####
#

    ## check if addresses exists
    chk_list = [os.path.isdir(mainFldr), os.path.isfile(headerCsv_Addrss), os.path.isdir(lnrb_Addrss),
                os.path.isdir(reslr_Addrss),
                os.path.isfile(spl_Addrss), os.path.isfile(lakeSDcsv_Addrss), os.path.isdir(modsimFldr_Addrss),
                os.path.isfile(MODSIMxy_Addrss),
                os.path.isfile(MODSIM_Exec_Addrss)]
    addrss_list = ["main folder", "header.csv", "lnrb folder", "reslr folder", "spl.csv", "lake_sd.csv",
                  "modsim folder", "xy file", "modsimCustom.exe"]

    # if any false in chk_list (i.e. missing)
    if not all(chk_list):
        missing_idx = [i for i, val in enumerate(chk_list) if not val]
        print ("Please check the location of the following files...")
        for i in missing_idx:
            print ("\t" + addrss_list[i])
        sys.exit("Please double check missing folder/file addresses. Exiting...")

# Part 1: Run WATFLOOD

```

```

def runWATFLOOD(addrss_lnrb, cntNum):
    # Purpose: Run WATFLOOD using cmd line
    #
    # Variables:
    # addrss_lnrb = Main WATFLOOD directory address with splx.exe
    # cntNum = coupled iteration number; To show iteration count for debugging purposes should module fail

    # check folder/directory exists
    if os.path.isdir(addrss_lnrb):
        os.chdir(addrss_lnrb)
        try:
            wat_startTime = dt.datetime.now()
            p = subprocess.Popen("splx") #runs splx
            (outValue, errValue) = p.communicate()
            sp_time = dt.datetime.now() - wat_startTime

            if sp_time.seconds > 240:
                # even if WATFLOOD doesn't run, exit code = 0 (WATFLOOD programed to safe crash)
                # WATFLOOD ran for more than 4 min: Assume no error
                print ("WATFLOOD run successful, returned: %s" % (str(outValue)))
                print "WATFLOOD Run Duration: " + str(dt.datetime.now() - wat_startTime)

                # Make copies of WATFLOOD results files to avoid files being overwritten
                os.chdir(addrss_lnrb+"\\results")
                shutil.copy(os.getcwd() + "\\lake_sd.csv", os.getcwd()+"\\lake_sd_v" + str(cntNum) + ".csv")
                shutil.copy(os.getcwd() + "\\stats.txt", os.getcwd() + "\\stats_v" + str(cntNum) + ".txt")
                shutil.copy(os.getcwd() + "\\spl.csv", os.getcwd() + "\\spl_v" + str(cntNum) + ".csv")
            else:
                # error during run
                msg = "WATFLOOD run failed: iteration %s, exit-code = %d, error = %s" % (str(cntNum), p.returncode,
str(errValue))
                sys.exit(msg)
            except OSError as e:
                # couldn't run the program
                sys.exit("failed to execute program WATFLOOD. Iteration:%s. Error: %s" % (str(cntNum), str(e)))
        else:
            # exit since directory not found
            exitMsg = "Iteration: " + str(cntNum)+ \
                "Error in runWATFLOOD()" + \
                "\nlnrb folder address doesn't exist\nPlease double check. Exiting..."
            sys.exit(exitMsg)
    return

# Part 2 & 3: Access WATFLOOD reservoir inflows and input data to MODSIM
def getWATFLOOD_resInflow_toMODSIM(startYr, endYr, addrss_lakeSDcsv, addrss_MODSIMxy, cntNum):
    # purpose: Format WATFLOOD reservoir inflows to input into MODSIM.xy
    # 1) extract reservoir data from WATFLOOD lake_sd.csv
    # 2) input reservoir inflow, calculate adjustment factors for mass balance
    # 3) rewrite MODSIM.xy file
    #
    # Variables :
    # startYr = simulation start year, excluding spin-up period; MODSIM do not require spin-up period
    # endYr = simulation end year
    # addrss_lakeSDcsv = directory location of WATFLOOD lake_sd.csv file; generally in WATFLOOD/results folder
    # addrss_MODSIMxy = directory location of MODSIM basin.xy file

```

```

# cntNum = coupled iteration number; To show iteration count for debugging purposes should module fail

# check .xy file exists in folder path
if os.path.isfile(addrss_lakeSDcsv) and os.path.isfile(addrss_MODSIMxy):
    # Step 1: Extract corresponding reservoir inflow from WATFLOOD lake_sd.csv
    #
    # Dataframe prep
    start_date = dt.datetime(startYr, 01, 01)
    curr_date = start_date
    #           yr, mm, d, hr, min, sec
    end_date = dt.datetime(endYr, 12, 31, 23, 59, 59)
    step = dt.timedelta(days=1)

    date_series = []
    while curr_date < end_date:
        date_series.append(curr_date.strftime('%m/%d/%Y %H:%M:%S'))
        curr_date += step

    # make date stamp column
    kettle_cap = pd.DataFrame(data=date_series, columns=['Dates'])
    split_cap = pd.DataFrame(data=date_series, columns=['Dates'])
    wuskDF = pd.DataFrame(data=date_series, columns=['Dates'])
    kelDF = pd.DataFrame(data=date_series, columns=['Dates'])
    splitFT_DF = pd.DataFrame(data=date_series, columns=['Dates'])
    kettleFT_DF = pd.DataFrame(data=date_series, columns=['Dates'])

    # eliminate spin-up period time series from WATFLOOD data
    # check if spin-up year was a leap year or not
    spinupYr = startYr-1
    if isleap(spinupYr):
        skiprows = 366
    else:
        skiprows = 365

    # read lake_sd.csv
    df = pd.read_csv(addrss_lakeSDcsv)

    # extract reservoir inflow from specified column of lake_sd.csv
    # add 100 (= 1 m3/s flow) as buffer for MODSIM stability
    kettle_cap['release'] = (df.iloc[skiprows:, 3]*100 + 100).reset_index(drop=True).astype(int) # Kettle Channel
cap
    split_cap['release'] = (df.iloc[skiprows:, 24] * 100 + 100).reset_index(drop=True).astype(
int) # split Channel cap
    wuskDF['release'] = (df.iloc[skiprows:, 10]*100).reset_index(drop=True).astype(int) # Wuskwatim Lake
inflow
    kelDF['release'] = (df.iloc[skiprows:, 129]*100).reset_index(drop=True).astype(int) # kelsey forebay
    splitFT_DF['release'] = (df.iloc[skiprows:, 24] * 100).reset_index(drop=True).astype(int) # split FlowThru
Demand; split lake inflow
    kettleFT_DF['release'] = (df.iloc[skiprows:, 3]*100).reset_index(drop=True).astype(int) # kettleGS FlowThru
Demand; kettleGS inflow

    # convert to string and ascii format
    kettle_inflow = kettle_cap.to_string(header=False, index=False)
    split_inflow = split_cap.to_string(header=False, index=False)
    wusk_inflow = wuskDF.to_string(header=False, index=False)
    kel_inflow = kelDF.to_string(header=False, index=False)

```

```
split_flowThru = splitFT_DF.to_string(header=False, index=False)
kettle_flowThru = kettleFT_DF.to_string(header=False, index=False)
```

```
kettle_inflow = '\n' + kettle_inflow
split_inflow = '\n' + split_inflow
wusk_inflow = '\n' + wusk_inflow
kel_inflow = '\n' + kel_inflow
split_flowThru = '\n' + split_flowThru
kettle_flowThru = '\n' + kettle_flowThru
```

```
kettle_inflow_ascii = kettle_inflow.encode('utf-8')
split_inflow_ascii = split_inflow.encode('utf-8')
wusk_inflow_ascii = wusk_inflow.encode('utf-8')
kel_inflow_ascii = kel_inflow.encode('utf-8')
split_flowThru_ascii = split_flowThru.encode('utf-8')
kettle_flowThru_ascii = kettle_flowThru.encode('utf-8')
```

```
# Step 2: Rewrite MODSIM reservoir inflow in basin.xy file
# basin.xy file = text file therefore search using regex and replace
```

```
with open(addrss_MODSIMxy, 'r') as xy_file:
```

```
    xy_lines = xy_file.read()
```

```
    # print xy_lines
```

```
    kettleLinkReg = re.compile(
```

```
        '(?<=lname Kettle_nudge_Kettle\ndescription \nlnum 3\nfromnum 42\ntonum 15\nlcost -
20\nmaxCap\nvariesbyyear True\nunits cms)(r?\n)'
```

```
        '.*?'
```

```
        '(?=\r?\nselect)', re.DOTALL)
```

```
    splitLinkReg = re.compile(
```

```
        '(?<=lname Split_nudge_Splitlake\ndescription \nlnum 43\nfromnum 45\ntonum 12\nlcost -
20\nmaxCap\nvariesbyyear True\nunits cms)(r?\n)'
```

```
        '.*?'
```

```
        '(?=\r?\nselect)', re.DOTALL)
```

```
    wuskLinkReg = re.compile(
```

```
        '(?<=name Wuskwatim_US\ndesc \nnum 34\nntype 2\nout 26\nntsinflow\nvariesbyyear True\nunits
cms)(r?\n)'
```

```
        '.*?'
```

```
        '(?=\r?\npos)', re.DOTALL)
```

```
    kelLinkReg = re.compile(
```

```
        '(?<=name Kelsey_US\ndesc \nnum 9\nntype 2\nout 1\nntsinflow\nvariesbyyear True\nunits cms)(r?\n)'
```

```
        '.*?'
```

```
        '(?=\r?\npos)', re.DOTALL)
```

```
    split_FTReg = re.compile(
```

```
        '(?<=name Split_FT\ndesc \nnum 44\nntype 3\nin 42\npos\n0 546.9478\n1 759.6472\nlabelpos\n0
513.5333\n1 751.9333\nselect 0\npcapUnits 1000 m\xc2\x3/day\ndemr\n0 -20\nidstrmx\n0 45\nidstrmfr\n1-9
0\npdstrm 29\nntsdemand\nvariesbyyear True\nunits cms)(r?\n)'
```

```
        '.*?'
```

```
        '(?=\r?\nnode)', re.DOTALL)
```

```
    kettle_FTReg = re.compile(
```

```
        '(?<=name kettle_FT\ndesc \nnum 41\nntype 3\nin 40\npos\n0 842.4666\n1 279.0667\nlabelpos\n0
842.4666\n1 287.5667\nselect 0\npcapUnits 1000 m\xc2\x3/day\ndemr\n0 -20\nidstrmx\n0 42\nidstrmfr\n1-9
0\npdstrm 39\nntsdemand\nvariesbyyear True\nunits cms)(r?\n)'
```

```
        '.*?'
```

```
        '(?=\r?\nnode)', re.DOTALL)
```

```
    startReg = re.compile(
```

```
        '(?<=startingDate 01/01/)'
```

```

'(.*)'
'(?=\r?\nendingDate)', re.DOTALL)
endReg = re.compile(
'(?<=endingDate 01/01/)'
'(.*)'
'(?=\r?\naccrualDate)', re.DOTALL)

# check if regex pattern found
kettleLink_Find = re.search(kettleLinkReg, xy_lines)
splitLink_Find = re.search(splitLinkReg, xy_lines)
wuskFind = re.search(wuskLinkReg, xy_lines)
kelFind = re.search(kelLinkReg, xy_lines)
splitFT_Find = re.search(split_FTReg, xy_lines)
kettleFT_Find = re.search(kettle_FTReg, xy_lines)

if kettleLink_Find and splitLink_Find and wuskFind and kelFind and kettleFT_Find and splitFT_Find:
    # substitute the inflow in the matching pattern
    new_lines = re.sub(kettleLinkReg, kettle_inflow_ascii, xy_lines) # Kettle Link max cap
    new_lines = re.sub(splitLinkReg, split_inflow_ascii, new_lines) # Split Link max cap
    new_lines = re.sub(wuskLinkReg, wusk_inflow_ascii, new_lines) # Wuskwat inflow
    new_lines = re.sub(kelLinkReg, kel_inflow_ascii, new_lines) # Kelsey inflow
    new_lines = re.sub(split_FTReg, split_flowThru_ascii, new_lines) # kettle FlowThru
    new_lines = re.sub(kettle_FTReg, kettle_flowThru_ascii, new_lines) # kettle FlowThru

    new_lines = re.sub(startReg, str(startYr) + " 00:00:00", new_lines) # simulation starting date
    new_lines = re.sub(endReg, str(endYr + 1) + " 00:00:00", new_lines) # simulation ending date

    # check .xy file exists in folder path
    if os.path.isfile(addrss_MODSIMxy):
        with open(addrss_MODSIMxy, 'w') as xy_check_file:
            xy_check_file.write(new_lines)

        print "Finished rewriting Modsim.xy file with WATFLOOD run"
    else:
        sys.exit("Modsim.xy file does not exist in specified path. Please double check. Exiting...")
else:
    exitMsg = "Iteration: " + str(cntNum) + \
        "\nError in getLocalQ_toMODSIM()\nregex pattern not found in the .xy file.\n" + \
        "\nkettleGS channel link found: " + str(kettleLink_Find) + \
        "\nsplit lake channel link found: " + str(splitLink_Find) + \
        "\nWuskwatimGS inflow node: " + str(wuskFind) + \
        "\nKelssyGS inflow node found: " + str(kelFind) + \
        "\nsplit FlowThru node found: " + str(splitFT_Find) + \
        "\nkettle FlowThru node found: " + str(kettleFT_Find) + \
        "\nPlease double check regex pattern. Exiting..."
    sys.exit(exitMsg)
else:
    MIA_exitMsg = "Iteration: " + str(cntNum) + \
        "\nError in getWATFLOOD_resInflow_toMODSIM()\n" + \
        "\nlake.csv file found" + str(os.path.isfile(addrss_lakeSDcsv)) + \
        "\nModsim.xy file found" + str(os.path.isfile(addrss_MODSIMxy)) + \
        "\nPlease double check. Exiting..."
    sys.exit(MIA_exitMsg)
return

```

# Part 4: Run MODSIM

```

def runMODSIM(addrss_modsimFldr, xyName, addrss_xy, addrss_MODSIMexe, cntNum):
    # Purpose: Run MODSIM.exe
    #
    # Variables :
    # addrss_modsimFldr = directory location of MODSIM.xy & MODSIM dll
    # xyName = name of MODSIM basin.xy file
    # addrss_xy = address of MODSIM basin .xy file
    # addrss_MODSIMexe = address of MODSIM.exe file
    # cntNum = coupled iteration number; To show iteration count for debugging purposes should module fail

    # check folder/directory exists
    if os.path.isfile(addrss_MODSIMexe) and os.path.isfile(addrss_xy) and os.path.isdir(addrss_modsimFldr):
        try:
            cmdLine = addrss_MODSIMexe + " " + addrss_xy
            mod_startTime = dt.datetime.now()
            p = subprocess.Popen(cmdLine)
            (outValue, errValue) = p.communicate()
            print p.returncode
            if p.returncode ==0:
                # no error
                print ("MODSIM run successful, returned: %s" % (str(outValue)))
                print "MODSIM Run Duration: " + str(dt.datetime.now() - mod_startTime)
                os.chdir(addrss_modsimFldr)
                shutil.copy(os.getcwd() + "\\\" + xyName + "OUTPUT.mdb", os.getcwd()+ "\\\" + xyName + "OUTPUT_v"
+ str(cntNum) + ".mdb")
            else:
                # error during run
                print ("MODSIM run failed: iteration %s, exit-code = %d, error = %s" % (str(cntNum), p.returncode,
str(errValue)))
                exitMsg = "Error in runMODSIM()\nFailed to execute program MODSIM. Iteration:%s." % (str(cntNum))
                sys.exit(exitMsg)
            except OSError as e:
                # couldn't run the program
                exitMsg = "Error in runMODSIM()\nFailed to execute program MODSIM. Iteration:%s. Error: %s" %
(str(cntNum),str(e))
                sys.exit(exitMsg)
        else:
            exitMsg = "Iteration: " + str(cntNum) + \
                "\nError in runMODSIM()\nFile & folder address must have been changed during run" + \
                "\nModsim.exe file found: " + str(os.path.isfile(addrss_MODSIMexe)) + \
                "\nModsim.xy file found: " + str(os.path.isfile(addrss_xy)) + \
                "\nmain folder found: " + str(os.path.isfile(addrss_modsimFldr)) + \
                "\nError in runMODSIM()\nFile & folder address must have been changed during run" + \
                "\nPlease double check file & folder address. Exiting..."
            sys.exit(exitMsg)
    return

# Part 5: Access MODSIM output.mdb file and retrieve reservoir releases
def getMODSIM_releases(addrss_ModsimMdb, cntNum):
    # Purpose: Connect and retrieve MODSIM reseroir release
    #
    # Variables :
    # addrss_ModsimMdb = address of MODSIM output file: access.mdb file
    # cntNum = coupled iteration number; To show iteration count for debugging purposes should module fail

    try:

```

```

# in order to access access.mdb file, Database Connection must be established
conn = pyodbc.connect(addrss_ModsimMdb)

# query and retrieve specified MODSIM-DSS releases
# NNo may be different under different setup; please check prior to running
StphnQuery = "SELECT * FROM RESOutput WHERE NNo = 15"
KlsyQuery = "SELECT * FROM RESOutput WHERE NNo = 10"
WuskQuery = "SELECT * FROM RESOutput WHERE NNo = 1"

# MODSIM in flow are in units of [1000 m3/d] and HEC-HMS flow is in units of [m3/s]
# make unit conversion to m3/s
StphnRel = (pd.read_sql(StphnQuery, conn).filter(items=['Dws_Rel'])*1000/86400
KlsyRel = (pd.read_sql(KlsyQuery, conn).filter(items=['Dws_Rel'])*1000/86400
WuskRel = (pd.read_sql(WuskQuery, conn).filter(items=['Dws_Rel'])*1000/86400
conn.close()
except pyodbc.Error as exn:
    sqlstate = exn.args[1]
    exitMsg = "Iteration: " + str(cntNum) + \
        "Error in getMODSIM_releases()" + \
        str(sqlstate)+ \
        "\nError in querying MODSIM releases: Please check mdb driver connection/address. Exiting..."
    sys.exit(exitMsg)

# check that length of all release dataframes are the same
if len(StphnRel) != len(KlsyRel) or len(StphnRel) != len(WuskRel):
    len_exitMsg = "Iteration: " +str(cntNum)+\
        "\nError in getMODSIM_releases()\nrelease time series do not match"+\
        "\nPlease check the MODSIM output.mdb"
    sys.exit(len_exitMsg)

# change column name from 'Dws_Rel' to specific WATFLOOD reservoir id number
# WATFLOOD id number may change depending on WATFLOOD configuration; please check prior to running
StphnRel.columns = ['1']
KlsyRel.columns = ['19']
WuskRel.columns = ['2']

# create dataframe of MODSIM reservoir release to export for convergence check
convgDF = StphnRel
convgDF = convgDF.join([WuskRel])
convgDF = convgDF.join([KlsyRel])

# create dataframe to match WATFLOOD reservoir file - rel.tb0
relDF = KlsyRel
# create empty columns for natural lakes; no releases specified for natural lakes
# natural lakes are in columns 3 to 19 for this setup
for colNum in range(3, 19):
    relDF.insert(0, str(colNum), '-9999')

## append controlled releases from Stephens and Wuskwatim
relDF2 = StphnRel.join([WuskRel])
relDF3 = relDF2.join(relDF)
relDF3.insert(0, str(0), '') # extra column for rel.tb0 header

print "Got Modsim release"
return relDF3, convgDF

```

```

# Part 6: Input reservoir releases as controlled releases (WATFLOOD rel.tb0 files)
def write_relTB0(startYr, endYr, addrss_resrl_fldr, addrss_headerCsv, MODSIM_rel3, simYrs):
    # Purpose: Create WATFLOOD rel.tb0 files using MODSIM release dataframe
    #
    # Variables :
    # startYr = simulation start year, excluding spin-up period; MODSIM do not require spin-up period
    # endYr = simulation end year
    # addrss_resrl_fldr = directory location of WATFLOOD resrl
    # addrss_headerCsv = address of csv file with rel.tb0 header
    # MODSIM_rel3 = WATFLOOD release dataframe created from "getMODIMS_releases()" sub-module
    # simYrs = simulation year range

    # Create header from csv (due to formatting) & append releases from MODSIM
    # filter = true; do not replace missing as NaN
    if os.path.isdir(addrss_resrl_fldr) and os.path.isfile(addrss_headerCsv):
        csvDF = pd.read_csv(addrss_headerCsv, na_filter=False)
        csvDF = csvDF.loc[0:34] # csvDF contain header rows until "EndHeader:"

        # in order to append dataframes together, header must be identical
        # get header names from csvDF & rename relDF3
        csvHeader = list(csvDF.columns.values)
        Mod_relDF = MODSIM_rel3.copy()
        Mod_relDF.columns = csvHeader

        Mod_relDF['Dates'] = pd.date_range(start=str(startYr)+"01/01", end=str(endYr)+"12/31") # add date column
        csvDF['Dates'] = "" # add date column for csvDF as well (if added before, can't append)

        # loop to create separate yyyy_rel.tb0 files
        for yrs in simYrs: # python range does not include last number i.e. only makes files till 2017
            selectDF = Mod_relDF[Mod_relDF['Dates'].dt.year == yrs] # do not include dates
            finalDF = csvDF.append(selectDF, ignore_index=True)
            formatDF = finalDF.iloc[:,0:20]
            relTB0_addrss = addrss_resrl_fldr + "\\\" + str(yrs) + "0101_rel.tb0"
            with open(relTB0_addrss, "w") as f:
                f.write(formatDF.to_string(index=False))

        print "Finished writing MODSIM release as rel.tb0"
    else:
        exitMsg = "Error in write_relTB0" + \
            "\nheader csv found: " + str(os.path.isfile(addrss_headerCsv)) + \
            "\nFile/directory must have changed during run" + \
            "\nlr results folder found: " + str(addrss_resrl_fldr) + \
            "\nPlease double check file / directory address"
        sys.exit(exitMsg)
    return

def convergenceChecker(Convg_relDF, Convg_relDF_old):
    # Purpose: Check MODSIM reservoir release convergence using RSR metric; return TRUE/FALSE
    #
    # Variables :
    # Convg_relDF = MODSIM release dataframe created from "getMODIMS_releases()" sub-module
    # Convg_relDF_old = Convg_relDF from previous iteration

    # check convergece from previous iteration - RSR (Moriassi et al.2007)
    # compare relDF from last run (need to keep a copy)
    relSTD = Convg_relDF_old.std()

```

```

diffDF = Convg_reIDF.sub(Convg_reIDF_old)
rowNum = diffDF.shape[0]

relRMSE = (((diffDF.pow(2)).sum()).div(rowNum)).pow(0.5)
relRSR = relRMSE / relSTD

# column indexing same as WATFLOOD lake_sd.csv
# 1 = Stephen's lake
# 2 = Wuskwatim lake
# 3 = Kelsey forebay
if relRSR['1'] <= 0.05 and relRSR['2'] <= 0.05 and relRSR['19'] <= 0.05:
    convergeCheck = True
else:
    convergeCheck = False

print "convergence met: " + str(convergeCheck)
print "Kettle GS RSR :" + str(relRSR['1'])
print "Wuskwatim GS RSR :" + str(relRSR['2'])
print "Kelsey GS RSR :" + str(relRSR['19'])

return convergeCheck

main()

```

## 8.5 Appendix E: HEC-HMS-MODSIM data exchange script

### Part 1: Master script

```
# Master script for coupled HecHMS-MODSIM framework
# Written by SJ Kim
# Contact at kims3411@myumanitoba.ca
#
# Updated 2019.10.30
# updated from HEC_masterScript_v1
# HEC back calculation issue resolved
# exportAll.py updated to export excluding spin-up; reservoirQ_toMODSIM() no longer has spinup skip
# lnrb_simplified.dss & QtoDSS.py updated
#
# Ran on Python 3.7
# Purpose of this script is to:
# 1) Run HEC-HMS
# 2) Access HEC-HMS reservoir inflows (calls VueDSS.exe and Jython script to export inflows)
# 3) Set HecHMS reservoir inflows into MODSIM .xy file as max link capacities
# 4) Run MODSIM-DSS (referred to as MODSIM)
# 5) Access MODSIM output.mdb file and retrieve reservoir releases
# 6) Input reservoir releases as controlled releases (HEC-DSSVue .dss files)
# 7) Loop until convergence criteria

# import required modules
import os
import sys
import subprocess
import datetime as dt
import re
import pandas as pd
import pyodbc
import shutil
from calendar import isleap

# loop within main()
def main():
    # set main folder
    oldGCMname = "LNRB_MR3r81"
    newGCMname = "LNRB_NOEr41"
    mainFldr_addrss = r"C:\Users\kims3411\Desktop\Cpld_HEC_hisGCM"
    os.chdir(mainFldr_addrss)

    # On initializatio, check all required file addresses
    addressCheck(mainFldr_addrss)

#####          specify          address          on          main()          call:
#####
# HEC-HMS
hechms_Adrss = os.getcwd() + "\\HecHMS"

# HecDSS-VUE
hecdsssVue_Adrss = os.getcwd() + "\\HecDSSVue"

# MODSIM folder
modsim_Adrss = os.getcwd() + "\\MODSIM_simplified_2019Oct"
xyFile_name = "MODSIMMODEL_OperationaltoSJ_modSimp"
```

```

modsimEXE_Adrss = modsim_Adrss + "\\MODSIMMODEL_OperationaltoSJ_modSimp Custom
Run\\OperationaltoSJ.exe"
MODSIMmdb_Adrss = modsim_Adrss + "\\\" + xyFile_name + "OUTPUT.mdb;"
mdbDriver_adrss = r'Driver={Microsoft Access Driver (*.mdb, *.accdb)};DBQ= ' + MODSIMmdb_Adrss

# Scripts folder
DSSscript_Adrss = os.getcwd() + "\\DSS_coupling_script"
hecCmdScript_Adrss = DSSscript_Adrss + "\\LNRB_compute.script"
QtoDSS_Script_Adrss = DSSscript_Adrss + "\\DSSVue_resOutQ_toDSS.py"
exportAllScript_Adrss = DSSscript_Adrss + "\\DSSVue_exportAllQ.py"

#####
#####

# set simulation years
startYear = 1981
endYear = 2010

## change hec GCM folder
jython_editor(newGCMname, oldGCMname, DSSscript_Adrss)

# looping criteria
# on initialization: convergence = False, interation count = 0
criteriaSatisfy = False
iter_count = 0

# initialize coupled run
startT = dt.datetime.now()
runHECHMS(hechms_Adrss, hecCmdScript_Adrss, iter_count)

saveHECHMS_results(hecDSSVue_Adrss,exportAllScript_Adrss,modsim_Adrss,iter_count) # export and save
12 obs gauge simulation results fromm .dss
getHECHMS_resInflow_toMODSIM(startYear, endYear, modsim_Adrss, xyFile_name, iter_count) # update
MODSIM.xy
timeMOD_start = dt.datetime.now()
runMODSIM(modsim_Adrss, xyFile_name, modsimEXE_Adrss, iter_count)
timeMOD_end = dt.datetime.now()
MODSIM_resOutDF = getMODSIM_releases(mdbDriver_adrss, iter_count)

# loop until convergence
while not criteriaSatisfy:
    iter_count += 1
    print("\nnumber of iteration : " + str(iter_count))
    print("time : " + str(dt.datetime.now()))

MODSIM_resOutDF_old = MODSIM_resOutDF*1 # make a copy resConvDF.copy() makes 'instancemethod'
type object which can't be used in convergenceChecker.

updateMODSIM_releases(hecDSSVue_Adrss, QtoDSS_Script_Adrss, iter_count)# updates DSS with
MODSIM releases (using Jython script)
runHECHMS(hechms_Adrss, hecCmdScript_Adrss, iter_count)

saveHECHMS_results(hecDSSVue_Adrss, exportAllScript_Adrss, modsim_Adrss, iter_count)
getHECHMS_resInflow_toMODSIM(startYear, endYear, modsim_Adrss, xyFile_name, iter_count)
runMODSIM(modsim_Adrss, xyFile_name, modsimEXE_Adrss, iter_count)

```

```

MODSIM_resOutDF = getMODSIM_releases(mdbDriver_addrss, iter_count)
criteriaSatisfy = convergenceChecker(MODSIM_resOutDF, MODSIM_resOutDF_old, iter_count)

print("\n*****")
print("\nnumber of iteration : " + str(iter_count))
print("Star time: " + str(startT))
print("Finish time: " + str(dt.datetime.now()))
print("Run Duration: " + str(dt.datetime.now() - startT))
# print("MODSIM 30 year Run Duration: " + str(timeMOD_end - timeMOD_start))
print("Run Complete")

return

def addressCheck(mainFldr):
# Purpose :
# a) checks all folder and file locations prior to the main code
# b) flags if wrong/missing address - error message popup
#
# Required variable: Main directory with HEC-HMS and MODSIM files

# set main folder address as main directory
os.chdir(mainFldr)

# HEC-HMS folder
hechms_Adrss = os.getcwd() + "\\HecHMS"

# HEC-DSS-VUE folder
hecdssVue_Adrss = os.getcwd() + "\\HecDSSVue"

# MODSIM folder
modsimFldr_Adrss = os.getcwd() + "\\MODSIM_simplified_2019Oct"
MODSIMxy_Adrss = modsimFldr_Adrss + "\\MODSIMMODEL_OperationaltoSJ_modSimp.xy"
MODSIM_Exe_Adrss = modsimFldr_Adrss + "\\MODSIMMODEL_OperationaltoSJ_modSimp Custom
Run\\OperationaltoSJ.exe"

# Scripts folder
DSSscript_Adrss = os.getcwd() + "\\DSS_coupling_script"
hecCmdScript_Adrss = DSSscript_Adrss + "\\LNRB_compute.script"
QtoDSS_Script_Adrss = DSSscript_Adrss + "\\DSSVue_resOutQ_toDSS.py"
exportAllScript_Adrss = DSSscript_Adrss + "\\DSSVue_exportAllQ.py"

#####
#

## check if addresses exists
chk_list = [os.path.isdir(mainFldr), os.path.isdir(hechms_Adrss), os.path.isdir(hecdssVue_Adrss),
os.path.isdir(modsimFldr_Adrss), os.path.isfile(MODSIMxy_Adrss),
os.path.isfile(MODSIM_Exe_Adrss), os.path.isdir(DSSscript_Adrss),
os.path.isfile(hecCmdScript_Adrss), os.path.isfile(QtoDSS_Script_Adrss),
os.path.isfile(exportAllScript_Adrss)]
addrss_list = ["main folder", "HecHMS folder", "HecDSSVue folder",
"modsim folder", "xy file",
"modsim exe", "DSS coupling scipt folder",
"HecHMS cmd file", "DSSVue resQ import py",
"DSSVue resQ export py"]

```

```

# if any false in chk_list (i.e. missing)
if not all(chk_list):
    missing_idx = [i for i, val in enumerate(chk_list) if not val]
    for i in missing_idx:
        print("t" + addrss_list[i])
    exitMsg = "Error in AddressCheck()\nPlease check the location of the following files. Exiting..."
    sys.exit(exitMsg)

def jython_editor(newGCM, oldGCM, fldr_addrss):
    computeScript_addrss = fldr_addrss + "\\LNRB_compute.script"
    with open(computeScript_addrss, 'r') as comptFile:
        scriptCmd = comptFile.read()
        scriptCmd = scriptCmd.replace(oldGCM, newGCM)
    with open(computeScript_addrss, 'w') as newComptFile:
        newComptFile.write(scriptCmd)

    expprtPY_addrss = fldr_addrss + "\\DSSVue_exportAllQ.py"
    with open(expprtPY_addrss, 'r') as expPyFile:
        expprtCmd = expPyFile.read()
        expprtCmd = expprtCmd.replace(oldGCM, newGCM)
    with open(expprtPY_addrss, 'w') as newExpprtPyFile:
        newExpprtPyFile.write(expprtCmd)

    dssImprt_addrss = fldr_addrss + "\\DSSVue_resOutQ_toDSS.py"
    with open(dssImprt_addrss, 'r') as imprtFile:
        imprtCmd = imprtFile.read()
        imprtCmd = imprtCmd.replace(oldGCM, newGCM)
    with open(dssImprt_addrss, 'w') as newImprtFile:
        newImprtFile.write(imprtCmd)

# Part 1: Run HEC-HMS
def runHECHMS(addrss_hechms, addrss_script, cntNum):
    # Purpose: Run HEC-HMS using cmd line
    #
    # Variables:
    # addrss_hechms = Main HEC-HMS directory address with hec-hms.cmd
    # addrss_script = address of HEC-HMS compute.script
    # cntNum =coupled iteration number; To show iteration count for debugging purposes should module fail

    # check folder/directory exists
    if os.path.isfile(addrss_hechms+"\\hec-hms.cmd") and os.path.isfile(addrss_script):
        os.chdir(addrss_hechms)
        cmdLine = "hec-hms.cmd -s " + addrss_script
        p = subprocess.Popen(cmdLine)
        if p.wait() != 0:
            # if subprocess fails - exit code doesn't equal 0
            p_output, p_error = p.communicate()
            errMsg = "Iteration: " + str(cntNum) + \
                "\nError" + str(p_error) + \
                "\nError with DSS Jython import step - please check cmd script"
            sys.exit(errMsg)
        else:
            print ("HEC-HMS run complete")
    else:

```

```

# Exit if file not found
exitMsg = "Iteration: " + str(cntNum) + \
    "\nHecHMS.cmd found: " + str(os.path.isfile(addrss_hechms+"\\hec-hms.cmd")) + \
    "\naddrss script Found: " + str(os.path.isfile(addrss_script))+ \
    "\nPlease double check the file/folder locations. Exiting..."
sys.exit(exitMsg)
return

# Part 2: Access HEC-HMS reservoir inflows
def saveHECHMS_results(addrss_hecdssVue, addrss_ExportAllscript, addrss_MODSIM, cntNum):
    # Purpose:
    # export major reservoir inflow/outflows from basin.DSS each iteration since basin.DSS will be updated each time
    # making copies of dss takes up too much disk space
    #
    # HEC-HMS results are saved in HEC-DSSVue .dss file is not a text file and cannot be accessed directly
    # .dss file can only be accessed through HEC-DSSVue's script editor function which uses Jython
    # therefore a separate Jython script is required
    #
    # Variables:
    # addrss_hecdssVue = directory loaction of HEC-DSSVue.exe
    # addrss_ExportAllscript = address of Jython script to extract specified time series
    # addrss_MODSIM = directory location of MODSIM basin.xy file
    # cntNum = coupled iteration number; To show iteration count for debugging purposes should module fail

    # check folder/directory exists
    if os.path.isfile(addrss_hecdssVue+"\\HEC-DSSVue.exe") and os.path.isfile(addrss_ExportAllscript):
        os.chdir(addrss_hecdssVue)
        cmdLine = "HEC-DSSVue.exe -s " + addrss_ExportAllscript
        p = subprocess.Popen(cmdLine)
        if p.wait() != 0:
            # if subprocess fails - exit code doesn't equal 0
            p_output, p_error = p.communicate()
            print(p_error)
            sys.exit("Error with DSS Jython import step - please check")
        else:
            # export successful, make a copy
            shutil.copy(addrss_MODSIM + "\\hec_reservoir_Results.xls", addrss_MODSIM +
                "\\hec_reservoir_Results_v" + str(cntNum) + ".xls")
            print("HEC results saved for iteration: " + str(cntNum))
        else:
            # Exit if file not found
            exitMsg = "\nIteration: "+str(cntNum)+ \
                "\nError in saveHECHMS_results()" + \
                "\nHecVue-DSS.exe Found: " + str(os.path.isfile(addrss_hecdssVue + "\\HEC-DSSVue.exe")) + \
                "\nDSS export script Found: " + str(os.path.isfile(addrss_ExportAllscript))+ \
                "\nPlease double check file address. Exiting..."
            sys.exit(exitMsg)
    return

# Part 3: Input HEC-HMS reservoir inflow to MODSIM
def getHECHMS_resInflow_toMODSIM(startYr, endYr, addrss_MODSIM, xyFile_name, cntNum):
    # Purpose: Format HEC-HMS reservoir inflows to input into MODSIM.xy
    #
    # Variables :
    # startYr = simulation start year, excluding spin-up period; MODSIM do not require spin-up period
    # endYr = simulation end year

```

```

# addrss_MODSIM = address of main MODSIM folder
# xyFile_name = name of MODSIM basin.xy file
# cntNum = coupled iteration number; To show iteration count for debugging purposes should module fail

# file checks - HecDSS-VUE.exe, DSSVue export Jython script, xyFile
modsimXY_addrss = addrss_MODSIM + "\\\" + xyFile_name + ".xy"
if os.path.isdir(addrss_MODSIM) and os.path.isfile(modsimXY_addrss):
    # Dataframe prep
    start_date = dt.datetime(startYr, 1, 1)
    curr_date = start_date
    #           yr, mm, d, hr, min, sec
    end_date = dt.datetime(endYr, 12, 30, 23, 59, 59)
    step = dt.timedelta(days=1)

    date_series = []
    while curr_date < end_date:
        date_series.append(curr_date.strftime('%m/%d/%Y %H:%M:%S'))
        curr_date += step

    # make copy of reservoir inflows from HecHMS
    # hec_reservoir_Results.xls is the name of the xls file Jython DSS script created to export releases from reservoirs
    # make date stamp column
    df = pd.read_excel(addrss_MODSIM + "\hec_reservoir_Results.xls", header=[1, 2])
    df = df.drop([0, 1, 2, 3], axis=0) # drop first 4 rows of HEC-HMS descriptions
    df = df.iloc[:, 1:] # drop unnecessary columns
    df = df.rename(index=str, columns={"B": "Dates", "C.1": ""})

    # make date stamp column
    kettle_cap = pd.DataFrame(data=date_series, columns=['Dates'])
    split_cap = pd.DataFrame(data=date_series, columns=['Dates'])
    wuskDF = pd.DataFrame(data=date_series, columns=['Dates'])
    kelDF = pd.DataFrame(data=date_series, columns=['Dates'])
    splitFT_DF = pd.DataFrame(data=date_series, columns=['Dates'])
    kettleFT_DF = pd.DataFrame(data=date_series, columns=['Dates'])

    # extract reservoir inflow from specified column of hec_reservoir_Results.xls
    # add 100 (= 1 m3/s flow) as buffer for MODSIM stability
    kettle_cap['release'] = (df.iloc[0:, 1] * 100 + 100).reset_index(drop=True) # Kettle Channel cap
    split_cap['release'] = (df.iloc[0:, 4] * 100 + 100).reset_index(drop=True) # split Channel cap
    wuskDF['release'] = (df.iloc[0:, 2] * 100).reset_index(drop=True) # Wuskwatim Lake inflow
    kelDF['release'] = (df.iloc[0:, 3] * 100).reset_index(drop=True) # kelsey forebay
    splitFT_DF['release'] = (df.iloc[0:, 4] * 100).reset_index(drop=True) # split FlowThru Demand; split lake inflow
    kettleFT_DF['release'] = (df.iloc[0:, 1] * 100).reset_index(drop=True) # kettleGS FlowThru Demand; kettleGS
inflow

    # ensure releases are integer format (decimals crash MODSIM run)
    kettle_cap = kettle_cap.astype({"Dates": str, "release": int})
    split_cap = split_cap.astype({"Dates": str, "release": int})
    wuskDF = wuskDF.astype({"Dates": str, "release": int})
    kelDF = kelDF.astype({"Dates": str, "release": int})
    splitFT_DF = splitFT_DF.astype({"Dates": str, "release": int})
    kettleFT_DF = kettleFT_DF.astype({"Dates": str, "release": int})

    # convert to string and ascii format
    kettle_inflow = kettle_cap.to_string(header=False, index=False)
    split_inflow = split_cap.to_string(header=False, index=False)

```

```

wusk_inflow = wuskDF.to_string(header=False, index=False)
kel_inflow = kelDF.to_string(header=False, index=False)
split_flowThru = splitFT_DF.to_string(header=False, index=False)
kettle_flowThru = kettleFT_DF.to_string(header=False, index=False)

kettle_inflow = '\n' + kettle_inflow
split_inflow = '\n' + split_inflow
wusk_inflow = '\n' + wusk_inflow
kel_inflow = '\n' + kel_inflow
split_flowThru = '\n' + split_flowThru
kettle_flowThru = '\n' + kettle_flowThru

# .encode not required in python3; no need to encode e.g. kettle_inflow_ascii = kettle_inflow.encode('utf-8')
kettle_inflow_ascii = kettle_inflow
split_inflow_ascii = split_inflow
wusk_inflow_ascii = wusk_inflow
kel_inflow_ascii = kel_inflow
split_flowThru_ascii = split_flowThru
kettle_flowThru_ascii = kettle_flowThru

# Rewrite MODSIM reservoir inflow in basin.xy file
# basin.xy file = text file therefore search using regex and replace
with open(modsimXY_addrss, 'r') as xy_file:
    xy_lines = xy_file.read()
    kettleLinkReg = re.compile(
        '(?<=lname Kettle_nudge_Kettle\ndescription \nlnum 3\nfromnum 42\ntonum 15\nlcost -
20\nmaxCap\nvariesbyyear True\nunits cms)(r?\n)'
        '(.*?)'
        '(?=\r?\nselect)', re.DOTALL)
    splitLinkReg = re.compile(
        '(?<=lname Split_nudge_Splitlake\ndescription \nlnum 43\nfromnum 45\ntonum 12\nlcost -
20\nmaxCap\nvariesbyyear True\nunits cms)(r?\n)'
        '(.*?)'
        '(?=\r?\nselect)', re.DOTALL)
    wuskLinkReg = re.compile(
        '(?<=name Wuskwatim_US\ndesc \nnum 34\nntype 2\nout 26\nntsinflow\nvariesbyyear True\nunits
cms)(r?\n)'
        '(.*?)'
        '(?=\r?\npos)', re.DOTALL)
    kelLinkReg = re.compile(
        '(?<=name Kelsey_US\ndesc \nnum 9\nntype 2\nout 1\nntsinflow\nvariesbyyear True\nunits cms)(r?\n)'
        '(.*?)'
        '(?=\r?\npos)', re.DOTALL)
    split_FTReg = re.compile(
        '(?<=name Split_FT\ndesc \nnum 44\nntype 3\nin 42\npos\n0 546.9478\n1 759.6472\nlabelpos\n0
513.5333\n1 751.9333\nselect 0\npcapUnits 1000 m\xc2\x3/day\ndemr\n0 -20\nidstrmx\n0 45\nidstrmfr\n1-9
0\npdstrm 29\nntsdemand\nvariesbyyear True\nunits cms)(r?\n)'
        '(.*?)'
        '(?=\r?\nnode)', re.DOTALL)
    kettle_FTReg = re.compile(
        '(?<=name kettle_FT\ndesc \nnum 41\nntype 3\nin 40\npos\n0 842.4666\n1 279.0667\nlabelpos\n0
842.4666\n1 287.5667\nselect 0\npcapUnits 1000 m\xc2\x3/day\ndemr\n0 -20\nidstrmx\n0 42\nidstrmfr\n1-9
0\npdstrm 39\nntsdemand\nvariesbyyear True\nunits cms)(r?\n)'
        '(.*?)'
        '(?=\r?\nnode)', re.DOTALL)

```

```

startReg = re.compile(
    '(?<=startingDate 01/01/)'
    '(.*?)'
    '(?=\r?\nendingDate)', re.DOTALL)
endReg = re.compile(
    '(?<=endingDate 01/01/)'
    '(.*?)'
    '(?=\r?\naccrualDate)', re.DOTALL)

# check if regex pattern found
kettleLink_Find = re.search(kettleLinkReg, xy_lines)
splitLink_Find = re.search(splitLinkReg, xy_lines)
wuskFind = re.search(wuskLinkReg, xy_lines)
kelFind = re.search(kelLinkReg, xy_lines)
splitFT_Find = re.search(split_FTReg, xy_lines)
kettleFT_Find = re.search(kettle_FTReg, xy_lines)

if kettleLink_Find and splitLink_Find and wuskFind and kelFind and kettleFT_Find and splitFT_Find:
    # substitute the inflow in the matching pattern
    new_lines = re.sub(kettleLinkReg, kettle_inflow_ascii, xy_lines) # Kettle Link max cap
    new_lines = re.sub(splitLinkReg, split_inflow_ascii, new_lines) # Split Link max cap
    new_lines = re.sub(wuskLinkReg, wusk_inflow_ascii, new_lines) # Wuskwat inflow
    new_lines = re.sub(kelLinkReg, kel_inflow_ascii, new_lines) # Kelsey inflow
    new_lines = re.sub(split_FTReg, split_flowThru_ascii, new_lines) # kettle FlowThru
    new_lines = re.sub(kettle_FTReg, kettle_flowThru_ascii, new_lines) # kettle FlowThru

    new_lines = re.sub(startReg, str(startYr) + " 00:00:00", new_lines) # simulation starting date
    new_lines = re.sub(endReg, str(endYr + 1) + " 00:00:00", new_lines) # simulation ending date

    # check .xy file exists in folder path
    if os.path.isfile(modsimXY_addrss):
        with open(modsimXY_addrss, 'w') as xy_check_file:
            xy_check_file.write(new_lines)
            print ("Finished rewriting Modsim.xy file with HecHMS run")
        else:
            sys.exit("Modsim.xy file does not exist in specified path. Please double check. Exiting...")
    else:
        exitMsg = "Iteration: " + str(cntNum) + \
            "\nError in getLocalQ_toMODSIM()\nregex pattern not found in the .xy file.\n" + \
            "\nkettleGS channel link found: " + str(kettleLink_Find) + \
            "\nsplit lake channel link found: " + str(splitLink_Find) + \
            "\nWuskwatimGS inflow node: " + str(wuskFind) + \
            "\nKelssyGS inflow node found: " + str(kelFind) + \
            "\nsplit FlowThru node found: " + str(splitFT_Find) + \
            "\nkettle FlowThru node found: " + str(kettleFT_Find) + \
            "\nPlease double check regex pattern. Exiting..."
        sys.exit(exitMsg)
else:
    # Files not found; ID missing file paths and exit system
    MIA_exitMsg = "Iteration: " + str(cntNum) + \
        "\nError in getHecHMS_resInflow_toMODSIM()\n" + \
        "\nModsim folder Found: " + str(os.path.isdir(addrss_MODSIM)) + \
        "\nxy file found: " + str(os.path.isfile(addrss_MODSIM + "\\\"+xyFile_name+\".xy\")) + \
        "\nPlease double check. Exiting"
    sys.exit(MIA_exitMsg)
return

```

# Part 4: Run MODSIM-DSS

```
def runMODSIM(addrss_MODSIM_fld, xyFile_name, addrss_MODSIMexe, cntNum):
    # Purpose: Run MODSIM.exe
    #
    # Variables :
    # addrss_MODSIM_fld = directory location of MODSIM.xy & MODSIM dll
    # xyFile_name = name of MODSIM basin.xy file
    # addrss_MODSIMexe = address of MODSIM.exe file
    # cntNum = coupled iteration number; To show iteration count for debugging purposes should module fail

    # check folder/directory exists
    if os.path.isfile(addrss_MODSIM_fld+"\\\" + xyFile_name + ".xy") and os.path.isfile(addrss_MODSIMexe):
        cmdLine = addrss_MODSIMexe + " " + addrss_MODSIM_fld + "\\\" + xyFile_name + ".xy"
        p = subprocess.Popen(cmdLine)
        p.wait()
        os.chdir(addrss_MODSIM_fld)
        shutil.copy(os.getcwd() + "\\\" +xyFile_name + "OUTPUT.mdb", os.getcwd()+"\\\" +xyFile_name+
"OUTPUT_v" + str(cntNum) + ".mdb")
    else:
        exitMsg = "Iteration" + str(cntNum) +\
            "\nError in runMODSIM()"+\
            "\nModsim.exe file found: " + str(os.path.isfile(addrss_MODSIMexe)) +\
            "\nModsim.xy file found: "+str(os.path.isfile(addrss_MODSIM_fld+"\\\" + xyFile_name + ".xy")) +\
            "\nPlease double chekc file addresses. Exiting..."
        sys.exit(exitMsg)
    return
```

# Part 5: Access MODSIM output.mdb file and retrieve reservoir releases

```
def updateMODSIM_releases(addrss_hecvueFldr, addrss_pyScript, cntNum):
    # Purpose: run HEC-DSSVue.exe with Jython script
    # - sql connect MODSIM.mdb to read release
    # - update release in .dss file

    # HEC-HMS results are saved in HEC-DSSVue .dss file is not a text file and cannot be accessed directly
    # .dss file can only be accessed through HEC-DSSVue's script editor function which uses Jython
    # therefore a separate Jython script is required

    # Variables
    # addrss_hecvueFldr = directory location of HEC-DSSVue.exe;
    # addrss_pyScript = directory location of jython script calling to update .dss file
    # cntNum = coupled iteration number; To show iteration count for debugging purposes should module fail

    # check folder/directory exists
    if os.path.isdir(addrss_hecvueFldr) and os.path.isfile(addrss_pyScript):
        os.chdir(addrss_hecvueFldr)
        cmd_command = "HEC-DSSVue.exe " + addrss_pyScript
        p = subprocess.Popen(cmd_command)
        if p.wait() != 0:
            # if subprocess fails - exit code doesn't equal 0
            p_output, p_error = p.communicate()
            print(p_error)
            sys.exit("Error with DSS Jython import step - please check")
        else:
            print("Got Modsim release" + "iteration: " + str(cntNum))
    else:
```

```

    exitMsg = "Iteration: " + str(cntNum) + \
        "\nError in updateMODSIM_releases()" + \
        "\nHecVUE-DSS folder found" + str(os.path.isdir(addrss_hecvueFldr)) + \
        "\nImport Jython file found" + str(os.path.isfile(addrss_pyScript)) + \
        "\nPlease double check file addresses. Exiting..."
    sys.exit(exitMsg)
return

# Part 6: Input MODSIM reservoir release as controlled release (HEC-HMS .dss file)
def getMODSIM_releases(addrss_ModsimsMdb, cntNum):
    # Purpose: Connect and retrieve MODSIM reservoir release
    #
    # Variables :
    # addrss_ModsimsMdb = address of MODSIM output file: access.mdb file
    # cntNum = coupled iteration number; To show iteration count for debugging purposes should module fail

    try:
        # in order to access access.mdb file, Database Connection must be established
        conn = pyodbc.connect(addrss_ModsimsMdb)

        # query and retrieve specified MODSIM-DSS releases
        # NNo may be different under different setup; please check prior to running
        StphnQuery = "SELECT * FROM RESOutput WHERE NNo = 15"
        KlsyQuery = "SELECT * FROM RESOutput WHERE NNo = 10"
        WuskQuery = "SELECT * FROM RESOutput WHERE NNo = 1"

        # MODSIM in flow are in units of [1000 m3/d] and HEC-HMS flow is in units of [m3/s]
        # make unit conversion to m3/s
        StphnRel = (pd.read_sql(StphnQuery, conn).filter(items=['Dws_Rel']))*1000/86400 # reservoir release files
        KlsyRel = (pd.read_sql(KlsyQuery, conn).filter(items=['Dws_Rel']))*1000/86400
        WuskRel = (pd.read_sql(WuskQuery, conn).filter(items=['Dws_Rel']))*1000/86400
        conn.close()
    except pyodbc.Error as exn:
        sqlstate=exn.args[1]
        exitMsg = "Iteration: " + str(cntNum) + \
            "\nError in getMODSIM_releases()\n" + \
            str(sqlstate) + \
            "\nError in querying MODSIM releases: Please check mdb driver connection/address. Exiting..."
        sys.exit(exitMsg)

    # check that length of all release dataframes are the same
    if len(StphnRel) != len(KlsyRel) or len(StphnRel) != len(WuskRel):
        # if don't match, then exit script
        len_exitMsg = "Iteration: " + str(cntNum) + \
            "\nError in getMODSIM_releases()\nrelease time series do not match" + \
            "\nPlease check the MODSIM output.mdb"
        sys.exit(len_exitMsg)

    # change column name from 'Dws_Rel' to specific res num
    # so when appending doesn't give in
    StphnRel.columns = ['Stephen']
    KlsyRel.columns = ['Kelsey']
    WuskRel.columns = ['Wuskwatim']

    ## append controlled releases from Stephens and Wuskwatim
    relDF = StphnRel

```

```

relDF = relDF.join([WuskRel])
relDF = relDF.join([KlisyRel])

print ("Got Modsim release")
return relDF

def convergenceChecker(Convrg_relDF, Convrg_relDF_old, cntNum):
    # Purpose: Check MODSIM reservoir release convergence using RSR metric; return TRUE/FALSE
    #
    # Variables :
    # Convrg_relDF = MODSIM release dataframe created from "getMODIMS_releases()" sub-module
    # Convrg_relDF_old = Convrg_relDF from previous iteration

    # check convergege from previous iteration - RSR (Moriassi et al.2007)
    # compare relDF from last run (need to keep a copy)
    relSTD = Convrg_relDF_old.std()

    diffDF = Convrg_relDF.sub(Convrg_relDF_old)
    rowNum = diffDF.shape[0]

    relRMSE = (((diffDF.pow(2)).sum()).div(rowNum)).pow(0.5)
    relRSR = relRMSE / relSTD

    # column indexing
    # Stephen = Stephen's lake
    # Wuskwatim = Wuskwatim lake
    # Kelsey = Kelsey forebay
    if relRSR['Stephen'] <= 0.05 and relRSR['Wuskwatim'] <= 0.05 and relRSR['Kelsey'] <= 0.05:
        convergeCheck = True
    else:
        convergeCheck = False

    print("Iteration: " + str(cntNum))
    print("convergence met: " + str(convergeCheck))
    print("Kettle GS RSR :" + str(relRSR['Stephen']))
    print("Wuskwatim GS RSR :" + str(relRSR['Wuskwatim']))
    print("Kelsey GS RSR :" + str(relRSR['Kelsey']))

    return convergeCheck

main()

```

## Part 2: Jython scripts

```

# Script name: DSSVue_resOutQ_toDSS.py
# Written by: Su Jin Kim
# Contact at: kims3411@myumanitoba.ca
# Purpose: This file goes in hand with "updateMODSIM_releases" function
#   Update HEC-HMS reservoir release time series in HEC-DSSVue .dss file by
#   connecting to MODSIM.mdb and extract reservoir releases and
#   overwrite reservoir release in HecHms basin.dss
#
# File requirements :
# a) HEC-DSSVue .dss file
# b) Jython script to command HEC-DSSVue formatting

```

```
# HEC-HMS results are saved in HEC-DSSVue .dss file is not a text file and cannot be accessed directly
# .dss file can only be accessed through HEC-DSSVue's script editor function which uses Jython
# therefore a separate Jython script is required
```

```
# Import all the built-in functions in hec library and java
```

```
from hec.script import *
from hec.heclib.dss import *
from hec.heclib.util import *
from hec.io import *
```

```
# In order to access access.mdb file, Database Connection must be established
# since opening in Jython environment, requires a Java Databased Connectivity (JDBC) driver
# Download and install open source JDBC UCanAccess
# For Youtube instructions : https://www.youtube.com/watch?v=8R4e2HxFSsk
# import additional UCanAccess JOBDC connector for import
```

```
from com.ziclix.python.sql import zxJDBC
from com.ziclix.python.sql import DataHandler
import java
```

```
try :
```

```
try :
    # make connection to HEC-HMS basin.dss
    myDss = HecDss.open("C:/Users/kims3411/Desktop/Cpld_HEC_hisGCM/LNRB_NOEr41/LNRB_Simplified.dss")
```

```
    # create time series objects
```

```
    Stphn = TimeSeriesContainer()
    Klsy = TimeSeriesContainer()
    Wusk = TimeSeriesContainer()
```

```
    # call reservoir time series to modify
```

```
    # start date has to match the first date in DSS; HEC-HMS is very specific about that; otherwise it won't run
```

```
    # just copy paste from DSS so there is no syntax error
```

```
    Stphn.fullName = "//TS_KETTLE/FLOW/01JAN1979/1DAY/GAGE/"
    Klsy.fullName = "//TS_KELSEY/FLOW/01JAN1979/1DAY/GAGE/"
    Wusk.fullName = "//TS_WUSKWATIM/FLOW/01JAN1979/1DAY/GAGE/"
```

```
    # HEC-DSSVue interval in unit of minute
```

```
    # Daily time step interval = 24 hour x 60 minute
```

```
    Stphn.interval = 1440
    Klsy.interval = 1440
    Wusk.interval = 1440
```

```
    # this is start date of your data, excluding the spin up period
```

```
    # start = HecTime("01Jan1981", "0000") corresponds to 31Dec1980 24:00 when you open up DSS
```

```
    start = HecTime("01Jan1981", "0000")
```

```
try:
```

```
    # parameters for establishing a JDBC connection
```

```
    jdbc_url = "jdbc:ucanaccess://C:/Users/kims3411/Desktop/Cpld_HEC_hisGCM/MODSIM_simplified_2019Oct/MODSIMMO
DEL_OperationaltoSJ_modSimpOUTPUT.mdb"
    usnm = ""
    pswd = ""
```

```

driver_class = "net.ucanaccess.jdbc.UcanaccessDriver"

# make a JDBC connection
# query and retrieve specified MODSIM-DSS releases
cnx = zxJDBC.connect(jdbc_url,usrnm,pswd,driver_class)

StphnQry = cnx.cursor()
StphnQry.executemany("SELECT Dws_Rel FROM RESOutput WHERE NNo = ?", ['15'])
StphnFlow = StphnQry.fetchall()

KlsyQry = cnx.cursor()
KlsyQry.executemany("SELECT Dws_Rel FROM RESOutput WHERE NNo = ?", ['10'])
KlsyFlow = KlsyQry.fetchall()

WuskQry = cnx.cursor()
WuskQry.executemany("SELECT Dws_Rel FROM RESOutput WHERE NNo = ?", ['1'])
WuskFlow = WuskQry.fetchall()

StphnQry.close()
KlsyQry.close()
WuskQry.close()

cnx.close()

except Exception, e :
    MessageBox.showError(" ".join(e.args), "Database Connection Error")

# MODSIM in flow are in units of [1000 m3/d] and HEC-HMS flow is in units of [m3/s]
# make unit conversion to m3/s
convNum = 1000/86400.0 # conversion factor in integer

# take it out of tuples, multiply by conversion factor and round to 2 decimal place
# since MODSIM is 2 decimal precision (ultimately won't matter since HEC DSS only takes single precision but
prints 11)
StphnQ = [round(i*convNum,2) for sub in StphnFlow for i in sub]
KlsyQ = [round(i*convNum,2) for sub in KlsyFlow for i in sub]
WuskQ = [round(i*convNum,2) for sub in WuskFlow for i in sub]

# create timestamp for dss file
times = []
for value in StphnQ :
    times.append(start.value())
    start.add(Stphn.interval)

## append timestamp
Stphn.times = times
Klsy.times = times
Wusk.times = times

## append flows
Stphn.values = StphnQ
Klsy.values = KlsyQ
Wusk.values = WuskQ

Stphn.numberValues = len(StphnQ)
Klsy.numberValues = len(KlsyQ)

```

```

Wusk.numberValues = len(WuskQ)

Stphn.units = "CMS"
Klsy.units = "CMS"
Wusk.units = "CMS"

Stphn.type = "PER-AVER"
Klsy.type = "PER-AVER"
Wusk.type = "PER-AVER"

## put in DSS
myDss.put(Stphn)
myDss.put(Klsy)
myDss.put(Wusk)

except NameError, e :
    MessageBox.showError(' '.join(e.args), "Name Error")
except OSError, e :
    MessageBox.showError(' '.join(e.args), "OS Error")
except Exception, e :
    MessageBox.showError(' '.join(e.args), "Python Error")
except java.lang.Exception, e :
    MessageBox.showError(e.getMessage(), "Error")
finally :
    myDss.close()

# Script name: DSSVue_exportAllQ.py
# Written by: Su Jin Kim
# Contact at: kims3411@myumanitoba.ca
# Purpose: This file goes in hand with "asdlf" function
#         Export reservoir flows to excel to be imported in MODSIM-DSS
#
# File requirements :
# a) HEC-DSSVue .dss file

# HEC-HMS results are saved in HEC-DSSVue .dss file is not a text file and cannot be accessed directly
# .dss file can only be accessed through HEC-DSSVue's script editor function which uses Jython
# therefore a separate Jython script is required

# import all the built-in functions in hec library and java
from hec.script import *
from hec.heclib.dss import *
from hec.dataTable import *
import java

# Open the file and get the data
try:
    # HecDss.open can open a *.dss file by specifying its full path name and the start and end date of events.
    # without the start/end time, dss will only select first value and return only 1 day data"
    #
    #         excluding spinup year: start date | end date
    #
    #         .dss in 24:00 marking therefore call 1 day earlier

```

```
dssFile = HecDss.open("C:/Users/kims3411/Desktop/Cpld_HEC_hisGCM/LNRB_NOEr41/TS_1980_2010.dss",  
"31DEC1980 2400, 30DEC2010 2400")
```

```
# Within the .dss file, select the dataset you want
```

```
# Dataset must be called with the first date of the dataset (therefore includes spinup)
```

```
# Just copy paste from DSS
```

```
StphnIn = dssFile.get("//KETTLEFOREBAY/FLOW-COMBINE/01JAN1979/1DAY/RUN:TS_1980_2010/")
```

```
WuskIn = dssFile.get("//WUSKWATIM_LAKE/FLOW-COMBINE/01JAN1979/1DAY/RUN:TS_1980_2010/")
```

```
KlsyIn = dssFile.get("//KELSEYFOREBAY/FLOW-COMBINE/01JAN1979/1DAY/RUN:TS_1980_2010/")
```

```
CrossIn = dssFile.get("//CROSS_LAKE_RES/FLOW-COMBINE/01JAN1979/1DAY/RUN:TS_1980_2010/")
```

```
SplitIn = dssFile.get("//SPLIT_LAKE_RES/FLOW-COMBINE/01JAN1979/1DAY/RUN:TS_1980_2010/")
```

```
StphnOut = dssFile.get("//KETTLEFOREBAY/FLOW/01JAN1979/1DAY/RUN:TS_1980_2010/")
```

```
WuskOut = dssFile.get("//WUSKWATIM_LAKE/FLOW/01JAN1979/1DAY/RUN:TS_1980_2010/")
```

```
KlsyOut = dssFile.get("//KELSEYFOREBAY/FLOW/01JAN1979/1DAY/RUN:TS_1980_2010/")
```

```
CrossOut = dssFile.get("//CROSS_LAKE_RES/FLOW/01JAN1979/1DAY/RUN:TS_1980_2010/")
```

```
SplitOut = dssFile.get("//SPLIT_LAKE_RES/FLOW/01JAN1979/1DAY/RUN:TS_1980_2010/")
```

```
except java.lang.Exception, e :
```

```
# Take care of any missing data or errors.
```

```
MessageBox.showError(e.getMessage(), "Error reading data")
```

```
# Add Data. Create a vector using the following statement and then add outflow rate to it.
```

```
datasets = java.util.Vector()
```

```
datasets.add(StphnIn)
```

```
datasets.add(WuskIn)
```

```
datasets.add(KlsyIn)
```

```
datasets.add(SplitIn)
```

```
datasets.add(CrossIn)
```

```
datasets.add(StphnOut)
```

```
datasets.add(WuskOut)
```

```
datasets.add(KlsyOut)
```

```
datasets.add(SplitOut)
```

```
datasets.add(CrossOut)
```

```
# Since we want to export the outlet flow rate to excel, we need to define a table that is readable by excel.
```

```
# Table only accept data in the format of list and we need to append the outflow rate data in the datasets vector to a list.
```

```
dataList = []
```

```
dataList.append(datasets)
```

```
# Create a table that is readable by excel.
```

```
table = HecDataTableToExcel.newTable()
```

```
# Read the list and export it to excel by creating an excel file with the name of "hec_reservoir_Results.xls".
```

```
table.createExcelFile(dataList,
```

```
"C:\Users\kims3411\Desktop\Cpld_HEC_hisGCM\MODSIM_simplified_2019Oct\hec_reservoir_Results.xls")
```

```
dssFile.done()
```