Simulating hydroelectric regulation and climate change in the Hudson Bay drainage basin

by

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Abstract

Beginning in the 1960s and increasing through to the present, regulation of reservoirs for hydroelectric generation has become more prevalent in the Nelson Churchill River Basin and the La Grande Rivière Complex, together making up close to half of the total freshwater flux entering Hudson Bay annually. Coincident with hydroelectric development, the effects of climate change have intensified and are more pronounced at higher latitudes, affecting the majority of the Hudson Bay Drainage Basin (HBDB). Whether the effects of climate change and hydroelectric regulation are additive or offsetting is unclear, creating uncertainty as to the driving cause of the observed changes; with added complication due to the relatively poor representation of regulation in continental-scale hydrologic models. This work aims to quantifiably distinguish the impacts of climate change and hydroelectric regulation on the majority of the freshwater supply to Hudson Bay by running two parallel sets of hydrological simulations using the HYPE model. The first set improves reservoir regulation in HYPE, and the second creates a wholly re-naturalized set of simulations with no anthropogenic influence. An ensemble of the Phase 5 Climate Model Intercomparison Project (CMIP5) general circulation models (GCMs) and representative concentration pathways (RCPs) drive simulations over the HBDB at a daily time-step from 1981 to 2070. By subjecting both models (regulated and re-naturalized) to climate change, the effects of hydroelectric regulation can be isolated and quantifiably distinguished from climate change. This research improves the performance of a hydrological model in a highly regulated system, and further succeeds in distinguishing the spatio-temporal scales of different change factors. Intra-annual changes of flow timing are primarily due to hydroelectric regulation, inter-annual change is driven by upstream storage, and inter-decadal impacts are the result of climate change. With these results, a variety of additional simulations (i.e., sea-ice, carbon-cycling, biogeochemical) can be run to ascertain the overall health of Hudson Bay and the effects of climate change and reservoir detention can be attributed quantitatively.

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Finally, I would like to dedicate this work to the memories of my father, Wayne Tefs and my uncle, Brian Hershfield who were constant inspirations in life.

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Contributions of Co-Authors

Portions of this work were aided by co-authors. They are noted by their contributions to the manuscripts, separated into Chapters 2 and 3. The results and analysis presented and the subsequent discussion are chiefly my own work.

Chapter 2: *Simulating effects of Nelson-Churchill River regulation controls on reservoir performance in HYPE* (Tefs, A., MacDonald, M., Stadnyk, T., Koenig, K., Hamilton, M., Slota, P., Crawford, J.).

Dr. MacDonald was instrumental in the prior development of the Hudson Bay HYPE (H-HYPE) model, the HYdrological Predictions for the Environment (HYPE) sub-model developed specifically for this project through his work with the Swedish Meteorological and Hydrological Institute (SMHI). Dr. MacDonald also contributed to my early training and overall understanding of HYPE. Dr. Stadnyk provided guidance on project scope and the editing of the manuscript. Kristina Koenig and Phil Slota provided industrial knowledge related to the Nelson-Churchill River Basin and the Manitoba Hydro regulated system as well as high-level guidance on reservoirs selected for regulation in hydrologic modelling. John Crawford developed the original Cedar Lake, Lake Winnipeg, S. Indian Lake, Lake of the Woods / Namakan Lake / Rainy Lake, and Lake St. Joseph / Lac Seul spreadsheet models. Phil Slota developed the original Reindeer Lake spreadsheet model. Phil Slota and John Crawford provided guidance in the early development of the Lake Diefenbaker spreadsheet model originated for this work. John Crawford was the primary developer of the ideal storage method used in the H-HYPE regulation routine and designed the reservoir-specific sub-functions of the spreadsheet models. Some of these sub-functions in the spreadsheet models would later be modified, adapted, aggregated and generalized to form the basis of the reservoir analysis tool (RAT) and the H-HYPE regulation routine.

Matthew Hamilton aided in the coding of the HYPE regulation routine used in this work. All authors contributed to the editing of the manuscript text.

Chapter 3: *Modelling the relative effects of climate change and hydroelectric development on the changing freshwater exports to Hudson Bay.* (Tefs, A.; MacDonald, M.K.; Stadnyk, T.A.; Koenig, K.; Déry, S.J.; Slota, P.; Guay, C.; Hamilton, M.; Thiemonge, N.; Vieira, M.; and Pokorny, S.).

Dr. MacDonald was instrumental in the prior development of the H-HYPE model, the HYPE sub-model developed specifically for this project through his work with SMHI. Dr. Stadnyk provided important guidance for project scope and the direction of the analysis as well as support in the publication and editing process. Kristina Koenig and Phil Slota provided industrial knowledge related to the Nelson-Churchill River Basin and the Manitoba Hydro regulated system. Mike Vieira provided tools related to equidistant quantile mapping used in post-processing of regulated results for previous iterations of the Hydro-Québec system results. Dr. Déry provided the tools used in trend analysis, the long-term, drainage-area corrected flow records, and invaluable proofreading and insight into trend analysis. Matthew Hamilton aided in the coding of the HYPE regulation routine used in this work. Catherine Guay provided data for the re-naturalization of the La Grande Rivière Complex land-cover and background data instrumental to the development of the net basin supply for the Hydro-Québec regulated basins. Nathalie Thiemonge provided regulated outflows for further analysis. Scott Pokorny provided secondary climatological analysis used in the calibration of the early stages of the H-HYPE model. All authors contributed to the editing of the manuscript text.

1 Introduction

1.1 Thesis organization

This thesis comprises four chapters, consisting of an introduction and background, research compiled in two manuscripts, and conclusions. Chapter 1 presents an introduction to the context of the BaySys project and the Hudson Bay Drainage Basin (HBDB). Chapter 1 also discusses the objectives and scope of Project 2.3, which makes up the work of this thesis. Chapter 2 describes the new regulation routine added to the Nelson-Churchill River Basin (NCRB) domain of the H-HYPE model and model performance improvements achieved by doing so. Chapter 2 fulfills the first research objective (objectives described in Section 1.3) and will be submitted to the Hydrological Sciences Journal. Chapter 3 describes the methodology of the full HBDB regulated results and the methods used in creation of the re-naturalized HBDB model. It further reports the results of the inter-comparison of the two models over the 90-year period of simulations and the quantitative attribution (spatially and temporally) of the impacts of climate change and hydroelectric reservoir regulation. Chapter 3 fulfills the second research objective and will be submitted to the Canadian Water Resources Journal. Chapter 4 summarizes findings and conclusions from Chapters 2 and 3 and recommends future work to improve results in studies of regulation in continental-scale hydrology and climate change impact studies of the HBDB and of the Hudson Bay ecosystem itself.

1.2 Background

The increasing effects of climate change have been observed more intensely in northern latitudes (Bring et al., 2017; Bring et al., 2016; Déry et al., 2011; Serreze et al., 2000). These regimes are characterized hydrologically by a drawdown in winter due to storage of fresh precipitation as snowpack and a spring flood due to melting of that snowpack. With increasing temperatures, the duration of the snow-on-ground period is shortening and the depth of the snowpack is shrinking (Kang et al, 2014). This gives smaller spring freshet peaks, and therefore flatter hydrographs and a shift away from the nival-dominated regime (Burn and Whitflield, 2017). The snowmelt-based spring freshets of the Hudson Bay Drainage Basin (HBDB) play an important role in driving the freshwater/saltwater (riverine/marine) interface, the flow dynamics of the bay, and the formation of sea-ice cover (Ridenour et al., 2018; Anctil and Couture, 1994). The observed effects of climate change have largely coincided with hydroelectric development over the past four decades (and associated reservoir regulation and storage) driven by Manitoba Hydro (MH) and SaskPower (SP) leveraging resources from the western Hudson Bay region, and Ontario Power Generation (OPG) and Hydro-Québec (HQ) leveraging James Bay resources in south-eastern Hudson Bay.

Diversion and reservoir regulation for hydroelectricity became more widespread beginning in the HBDB in the 1960s, with major projects contributing to regulation, diversion, and long-term storage (basin fragmentation) in the subsequent decades (Grill et al., 2014; Dynesius and Nilsson, 1994). This reservoir regulation has resulted in a relative flattening of the hydrographs of larger reservoirs and their downstream outlets to Hudson Bay (Déry et al., 2018). Increased demand for hydroelectricity in the winter months (i.e. heating demand) is in opposition to the timing of peak runoff during the spring freshet in this region. Hydroelectric reservoirs in regions dominated by nival regimes are operated to retain the large spring floods through the summer and release water steadily over the winter.

Happening in parallel to these global changes (climate change) and the localized terrestrial changes (hydroelectric regulation), is an observed shortening of the ice-cover season of Hudson Bay

(Andrews et al., 2017; Landy et al., 2017). Stressors on the development of ice, and timing of ice-related processes and thermohaline circulation in Hudson Bay include but are not limited to the ice/open water/albedo feedback loop (driven by climate change), and the flattening of traditionally nival hydrographs feeding the Bay (i.e., combined impact of climate change and hydroelectric regulation). Shortening of the sea-ice season affects every level of the Hudson Bay biome, as reduced ice-cover will affect the timing and nutrient-density of microflora and microfauna that grow near and on the underside of ice (Campbell et al., 2018; Leu et al., 2015). The effect of climate change on the balance of first-year and multi-year ice also affects the speciation and productivity of this biologically active zone (Campbell et al., 2017). This has a trickle-down effect on all trophic levels in Hudson Bay, stressing the overall health of the ecosystem.

This research contributes to the larger BaySys group of projects (Barber et al., 2014), which aims to study the health of the Hudson Bay system as a whole. The core goal of the overall project is to distinguish the effects of climate change and hydroelectric regulation on the overall ecological health of Hudson Bay. This thesis falls into the hydrology working group (Team 2: Freshwater) and is focused on the reservoir regulation and inter-comparison of effects (Project 2.3: Regulated System Modelling).

Reservoir regulation routines available in the HYdrological Predictions for the Environment (HYPE) hydrologic model (Lindstrom et al., 2010) have been used in numerous studies of smaller regions (less than 500,000 km^2) and have been proven effective in these basins (Arheimer et al., 2017). In large-scale studies using HYPE (Pechlivanidis and Arheimer, 2015; Donnelly et al., 2014), and continental-scale hydrologic modelling as a whole (Coerver et al., 2017; Zhao et al., 2016; Pokhrel et al., 2012), the representation of reservoir regulation in hydrologic modelling is a concern. This relatively poor representation of regulation as a process has negative impacts on researchers' abilities to attribute the effects of regulation in large-scale, long-term modelling studies. With climate change and regulation possibly having similar effects on future outflows (flattened spring outflow, increased winter outflow; Arehimer et al., 2017), the representation of regulation processes in modelling becomes a primary concern.

In the previous stages of the freshwater modelling in the BaySys project, the regulation of two important downstream regulation points in the NCRB (Lake Winnipeg and Southern Indian Lake) were added to the Hudson Bay HYPE (H-HYPE) model implicitly (MacDonald et al., in revision). The routines used in these regulation functions were embedded in the HYPE code and could not be edited or calibrated. The algorithms that made up those routines were specific to the reservoirs themselves. Rather than calibrating parameters for the reservoir, regulation rules were hard-coded. This introduces a significant black-box effect to the model and also establishes a framework which is difficult to apply to new reservoirs. These efforts were deemed inadequate for application in other reservoirs, which were modelled with default Arctic HYPE (A-HYPE) regulation routines. For this reason, a new generalized regulation routine was developed for application to regulated reservoirs in the NCRB.

Whether the changes seen to the ice-cover season in Hudson Bay are an early indicator of climate change or a by-product of anthropogenic changes to the control of the terrestrial freshwater system is unknown. Additionally, whether the freshwater changes are more affected by climate change (shift from nival to mixed regime), or regulation is unknown. Studies used to differentiate the terrestrial effects of climate change and regulation have been published previously for other snow-fed river systems (Arheimer et al., 2017), but none exist yet for the HBDB.

The differentiation of these intermingled and spatio-temporally overlapping impacts for the terrestrial environment makes up the basis of Project 2.3. The purpose of this project is to quantifiably separate the impacts of climate change and hydroelectric regulation on the terrestrial hydrology of Hudson Bay by improving representation of reservoir regulation in a continental-scale model. By coupling these results with sea-ice, carbon-cycle, and biogeochemical models, Hudson Bay's spatio-temporal sensitivity to changes (Ridenour et al., 2018) can be analyzed. The long-term impacts of climate change and hydroelectric regulation can be distinguished in a region where these impacts have previously only been observed and planned for cumulatively, not individually. By examining the spatial changes produced with and without hydroelectric anthropogenic effects (both with climate change effects), the global anthropogenic impacts (global warming) and local industrial impacts (Manitoba Hydro, Hydro-Québec) can be examined with greater certainty.

1.3 Thesis objectives

The effects of hydrologic regime shift due to climate change and hydroelectric regulation on the freshwater-marine coupling in Hudson Bay have been observed, with the cumulative effects being studied for more than three decades. However, the individual contributions of these two factors are not well understood in a quantitative way. To distinguish, quantitatively, the effects of climate change and hydroelectric reservoir regulation, the objectives of this work are to:

1) Develop a generalized reservoir regulation routine to be applied to reservoirs in the NCRB, which must improve the performance (short-term) and reliability (long-term) of simulated historical outflow; and to

2) Differentiate the scale and timing of the impacts of climate change and hydroelectric regulation on freshwater outflow (river discharge) and the terrestrial water-cycle (basin hydrology) of the HBDB major regulated basins.

1.4 Scope of work

In achieving the objectives stated, this project will establish two versions of the HYPE hydrological model for the HBDB region (i.e., regulated and re-naturalized) that are forced by 19 climate model scenarios at a daily resolution, and analysed over two major regulated basins across three time periods spanning the 90 years from 1981 to 2070.

For hydrological simulations, the HYPE hydrological model (Lindstrom et al., 2010) was selected for its strength in cold-regions processes and performance at the continental scale (Pechlivanidis and Arheimer, 2015). The Arctic HYPE model domain was trimmed to the HBDB domain and this Hudson HYPE (H-HYPE) model was calibrated and validated over the BaySys historical period (1981 to 2010), using five years of each decade in a split sample validation (MacDonald et al., in revision). The effects of climate change on this model were simulated and analysed over the BaySys near-future and future periods (MacDonald et al., 2018; Stadnyk et al., in press). The H-HYPE model calibration was refined using an updated, near real-time global climate forcing product, the HydroGFD re-analysis dataset (Berg et al., 2017).

Two versions of the HYPE model were developed: the (1) regulated version, and the (2) re-naturalized version of the model. The development of the regulated HYPE model entailed the creation of a new, generalized regulation routine coded into HYPE, applied and validated at 13 reservoirs in the Nelson-Churchill River Basin (NCRB). Improved regulation also entailed providing climate forcing to Hydro-Québec (HQ) for their regulated basins in the La Grande Rivière Complex (LGRC). These net basin supplies were regulated and routed by HQ using methods consistent with the regulation routine added to the NCRB (regulation) and HYPE (routing). HQ regulation was used to achieve the most realistic operations, based on decades of experience modelling the infrastructure and operations of the system. Development of a re-naturalized model entailed the removal of all regulation processes, diversions, irrigation withdrawals, and flooding of reservoirs. Pre-development reservoir outflow conditions were recreated using historical stage-discharge data from reservoirs prior to the period of their regulation. Removal of flooded reservoirs was done by reverting land flooded for hydroelectric storage to its pre-development land-use and soil-type to match the proportionality of the surrounding soil-land classes. Shapefiles of reservoir extent pre- and post-development were provided by HQ (for the LGRC). Pre- and post-development areas from previous studies were used in the NCRB (Smith and Kells, 1993; Hammer, 1988; Newbury et al., 1984).

The 19 climate scenarios chosen comprises 14 General Circulation Models (GCMs) driven by one or both of RCP 4.5 and 8.5. RCPs (Representative Concentration Pathways) are the carbon and anthropogenic scenarios applied to GCMs as an input. The 19 scenarios represented 90% of the total climate variability (precipitation and temperature change, along with eight other distinct climate signatures, over the HBDB) (Stadnyk et al., in press) of the 154 members of the Phase 5 Climate Model Intercomparison Project (CMIP5). This provided a robust ensemble describing the effects of both RCP 4.5 (business-as-usual climate change) and RCP 8.5 (severe climate change) for Hudson Bay. Climate models were bias-corrected by the Ouranos consortium (Chen et al., 2013a; Chen et al., 2013b) using the HydroGFD re-analysis product (Berg et al., 2017), the same product used for calibration of the terrestrial hydrologic model and Nucleus for European Modelling of the Ocean (NEMO) sea-ice and circulation model (Ridenour et al., 2018) of the Hudson Bay Complex.

The basins analysed for this work were limited to those with "major" hydroelectric regulation affecting freshwater flux into Hudson Bay. Two basins were selected (the NCRB and LGRC), which when combined, represent close to a third of the freshwater flux into Hudson Bay and Canada's third largest river by annual flow volume (Déry et al., 2018). The NCRB spans four US states (ND, SD, MN, MT) and four Canadian provinces (AB, SK, MB, ON), affecting two rivers draining to Hudson Bay (the Nelson and Churchill Rivers) with a combined drainage area of 1,400,000 km^2. The LGRC is located in Québec and affects four rivers draining to Hudson Bay and Ungava Bay (La Grande Rivière, la Rivière Rupert, la Rivière Eastmain, and la Rivière Koksoak) with a combined drainage area of 325,000 km^2. Other basins in the HBDB contain varying degrees of regulation. The Albany and Moose Rivers are considered moderately and strongly affected, respectively (Dynesius and Nilsson, 1994), but lack storage and detention significant enough to influence the freshwater export to Hudson Bay. These basins were left with little or no regulation in the regulated model (as they existed in A-HYPE) and were converted to fully un-regulated in the re-naturalized model.

The two models were run using climate forcing input at a daily resolution from 1981 to 2070, inclusively. A 5-year spin-up period (1976 to 1980) was used to initialize the model. Simulation results were broken into three 30-year time periods for analysis: 1981 to 2010 (historical), 2021 to 2050 (near-future), and 2041 to 2070 (future). These 30-year periods were selected to each represent climate-normal periods of 30 years, while still allowing multiple inter-comparisons between periods of lesser (historical) and greater (near-future and future) climate change. These periods are consistent with other studies in the BaySys group of projects. Major hydrologic variables (i.e., liquid precipitation, solid precipitation, total precipitation, air temperature, evapotranspiration, snow-water equivalent, runoff, and groundwater depth) were evaluated at a monthly time scale, using the ensemble-mean values. Discharge was evaluated at a daily time scale, also using the ensemble-mean. The ensemble mean may smooth out the variability of the climate models, so additional inter-scenario and inter-annual variability analyses were run on each variable. All variables were analysed for trend, trend significance, inter-scenario coefficient of variation (at the time-scale of the reported values), inter-annual coefficient of variation (within the 30-year periods), percent change between model configurations (effect of regulation vs. re-naturalization) and percent change over time (effect of climate change).

At the same time that the results were simulated for the two largest freshwater complexes (NCRB and LGRC) the H-HYPE model generated results for the other 391 basin outlets in the HBDB. This full suite of freshwater discharge results will be passed to the BaySys marine modelling group (Team 6: Sea Ice Modelling). These freshwater fluxes make up part of the input condition to the NEMO model. The NEMO model has been selected for its robustness in modelling freshwater-marine interfaces, thermohaline dynamics, and sea-ice cover (Hu et al., 2018, Madec et al., 2008). Additional climatological input is added (over the Hudson Bay area) using the same GCM/RCP forcing as the terrestrial (hydrological) models. Additional hydrologic input is generated at a monthly resolution using the full A-HYPE model domain (all watersheds draining to the Arctic Ocean). This hydrological modelling is outside the scope of this work (Project 2.1: Far-field runoff).

Chapter 2

Simulating effects of Nelson-Churchill River regulation controls on reservoir performance in HYPE

(Tefs, A., MacDonald, M., Stadnyk, T., Koenig, K., Hamilton, M., Slota, P., Crawford, J.).

2.0 Abstract

This study focuses on the heavily regulated Nelson-Churchill River Basin (NCRB) that drains the western portion of the Hudson Bay Drainage Basin (HBDB). We develop a new reservoir regulation routine for incorporation into a continental-scale hydrologic model. In predictable and stable climates, calibration of default regulation routines available in hydrologic models are a proven, effective tool for simulating reservoir releases. Under unstable flow regimes, however, the assumption of stationarity in reservoir-releases tends to be erroneous and can lead to unreliable discharge projections. Two new regulation sub-routines were developed for the NCRB and integrated into the HYPE hydrological model and are adapted to various types of reservoir operation (i.e., flood control, irrigation management, hydroelectricity). Historical flow regimes (1981 to 2010) simulated at 16 regulated outlets at 13 reservoirs within the NCRB show consistent seasonal improvement. Regulation rules were developed from historic regulated data from the 2001 to 2010 reference period, yet the hydrologic model shows statistical improvement across both the reference period and the larger validation (1981 to 2010) period. By applying this simulation tool to key reservoirs in the NCRB, results at individual reservoirs are more robust and better able to respond to future extreme hydrologic conditions. This is measured at a monthly and seasonal resolution using the Nash-Sutcliffe Efficiency (NSE) and percent bias of mean outflow. This is due to the new regulation routine allowing more effective simulation of reservoir response to both long-term climate change and inter-annual climatic variability. The goal of our study is to provide a hydrological modelling framework for long-term simulation of climate change effects with corresponding reservoir regulation for the NCRB.

2.1 Introduction

The climate is changing rapidly in northern Canada (Déry et al., 2011; Déry et al., 2009) leading to changes in the duration and depth of snowpacks (Kang et al., 2014), and ultimately resulting in alteration of both the timing and volume of freshwater export to Hudson Bay. At the same time, regulation control over western freshwater exports from the Nelson-Churchill River basin (NCRB), as well as eastern exports through the La Grande Rivière Complex (LGRC) have been increasing through time, and also influence the timing and volume of freshwater exports (Déry et al., 2018). The BaySys group of projects (Barber et al., 2014) was designed to examine the full extent of the impacts these changes in the terrestrial freshwater system are having on the marine system of Hudson Bay. Of particular interest is the question: "Is it climate change or hydroelectric regulation driving changes in Hudson Bay?". Moreover, are the effects of climate change and hydroelectric regulation additive, or offsetting one another? To determine the answers, the effects of both drivers must be quantifiably simulated (past, present and future), separated, and analyzed. Models used to project future terrestrial freshwater exports must be adaptive to changing climates, reliable for long-term projections in cold regions, and responsive to changing inflow conditions to regulated reservoirs in the basin; which was not the case in previously existing hydrological models.

Sophisticated reservoir regulation exists as an optional extension to some extent in most hydrologic models. HEC-HMS, a free model created and managed by the US Army Corps of Engineers, has a coupled model called HEC-HMS ResSim (Reservoir Simulation) that has been shown to improve operational regulation modelling (Piman et al., 2016; Uysal et al., 2016a; Uysal et al., 2016b; Ahn et al., 2014). Other studies have created ad-hoc reservoir models developed for specific sites or specific studies integrated into hydrological models using net basin supply (Huaringa Alvarez et al., 2014; Li et al., 2010a; Minville et al., 2010a; Minville et al., 2009). Operational rule curves with hedging, or with curves optimized dynamically using a variety of methods and tied to different applications have been validated on historical periods and proposed for operational use (Prasanchum et al., 2018; Zhang et al., 2017; Costa-Nunes et al., 2016; Adeloye et al., 2016; Fang et al., 2014; Taghian et al., 2014; Liu et al., 2011). Looking at the context of reservoir modelling within climate change, many studies are developed using historical data, but then applied to overtly non-stationary future climates using dynamically or stochastically optimized methods (Denaro et al., 2017; Haguma et al., 2015; Haguma et al., 2014). The new regulation routine looks to reduce computational demand on the hydrologic model by excluding optimization methods. Other studies of the region have used future climate scenario ensembles and current reservoir operations rules, as the work presented in this paper does, to analyse reservoir reliability or outflow uncertainty (Li et al., 2010a; Minville et al., 2010b). There has been recent interest in integrating regulation into larger scale (continental or global) models to simulate the combined impact of anthropogenic intervention and climate change, with varying degrees of success at the regional scale (Arheimer, 2017; Coerver et al., 2017; Zajac et al., 2017; Zhao et al., 2016; Pechlivinadis and Arheimer, 2015; Zhou et al., 2013; Pokhrel et al., 2012).

The HYPE model is proven to be useful for simulating hydrologic response at the continental-scale (Pechlivinadis and Arheimer, 2015), but the regulation routine can be problematic. This routine has been indirectly evaluated by several studies (Donnelly et al., 2016; Andersson et al., 2015; Bergstrand et al., 2014; Donnelly et al., 2014) and found to be poorly represented at larger scales in data-sparse regions. Human-water interactions (reservoir management, irrigation, etc.) are noted as a problem-area in other continental-scale hydrologic models or (world-wide) land surface models in further studies (Zaherpour et al., 2018; Wada et al., 2017; Wanders and Wada, 2015; Zhou et al., 2013; Pokhrel et al., 2012; Hanasaki et al., 2006). The Hudson Bay Drainage Basin (HBDB) in

HYPE contains multiple regulation points, with close to 50% (by volume) of its freshwater exports being impacted by regulation or human alteration (Déry et al., 2018).

The Freshwater Systems team (Team 2) of the BaySys group of projects is tasked with generating two versions of a HBDB hydrologic model to conduct simulation experiments for an ensemble of climate scenarios, using (1) a regulated system model, and (2) a re-naturalized model. The objective of this study is to develop a reservoir regulation routine using fixed regulation rules to effectively simulate reservoir outflows under natural climatic variability (year-to-year) and long-term climatic change (i.e., >30-year period). This will be used to assess anthropogenic influence on freshwater exports resulting from reservoir regulation. We develop a more robust and reliable regulation routine for the HYPE continental-scale hydrologic model to describe the regulation control of 13 major reservoirs of the NCRB. Regulation rules are defined based on historic (near-current) operations (2001 to 2010), and do not account for new hydropower infrastructure developments, altered future power-sales market conditions, or future power demands (i.e., no dynamic system optimization). We focus on the Nelson and Churchill Rivers as they are the two largest contributors of freshwater outflows to Western Hudson Bay (Déry et al., 2016), and have had increasing anthropogenic influence on their freshwater regimes since the early 1970s (Déry et al., 2018).

2.2 Study domain

The domain of study is the NCRB, with a specific focus on 13 reservoirs within the basin. The simulation of the regulation applied to the outlets of these reservoirs within a hydrologic model makes up the core of this work. Although many of these reservoirs have a theoretical storage time of less than a year (no inter-annual storage), most have between one third and two thirds of a year of theoretical maximum detention time (Table 2-1), and the NCRB is classified as a heavily fragmented basin (Grill, 2014; Dynesius and Nilsson, 1994). The NCRB also has a high degree of natural storage (visually comparing the degree of hydrographic cover shown in Figure 2-1). The regulated storage capacity is heavily leveraged to re-apportion the mixed-to-nival flow regime (Table 2-3) (i.e., large rise in spring, slow fall drawdown, lowest flows in winter) to produce a hydrograph more consistent with hydroelectric production needs (i.e., flows held in the summer, released consistently throughout the winter), as shown by Déry et al. (2018).

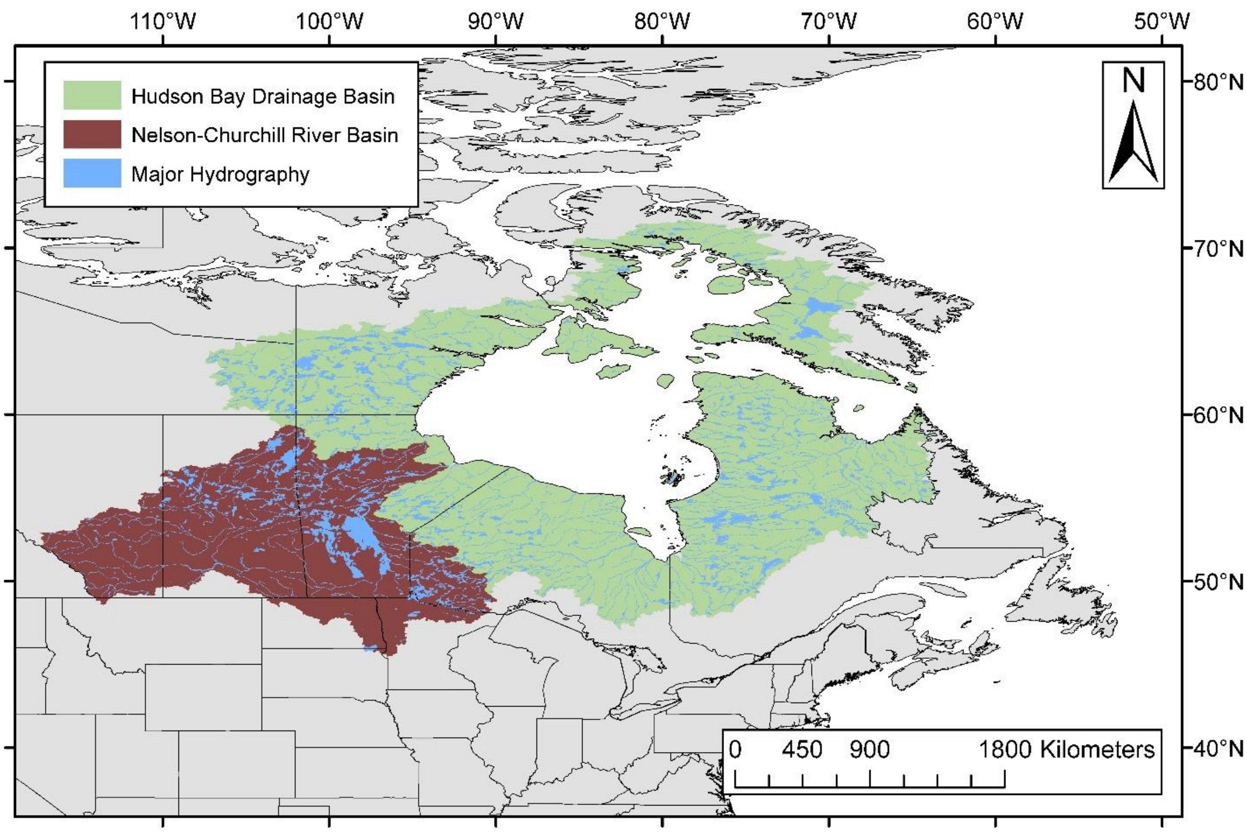


Figure 2-1: *The Nelson Churchill River Basin within the Hudson Bay Drainage Basin.*

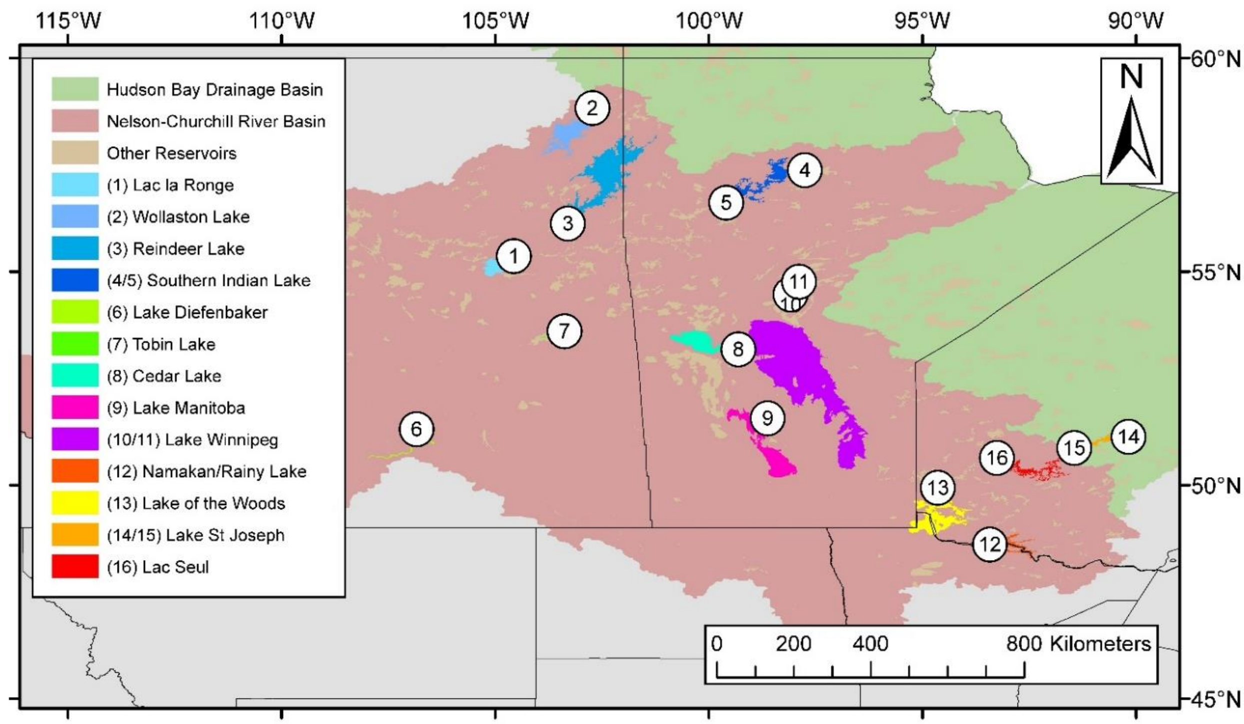


Figure 2-2: *Reservoir outlets in the H-HYPE model. Note that outlet numbers correspond to rows of Tables 2-1, 2-2, and 2-3 and Figure 2-3.*

The 13 reservoirs were selected to encapsulate the greatest downstream effect on flow. This is generally proportional to the potential storage (Table 2-1), as reservoirs with more storage will have a greater intra- and/or inter-annual effect on flow seasonality. The 10th and 12th through 15th ranked reservoirs (by total volume) were excluded from this study (Table 2-2). Though they are large reservoirs, their potential detention time was calculated as less than 2 weeks, which was the smallest of all evaluated reservoirs. These excluded reservoirs were: Split Lake, Stephens Lake, Sipiwesk Lake, and the Kelsey Generating Station (GS) Forebay on the Lower Nelson River and Umfreville Lake on the English River. Average discharge and average throughflow are calculated for the reservoirs using daily data from the sources in Table 2-4 over the period 1981-2010. HYPE reservoir surface area is derived from Global Lake and Wetland Database (GLWD) and Global Reservoir and Dam database (GRanD). Live depth is the depth in H-HYPE between the drought and flood level.

Live storage within HYPE is calculated as the live depth multiplied by the surface area (maximum theoretical change in storage). Detention time is the ratio of storage to average throughflow, expressed in years. Drainage area is calculated using upstream sub-basins in HYPE. Percentage of basin storage and storage rank are based on total live storage calculated for all regulated reservoirs within the NCRB in HYPE (85 reservoirs). All selected reservoirs had theoretical detention times greater than two weeks. The selected reservoirs make up 95% of the total regulated storage of the NCRB (Table 2-2). Of the reservoirs not selected for use in H-HYPE, those with a large volume (> 2.5% of the basin total storage volume) have a detention time less than two weeks (0.038 years) (i.e., Split Lake, Stephens Lake, Umfreville Lake, Sipiwesk Lake, Kelsey GS Forebay). Those excluded reservoirs with meaningful detention time (> 4 months) have a volume less than 2% of the total basin storage. There are two exceptions to this: Tobin Lake which *was* included despite being a smaller reservoir with less flow impact (detention time), and Red Lake which *was not* included despite having a large storage and high detention time. Tobin Lake was included as a test reservoir for the automatic parameter derivation using the RAT. Red Lake was excluded due to being located so far upstream that it had little impact on other reservoirs in the system.

Figure 2-3 isolates the regulated reservoirs used in this study and shows the relative locations of large storage basins in relation to mean throughflow. Lake Winnipeg (outlets 10, 11) has the largest regulated live storage in the basin and is sufficiently close to Hudson Bay to heavily affect the performance of the terrestrial outflow. Cedar Lake (8) is a large reservoir located immediately upstream of Lake Winnipeg. Cedar Lake’s outflow makes up ~20% of Lake Winnipeg’s inflow, heavily affecting Lake Winnipeg’s ability to regulate its outflow properly. Lake St. Joseph (14, 15) diverts water from its natural outlet in the Albany River watershed (14) to the Winnipeg River generating complex via the Root River diversion (15). Southern Indian Lake (SIL) (4, 5) is a relatively small reservoir (by detention time), but is the location of the Churchill River Diversion (CRD), which diverts more than three quarters of the Churchill River flow (~750 $m^3 s^{-1}$) to the Lower Nelson River Basin (LNRB) generating complex. The performance of the CRD (5) therefore heavily influences the performance of the regulated LNRB, and the Churchill River outlets. SIL (4) at the Missi Falls control structure is the furthest downstream regulation point of the Churchill River modelled in this study.

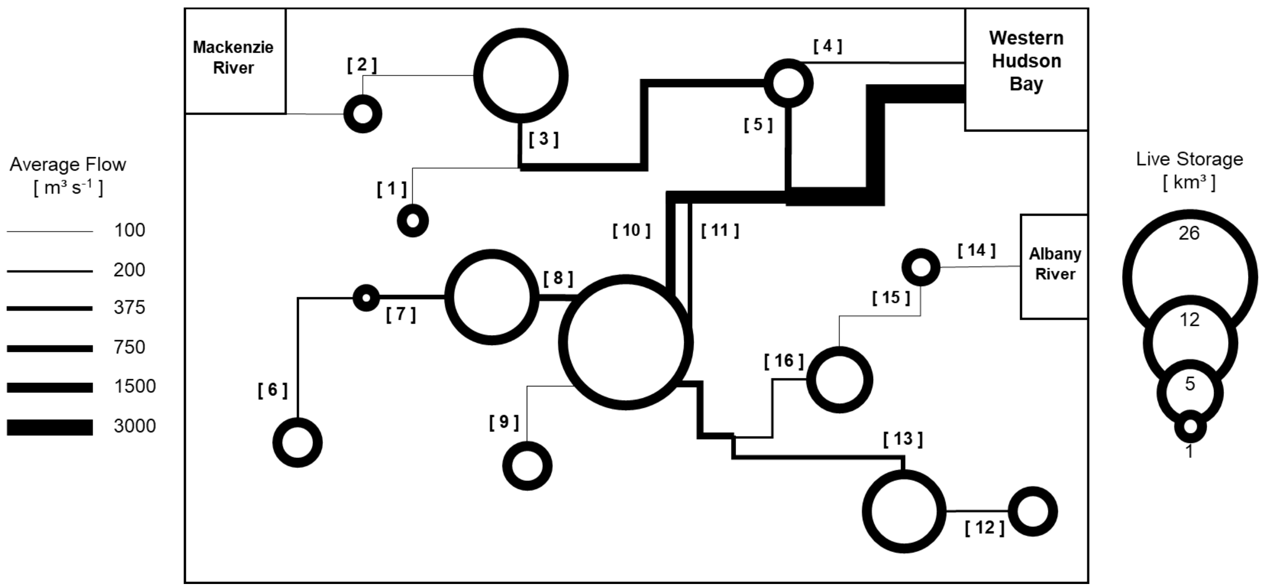


Figure 2-3: *Storage volume and average streamflow for NCRB regulated reservoir system within HYPE. Note that outlet numbers correspond to Figure 2-2, Table 2-1, and Table 2-2. Adapted from Manitoba Hydro Drawing (1986). Live storage and average flow calculated as described in Table 2-1. Live storage and average flow taken from Table 2-1.*

Table 2-1: *Regulated reservoir characteristics.*

#	Reservoir	Outlet	Average Inflow**	Surface Area*	Active Depth*	Live Storage*	Detention Time*	Drainage Area*	Operated by***	Average Discharge**	Basin Storage*	Storage Rank*
			[m^3 s^{-1}]	[km^2]	[m]	[km^3]	[years]	[km^2]	[Agency]	[m^3 s^{-1}]	[%]****	[-]
1	Lac la Ronge	la Ronge C.S.	12	1318	0.80	1.05	2.784	15,679	PC	12	1.7	17
2	Wollaston Lake	Cochrane River outlet	96	2272	0.75	1.70	0.562	18,240	N/A	96	1.0	19
3	Reindeer Lake	Whitesand Dam	347	5596	2.50	13.99	1.278	65,001	SP	347	13.8	2
4	S. Indian Lake	Missi Falls C.S.	926	2227	1.40	3.11	0.107	264,706	MH	145	3.1	11
5		Notigi C.S.								781		
6	Lake Diefenbaker	Gardiner Dam G.S.	181	458	7.00	3.21	0.561	155,162	SP / SWA	181	3.2	9
7	Tobin Lake	EB Campbell G.S.	420	262	2.00	0.52	0.040	343,316	SP	420	0.5	22
8	Cedar Lake	Grand Rapids G.S.	531	2817	4.00	11.27	0.672	394,025	MH	531	11.1	3
9	Lake Manitoba	Fairford Dam C.S.	82	4791	0.80	3.83	1.481	86,180	MH	82	3.8	7
10	Lake Winnipeg	Jenpeg G.S.	2278	23809	1.10	26.19	0.364	1,006,783	MH	1918	25.8	1
11		Nelson River East Ch.								359		
12	Namakan / Rainy Lake	Fort Frances G.S.	282	1274	3.00	3.82	0.429	37,222	LWCB / IJC	282	3.8	8
13	Lake of the Woods	Whitedog G.S.	462	4168	1.50	6.25	0.429	69,457	LWCB / IJC	461	6.2	4
14	Lake St. Joseph	Albany River outlet	103	628	2.60	1.63	0.502	14,011	LWCB / OPG / MH	21	1.6	18
15		Root Diversion C.S.								82		
16	Lac Seul	Ear Falls G.S.	286	1611	2.90	4.67	0.518	26,210	LWCB / MH	286	4.6	5

C.S.: Control Structure, G.S. Generating Station

* Physical characteristics taken from A-HYPE model: Global Lake and Wetland Database (GLWD: Lehner and Döll, 2004), Global Lake Database v2 (Kourzeneva, 2010), Global Reservoir and Dam database (GRaND v1.1: Lehner et al., 2011).

** Discharge characteristics taken from 1981-2010 Water Survey of Canada (WSC) records. Inflow records are gap-filled (Section 2.3.2.1), outflow records are calculated as available.

*** PC: Parks Canada, N/A: no regulation or operator, SP: SaskPower, MH: Manitoba Hydro, SWA: Saskatchewan Watershed Authority, LWCB: Lake of the Woods Control Board, IJC: International Joint Commission, OPG: Ontario Power Generation.

**** Represents percentage of NCRB regulated reservoir (live) storage contained in that reservoir

Table 2-2: *Values and rankings of live storage volume and detention time for the 25 largest (by storage) reservoirs within the NCRB.*

Reservoir	Basin Volume	Cumulative Volume	Volume Rank	Basin Detention	Cumulative Detention	Detention Rank	H-HYPE Number
	[%]	[%]	[-]	[%]	[%]	[-]	[-]
Lake Winnipeg	25.8	25.8	1	1.3	1.3	18	10 / 11
Reindeer Lake	13.8	39.6	2	4.5	5.7	7	3
Cedar Lake	11.1	50.7	3	2.4	8.1	10	8
Lake of the Woods	6.2	56.9	4	1.5	9.6	16	13
Lac Seul	4.6	61.5	5	1.8	11.4	13	16
Lake Manitoba	3.8	65.3	7	5.2	16.6	6	9
Namakan/Rainy Lake	3.8	69.1	8	1.5	18.1	15	12
Lake Diefenbaker	3.2	72.2	9	2.0	20.1	12	6
S. Indian Lake	3.1	75.3	11	0.4	20.4	19	4 / 5
Wollaston Lake	1.7	77.0	17	2.0	22.4	11	2
Lake St. Joseph	1.6	78.6	18	1.8	24.2	14	14 / 15
Lac la Ronge	1.0	79.6	19	9.7	33.9	5	1
Tobin Lake	0.5	80.1	22	0.1	34.1	21	7
Red Lake	4.2	84.3	6	15.5	49.6	1	Not used in H-HYPE model
Split Lake	3.1	87.4	10	0.1	49.7	22	
Stephens Lake	2.5	89.9	12	0.1	49.8	24	
Umfreville Lake	1.9	91.9	13	0.2	50.0	20	
Sipiwesk Lake	1.8	93.7	14	0.1	50.1	23	
Kelsey G.S. Forebay	1.8	95.5	14	0.1	50.2	25	
Abraham Lake	1.7	97.3	16	3.4	53.6	8	
Ottertail Lake	0.7	97.9	20	13.2	66.8	4	
Rafferty Lake	0.6	98.6	21	14.1	80.9	3	
Brazeau Reservoir	0.5	99.0	23	1.4	82.3	17	
Oldman Reservoir	0.5	99.5	23	2.5	84.8	9	
Shellmouth Reservoir	0.5	100.0	25	15.2	100.0	2	

The upstream basins of each reservoir are largely nival regimes (Table 2-3). The snowfall ratio, coupled with low mean annual temperatures, produces a deep snowpack which melts rapidly in spring. With cold winters (below freezing), there is significant snowfall (static storage), with subsequent snow melt (live storage), yielding a hydrograph dominated by a large spring flood. Such hydrograph responses are typical throughout northern Canada, but are inconsistent with desired average annual hydroelectric outflows. The most clearly nival upstream basins occur in the Churchill River basin (including the large Reindeer Lake and Southern Indian Lake reservoirs). Compared to the NCRB as a whole, Lake Winnipeg also shows an above average depth of snowfall but a less than average snowfall ratio.

Table 2-3: *Mean values of annual meteorological input (averaged 1981-2010) of upstream watershed area, by reservoir (generated using H-HYPE with HydroGFD forcing, Berg, 2017). See Table 2-1 for drainage areas. Columns next to mean values indicate greater (+) or less (-) than basin mean (last row). Note that numbers correspond to Figure 2-2.*

#	Reservoir	Yearly Total Rainfall [mm]		Yearly Total Snowfall [mm]		Yearly Total Precipitation [mm]		Percent Snow [%]		Yearly Mean Temperature [°C]	
1	Lac la Ronge	326	-	121	+	447	-	27	+	0.44	-
2	Wollaston Lake	290	-	142	+	432	-	33	+	-3.02	-
3	Reindeer Lake	301	-	146	+	447	-	33	+	-3.06	-
4 / 5	S. Indian Lake	323	-	129	+	452	-	29	+	-1.04	-
6	Lake Diefenbaker	309	-	114	-	423	-	27	+	4.07	+
7	Tobin Lake	318	-	114	-	431	-	26	+	3.00	+
8	Cedar Lake	322	-	114	-	436	-	26	+	2.67	+
9	Lake Manitoba	364	-	112	-	476	-	24	-	1.57	+
10 / 11	Lake Winnipeg	387	+	110	-	497	+	22	-	2.64	+
12	Namakan/Rainy Lake	580	+	142	+	722	+	20	-	2.78	+
13	Lake of the Woods	563	+	128	+	691	+	19	-	3.00	+
14 / 15	Lake St. Joseph	510	+	185	+	695	+	27	+	1.01	-
16	Lac Seul	544	+	175	+	719	+	24	-	1.87	+
N/A	**Nelson-Churchill Basin**	**370**		**118**		**488**		**24**		**1.44**	

2.3 Methodology

2.3.1 Dam modelling

2.3.1.1 Dams in the default HYPE model

The HYPE hydrological model (Lindström et al., 2010), developed by the Swedish Meteorological and Hydrological Institute (SMHI), includes a dam routine that simulates the basic processes involved in reservoir regulation. This HYPE dam routine includes sub-routines for four dam types, used for different applications: (1) irrigation, (2) water supply, (3) hydroelectric and (4) flood control. Reservoirs can use one outlet or multiple outlets (to separate downstream sub-basins). Two new sub-routines are proposed to be added to the HYPE model-code (developed in FORTRAN) with deeper parameterization and potential for customization, while maintaining general applicability.

This generality allows the routines to be applied to any reservoir with a minimum of set-up data necessary prior to running the model. The new routine was applied to various reservoirs throughout the Nelson-Churchill River Basin (NCRB), to improve robustness of historic results and reliability of future results. The existing HYPE routine for regulated dams blends conceptual parameterization and physically-based variables (Lindström et al., 2010). Complete details regarding the routines governing dam outflow operations in HYPE can be found on SMHI's HYPE wiki under the Rivers and Lakes section ("River and Lakes", 2018). Figure 2-4 contains a visual representation of the behavioural response and variables employed.

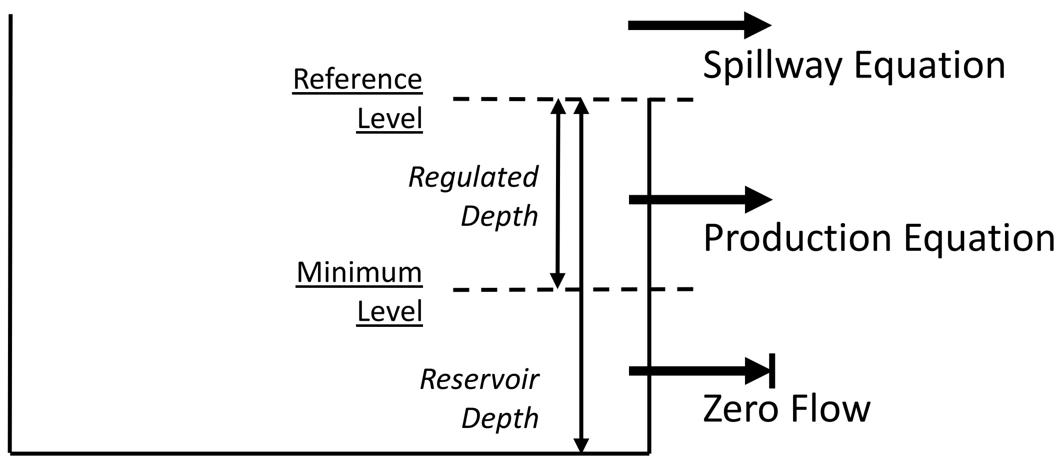


Figure 2-4: *Conceptual diagram describing HYPE dam regulation variables and outflow type used at each level. Adapted from diagram found in SMHI's HYPE wiki ("Rivers and Lakes", 2018).*

Reservoirs in HYPE are divided into lakes and dams, whose outflows are natural and regulated, respectively. Both are modelled as rectangular storage units with uniform surface area and variable depth. Computation of daily dam outflow will take different algorithmic paths depending on Water Surface Level (WSL) (also calculated daily) and two threshold parameters (described in Figure 2-4 as Minimum Level and Reference Level). These levels divide the reservoir into three stages: low-flow stage (below Minimum Level), spillway-flow stage (above Reference Level), and production-flow stage (between Minimum and Reference Levels). How water is withheld or discharged from the reservoir in the production-flow stage will depend on the user specified dam type (i.e., irrigation, water supply, flood control or hydroelectricity).

$WSL_i \leq WSL_{min}$	$Q_i = 0$	[Equation 2-1a]
$WSL_{min} \leq WSL_i \leq WSL_{ref}$	$Q_i = \emptyset_{prod} \times \left(\emptyset_{amp} \times \sin\left(\frac{2 \times \pi \times (DOY_i + \emptyset_{phase})}{365}\right)\right)$	[Equation 2-1b]
$WSL_{ref} \leq WSL_i$	$Q_i = \emptyset_{coeff} \times \left(WSL_i - WSL_{ref}\right)^{\emptyset_{exp}}$	[Equation 2-1c]

i	time-step of computation
WSL_i	current computation water surface level
DOY_i	current computation day-of-year (Julian Day)
WSL_{min}	water surface level for production flow (lower limit)
WSL_{ref}	water surface level for production flow (upper limit)
$Ø_{prod}$	production flow sine-curve mean value
$Ø_{amp}$	production flow sine-curve amplitude
$Ø_{phase}$	production flow sine-curve phase (in days) of origin
$Ø_{coeff}$	spillway outflow curve coefficient
$Ø_{exp}$	spillway outflow curve exponent

Prior to this study and within the BaySys group of projects, two important reservoirs for hydroelectric production were embedded and overtly coded into the HYPE model (MacDonald et al., in revision): Southern Indian Lake (Churchill River Diversion) and Lake Winnipeg Regulation (Jenpeg generating station). All other regulation points were calibrated for the HBDB using the existing HYPE regulation routine (Stadnyk et al., in press) and all HYPE dams simulated in the HBDB were modelled as hydroelectric dams with a sine curve outflow (Equation 2-1b).

2.3.1.2 Manitoba Hydro dam models

Thirteen reservoirs of regional importance and industrial interest were selected for this study (Figure 2-2, 2-3 and Tables 2-1, 2-2). Each was converted from an existing HYPE dam (referred to as Arctic HYPE or A-HYPE dams) to an updated HYPE dam (referred to as Hudson HYPE or H-HYPE dams) using the new dam routine developed in this study.

The rationale used for the development of two new dam types in H-HYPE was derived from the synthesis of seven reservoir regulation spreadsheet models developed by Manitoba Hydro (MH) using Microsoft Excel®, with specific sets of rules and algorithms for each site. These sites were: (1) Lake Winnipeg, (2) Southern Indian Lake, (3) Reindeer Lake, (4) Cedar Lake, (5) Lake St. Joseph and Lac Seul, (6) Namkan Lake, Rainy Lake, and Lake of the Woods, and (7) Lake Diefenbaker. These spreadsheet models were developed using proprietary operational reports and some proprietary WSL and flow records (listed in Table 2-4), which were obtained from Manitoba Hydro (personal communications, Phil Slota and John Crawford). Manitoba Hydro models were driven only by their inflow time-series, and were not explicitly integrated into any hydrological modelling framework. This means the reservoirs were not affected by evaporation or precipitation, and that the performance of one spreadsheet model was independent of any of the others, regardless of where it appeared in the real-life drainage order. The models employed highly specific algorithms, sub-routines and processes particular to each reservoir. Each reservoir's operational methodology varied by its role or significance within the larger hydroelectric complex, or the specifics of its inter-jurisdictional importance. This high degree of specificity translated to a high degree of accuracy for studies undertaken by Manitoba Hydro; however, the proprietary nature of the rules for each reservoir, and the degree of specificity of each rule, made this approach undesirable for hydrological modelling.

With the desire to integrate a new reservoir regulation routine into HYPE, coding these rules as they existed would have introduced several problems. First, their high degree of specificity would have made it difficult to code them directly into HYPE without creating many additional parameters and variables while introducing a significant “black-box” effect during model calibration (Kirchener, 2006). This would introduce significant model structural and parameterization uncertainty since users would be unaware of the processes used within the model, and unable to calibrate regulation processes in a meaningful (physically-based) way (Beven, 2012; Juston et al., 2013). Second, several of the existing spreadsheet models were developed by aggregating multiple reservoirs together. The high degree of interaction between individual reservoirs may be indispensable for Manitoba Hydro’s internal needs, but imposed a structural limitation on their integration into a semi-distributed, sub-basin scale hydrological model where multiple sub-basins existed between reservoirs. Namakan Lake and Rainy Lake, for example, are lumped together in the H-HYPE model due to the original delineation from the A-HYPE sub-basins, but exist ten sub-basins upstream of Lake of the Woods. These three reservoirs were modelled together by MH, but is impractical in HYPE.

2.3.1.3 New dam routine development

Two generalized reservoir sub-routines were created to best capture the strengths and benefits of the highly-specified (non-generalized) MH models, without introducing the weaknesses (in the context of a semi-distributed hydrologic model) of their over-specialization. For simple reservoirs with one outlet, an **InLine** model (reservoirs with an inflow and only one outflow) was developed. More complex reservoirs were simulated by developing an **O**ffline, **C**onditioned, **B**ifurcated, or **D**iversion (**OCBD**) model. The latter was used to simulate regulation that used reservoir storage for hydroelectric generation done on a downstream river (offline storage); reservoirs whose operations are dependent on another reservoir or stream (conditioned outflows); reservoirs with two outlets (bifurcated reservoirs) or, reservoirs used to move flows into/out of a separate stream or watershed system (diversion outlets). The InLine and OCBD models were developed for the NCRB in such a way that any reservoir could be modelled at least as or more accurately, than they could otherwise be simulated using the built-in A-HYPE dam routine. A requirement was to use only readily available inputs (i.e., flow records, WSL records) to force the model. Running the operations of a new reservoir using this routine required any three of the following four data sets: stage-storage relationship, inflow record, outflow record, and water surface level record. Parameters were added to the limited parameterization of HYPE to modify the regulation processes used. These are discussed in-depth in Section 2.3.3 (H-HYPE Dam Routine Development).

2.3.2 Reservoir data

2.3.2.1 Hydraulic characteristics

Before introducing new code to HYPE, both the InLine and OCBD models were developed in a reservoir analysis tool (RAT) created in Microsoft Excel®. This tool replicated the routine added to H-HYPE, but allowed more efficient calibration. Calibration was done in this spreadsheet model rather than within H-HYPE to save computation time required to run the full hydrological model. The sub-model encompassing the NCRB requires approximately one hour to run, which would have made calibration too time-consuming. Full hydrologic processes are applied in HYPE, but when using this external reservoir simulation tool, losses due to evapotranspiration and gains from precipitation on/off the reservoir surface were ignored (as in the original Manitoba Hydro models). This eliminated the need for temperature or precipitation records. These processes are applied again once the code is embedded into HYPE, but ignored in calibration. This tool was used only for model development and calibration; validation results (generated in H-HYPE) are presented in Section 2.4. The scope of the BaySys group of projects excludes optimization of cascading reservoirs. Reservoirs were calibrated individually on their individual skill scores, not on an aggregated basin-wide score. Regulation rules were also designed to be static. These rules do not change or adapt to future climatological conditions. The rules are based on safe reservoir levels and once calibrated are fixed for the simulation period. In future studies, reservoirs will be operated using the same rules they currently employ in the developed regulation routine. To achieve reliable results with these static rules, the reservoir operation routines must strive to maintain safe reservoir levels, rather than dictating optimal outflow (as inflows are likely to change in the future). No future development of hydroelectric resources within the NCRB was also assumed. This is known to be untrue, but was necessary as it is impossible to define when and where those developments may occur and what their operating conditions may be.

Much like its Manitoba Hydro (MH) predecessors, the RAT required only one hydrologic/hydraulic input (i.e., aggregated daily inflow from all tributaries, referred to hereafter as inflow or Q_{in}). The output generated by this model (i.e., water surface elevation, WSL in metres above sea level or MASL, and daily outflow, called Q_{out}, in cubic metres per second or $m^3 s^{-1}$) was used for outflow calibration at the outlet(s). Accuracy and robustness of the calibration required long, gap-free records for Q_{out} and WSL. Many of these data are made publicly available (WSC, 2016), all others were obtained from other sources (Table 2-4), or derived synthetically (Section 2.3.2.1).

Where direct records were unavailable of inflow to a reservoir from a gauged station upstream that included all tributaries (WSC, 2016), flows from the *nearest* upstream station were extracted and scaled-up using proportional drainage areas to develop an inflow record for the reservoir. Where significant gaps existed in these data (> 2 days), gap-filling was performed using the next upstream station and proportional area scaling (Déry et al., 2016; Hernandez-Henriquez et al., 2010; Déry et al., 2005). Shorter gaps in flow data (≤ 2 days) were in-filled using simple linear interpolation. Outflow and WSL were also extracted from the Water Survey of Canada (WSC) database but were not gap-filled since these data were used exclusively for calibration. Existing gaps were preserved (but ignored during calibration and other statistical calculations) so as not to introduce added uncertainty into the results. Where no inflow data were available (i.e. where an upstream gauged station excluded ungauged tributaries), synthetic time series were developed to derive inflows for the model. These were created using a relationship between storage, Q_{out}, Q_{in} and WSL (summarized in Table 2-4). This followed standard practice used by Manitoba Hydro and was consistent with their analyses of regulated reservoirs (personal communications, Phil Slota and John Crawford).

Once synthetic inflows were generated, they were smoothed using a moving-window average of 15 days (centred on day 7) to remove the effect of "wind-push". A wind-push event can cause artificially high or low water levels that result in excessive *perceived* storage change and then a spiking of the synthetic inflow (or outflow) time series when calculating a synthetic timeseries. Correct application of the synthetic inflow record method relies heavily on development of an accurate WSL-volume relationship (i.e., stage-storage curve). Such relationships are typically published in guidelines or operational documents by governing agencies for sufficiently sized reservoirs, where there is an ecological or hydrological impact of water control. Published guidelines are available for public reservoirs (i.e. Lake of the Woods Control Board, Lake Diefenbaker), but may be proprietary for privately operated reservoirs (e.g., Reindeer Lake). In these cases, stage-storage relationships have been determined from historical records.

Rules for the new regulation were derived using records from 2001 to 2010, referred to hereafter as the reference period. This reference period was selected to provide the most up-to-date as possible regulation rules for the studied historical period. The statistical performance of the new routine was tested over a validation period from 1981 to 2010.

Observed inflow records are also used in the direct comparison of A-HYPE and H-HYPE. All 13 reservoirs in both HYPE models are forced using observed inflow. This allows direct testing of each reservoir's performance, rather than testing the overall cascading statistical error effects of the reservoir regulation. This also excludes reliance on the upstream hydrological performance of the overall HYPE model, creating the purest evaluation of each reservoir's regulation skill.

Table 2-4: *Source of total inflow, outflow and water surface level datasets by reservoir and modifications made.*

Reservoir	River	Data Type	WSC Gauge	Period	Alteration
Lac la Ronge	N/A	WSL	06CB001	1930-2015	Unaltered
	Montreal River	Q_{in}	06CA001	1967-2015	Unaltered
	Rapid River	Q_{out}	Synthetic	1981-2010	N/A
Wollaston Lake	N/A	WSL	06AD001	1971-2015	Unaltered
	Cochrane River	Q_{out}	06DA002	1968-2016	Scaled Down
	Fond du Lac River	Q_{out}	Synthetic	1981-2010	N/A
	Geikie River	Q_{in}	06DA004	1966-2015	Scaled Up
Reindeer Lake	N/A	WSL	06DB001	1930-2016	Unaltered
	Reindeer River	Q_{out}	06DD002	1985-2016	Unaltered
	Reindeer River	Q_{out}	06DB002	1929-1987	Unaltered
	Cochrane River	Q_{in}	06DA002	1968-2015	Scaled Up
	Wathaman River	Q_{in}	06DC001	1071-2015	Scaled Up
S. Indian Lake	N/A	WSL	06EC001	1956-2016	Unaltered
	Churchill River	Q_{in}	06EB004	1973-2016	Scaled Up
	Churchill River	Q_{out}	06FB001	1960-2016	Scaled Down
	Gauer River	Q_{out}	06FA001	1979-2016	Tributary
	S. Channel Diversion	Q_{out}	06EC002	1993-2010	Unaltered
	S. Channel Diversion	Q_{out}	Synthetic	1981-1993	N/A
Lake Diefenbaker	N/A	WSL	05HF003	1964-2015	Unaltered
	S. Saskatchewan River	Q_{out}	05HG001	1911-2015	Scaled Down
	Total Inflow	Q_{in}	Synthetic	1981-2010	N/A
Tobin Lake	N/A	WSL	05KD004	1962-2015	Unaltered
	Saskatchewan River	Q_{out}	05KD003	1962-2015	Scaled Down
	Total Inflow	Q_{in}	Synthetic	1981-2010	N/A
Cedar Lake	N/A	WSL	05KL005	1940-2014	Unaltered
	Saskatchewan River	Q_{out}	05KL001	1909-2014	Unaltered
	Saskatchewan River	Q_{in}	05KJ001	1913-2016	Scaled Up
Lake Manitoba	N/A	WSL	05LK002	1923-2016	Unaltered
	Fairford River	Q_{out}	05LM001	1912-2015	Unaltered
	Waterhen River	Q_{in}	05LH005	1950-2015	Unaltered

	Whitemud River	Q_{in}	05LL002	1971-2015	Scaled Up
	Portage Diversion	Q_{in}	05LL019	1970-2015	Unaltered
Lake Winnipeg	N/A	WSL	05RE003	1983-2015	Unaltered
	Nelson River E. Channel	Q_{out}	05UB008	1967-2014	Scaled Down
	Nelson River JENPEG	Q_{out}	05UB009	1975-2014	Scaled Down
	Dauphin River	Q_{in}	05LM006	1077-2015	Unaltered
	Saskatchewan River	Q_{in}	05KL001	1909-2014	Unaltered
	Winnipeg River	Q_{in}	05PF063	1907-2014	Scaled Up
	Red River	Q_{in}	05OJ010	1962-2008	Scaled Up
	Pigeon River	Q_{in}	05RD008	1957-1996	Scaled Up
	Beren's River	Q_{in}	05RD007	1957-1992	Scaled Up
	Poplar River	Q_{in}	05RE001	1967-1996	Scaled Up
	Total Inflow	Q_{in}	Partial Synth.	1981-2010	N/A
Namakan / Rainy Lake	N/A	WSL	05PB007	1911-2015	Unaltered
	N/A	WSL	05PA003	1912-2007	Unaltered
	Rainy River	Q_{out}	05PC019	1905-2015	Unaltered
	Seine River	Q_{in}	05PB009	1963-2015	Scaled Up
	Turtle River	Q_{in}	05PB014	1914-2015	Scaled Up
	Namakan River	Q_{in}	05PA006	1921-2015	Scaled Up
Lake of the Woods	N/A	WSL	05PE012	1913-2015	Unaltered
	LOTW Eastern Outlet	Q_{out}	05PE006	1907-2015	Unaltered
	LOTW Western Outlet	Q_{out}	05PE011	1913-2015	Unaltered
	Rainy River	Q_{in}	05PC018	1928-2015	Scaled Up
Lake St. Joseph	N/A	WSL	05GA004	1934-1994	Unaltered
	N/A	WSL	LCWB	1994-2010	N/A
	Albany River	Q_{out}	04GA001	1968-1994	Unaltered
	Albany River	Q_{out}	04GC002	1970-2015	Scaled Down
	Albany River	Q_{out}	Synthetic	1994-2006	N/A
	Root River	Q_{out}	05QB006	1957-1994	Unaltered
	Root River	Q_{out}	Synthetic	1994-2010	N/A
	Cat River	Q_{in}	04GA002	1970-2015	Unaltered
Lac Seul	N/A	WSL	05QB003	1917-2016	Unaltered
	English River	Q_{out}	05QE006	1907-1994	Unaltered
	English River	Q_{out}	OPG	1994-2010	N/A
	Root River	Q_{in}	05QB006	1957-1994	Unaltered
	Total Inflow	Q_{in}	Synthetic	1981-2010	N/A

The H-HYPE regulation routine was developed to include new regulated reservoirs in the larger HYPE model with little to no availability of proprietary data. A new reservoir can be added into the larger H-HYPE model by analyzing it in the offline spreadsheet tool with only an inflow record for model function and WSL, or outflow records for calibration. The model only requires (generally) publically available data, such as maximum and minimum WSLs. In this way, it incorporates the simpler elements of other models such as the Water Evaluation and Planning (WEAP; Kirshen et al, 1995) or MODSIM (Graham et al., 1990) models, while excluding the need for complex and proprietary system optimization rules or turbine efficiency curves. For the purposes of BaySys, dynamic optimization of reservoirs for power production, or financial gain, is ignored, with the maintenance of safe reservoir levels prioritized instead.

2.3.2.2 Operational summaries

Data used in creating ideal WSL curves have been obtained from operating guidelines and publically available reports produced by regulators, including the Saskatchewan Watershed Authority (SWA), the Lake of the Woods Control Board (LWCB), Manitoba Hydro (MH), SaskPower (SP) and Ontario Power Generation (OPG). Some data were obtained through personal communication with regulators and internal, proprietary reports (Table 2-5). Those reservoirs with their data-source listed as "none" were calibrated without any operational guidelines. These were used to test the ability of the RAT to be applied to new reservoirs with only inflow, outflow and WSL records. These reservoirs were generally smaller (e.g., Lake Manitoba, Lac la Ronge, Tobin Lake, and Wollaston Lake).

Reservoirs with "MH Proprietary" listed as their source were modelled initially by Manitoba Hydro. These reservoirs were initialized for H-HYPE using the automatic calibration of the RAT. Afterward, minor calibrations were done using the operational guidelines where the rules they describe were compatible with functions available in the new regulation routine.

Table 2-5: *Sources used for operational summaries to develop reservoir routine in H-HYPE. "Synth." records are synthetic inflow records, "WSC" records are WSC data, and "Mixed" are mixed synthetic and WSC data records.*

#	Reservoir	Outlet	WSL	Q_{in}	Q_{out}	Operational Data Used in H-HYPE	Reference
1	Lac la Ronge	la Ronge C.S.	WSC	WSC	Synth	**None**	--
2	Wollaston Lake	Cochrane River outlet	WSC	WSC	WSC	**None**	--
3	Reindeer Lake	Whitesand Dam	WSC	WSC	WSC	MH Proprietary	--
4	S. Indian Lake	Missi Falls C.S.	WSC	WSC	WSC	MH report	"Regional Cumulative Effects…" (2015) Manitoba Hydro
5		Notigi C.S.			Mixed		
6	Lake Diefenbaker	Gardiner Dam G.S.	WSC	Synth	WSC	Published	Shook and Pomeroy, 2015
7	Tobin Lake	EB Campbell G.S.	WSC	Synth	WSC	**None**	--
8	Cedar Lake	Grand Rapids G.S.	WSC	WSC	WSC	MH Proprietary	--
9	Lake Manitoba	Fairford Dam C.S.	WSC	WSC	WSC	**None**	--
10	Lake Winnipeg	Jenpeg G.S.	WSC	WSC	WSC	MH report	"Water Power Licences…" (2010) Manitoba Hydro "Lake Winnipeg Regulation" (2014) Manitoba Hydro
11		Nelson River East Ch.			WSC		
12	Namakan/Rainy Lake	Fort Frances G.S.	WSC	WSC	WSC	Lake of the Woods Control Board website	"Lake of the Woods", 2006
13	Lake of the Woods	Whitedog G.S.	WSC	WSC	WSC		
14	Lake St. Joseph	Albany River outlet	Mixed	WSC	Mixed		
15		Root Diversion C.S.			Mixed		
16	Lac Seul	Ear Falls G.S.	WSC	Mixed	Mixed		

2.3.3 H-HYPE dam routine development

In both the InLine and OCBD dam routines, the reservoir is divided into seven stages based on seven WSLs (Figure 2-5). The stage of the flow for each simulated day will dictate the behaviour of the reservoir outlet. WSL_{fl} and WSL_{dr} are user specified as a two, year-round values. These can be specified as a minimum/maximum historical observed value, or based on operational guidelines where available (Table 2-5). WSL_{tr+} and WSL_{tr-}, the upper and lower extents of the transition zones, are specified by a single parameter that indicates the distance between WSL_{op+} and WSL_{op-} and the outer edge of their respective transition zones. WSL_{op+} and WSL_{op-} are specified using two sets of 12 parameters (first day of each month for both zones).

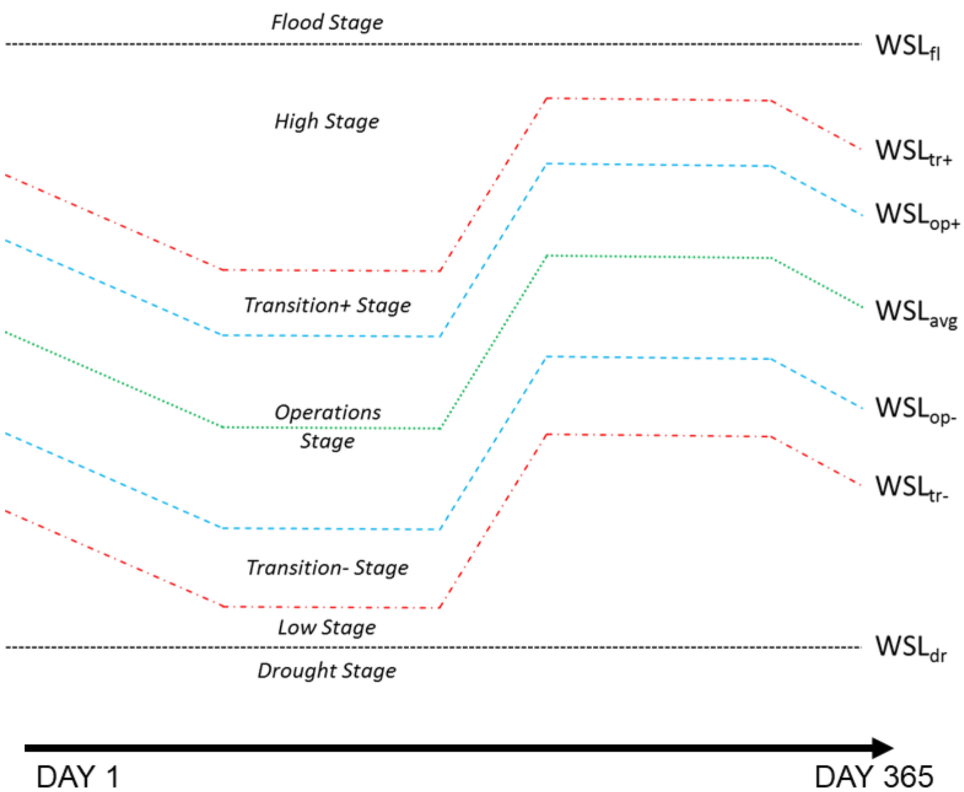


Figure 2-5: *Water surface levels (WSLs) specified in H-HYPE regulation routine and stages between (and outside) those WSLs, which govern outflow behaviour.*

2.3.3.1 Governing WSL stages and storage function

Seven daily water surface levels (WSL for day *i*) describing the seven stages used to determine reservoir outflow are computed using Equation A-3 (Table A-1). The user specifies the upper and lower boundary of the operations-stage for the first day of each month, allowing the user to calibrate without excessive parametrization. Depths of the low-flow and high-flow stages are determined from three additional parameters; one specifying the depths of the transition zones, and two more that dictate the stage used for drought and flood-flow stages.

Daily inflow, daily outflow, and the depth-storage relationships are used to determine the daily stage (Figure 2-5) are described by Equation A-4 (Table A-1). A four-parameter stage-storage curve is used to explain complex or simple reservoir geometry. In the case of double outlets, because the WSL is shared, the stage of the reservoir is shared between both outlets. However, each outlet may have a different outflow-type option specified. Some outlet flow-type options are limited to primary or secondary outlets, detailed in Table 2-6.

2.3.3.2 Outflow functions available to all outlets

Within each stage, behaviour is user-specified based on the options from Table 2-6. Outflow functions are specified at each stage, for each outlet. The option selected will vary based on available information, or user-specified reservoir operation in the model. Several options (percentile, fixed stage-discharge, monthly stage-discharge, and fixed value) are available for both primary outlets (InLine and OCBD models) and secondary outlets (OCBD models only).

Equation A-5 (Table A-2) is used to calculate the day-of-year percentile flow ("*Perc.*" in Table 2-6). The percentile is user-specified for each stage based on historical data from the reference period (2001 to 2010). This option is available for all five stages where options are available (transition zones have a set function). A seven-day-centered moving-window average of the daily percentile is applied, with percentile flows used to mimic licensed, seasonally varying minimums (e.g., S. Indian Lake at Missi Falls), or seasonally varying maximum allowable outflows. Percentile flows are an approximation of the A-HYPE method that specifies a desired outflow by day-of-year. Using historical percentile flows to determine regulated flow is a safe method used for historical simulations with stationary climate and inflow trends; for this reason, it is largely unused in this study, as these results will be applied to future projections done in the work following this study. Only Missi Falls uses a percentile-based option for low-stage or operations-stage. This reflects the minimum outflow by day-of-year as specified by Manitoba Hydro's operating license.

Equation A-6 (Table A-3) is used to calculate daily outflow using a fixed stage-discharge curve (*"ABCD"* in Table 2-6). This option is available for low, operations, and high-flow stages. These curves relate the current WSL to the desired outflow using four parameters, which allow the user to develop a complex or simple (linear) relationship between historical stage and discharge or to mimic a known relationship for that reservoir (i.e., based on turbine efficiency, spillway geometry). These are used in instances where the relationship between stage and discharge is constant year-round, or the observed record data are insufficient to develop reliable monthly stage-discharge relationships. These curves are used in the high-flow stage for all but two reservoirs in H-HYPE due to their consistent performance and relatively little parameterization.

Equations A-7 and A-8 (Table A-4) are used to calculate daily outflow based on monthly stage-discharge relationships ("*Monthly*" in Table 2-6). The parameters of these linear relationships are determined using historical stage-discharge data and Equations A-9 to A-11 (Table A-4). This option is used for low-stage and operations-stage where inflow is less predictable, or storage is limited (i.e., by physical reservoir size or by strict governance of the reservoir). This option creates a stage-discharge relationship based on the aggregated data for that month, but the stages are defined and change daily. This makes outflows calculated using this option twice as sensitive to daily WSL, creating outflows that are more reactive throughout the year to WSL, and less driven by a storage-insensitive desired-outflow curve (as was seen in A-HYPE). The monthly stage-discharge curves are used to achieve more finely-tuned changes in behaviour throughout the year. When done with the automatically calculated monthly relationships (based on historical stage-discharge data), this bypasses any manual calibration.

Equation A-12 (Table A-5) is used to specify daily outflow where the stage is above flood-stage or below drought-stage (i.e., available for flood and drought stage only; *"Ecological"* or "*Fixed Max.*" in Table 2-6 for drought and flood, respectively). This method is applied to flood-stage where there is a fixed, maximum allowable outflow based on safety or downstream channel geometry, and is applied for drought-stage where there is a fixed, minimum allowable outflow based on ecological demands or downstream flow needs (i.e., a municipal supply). The only other option available for flood-stage is to extend the option selected for the high-stage flows ("*Extend*" in Table 5). Since high-stage outflow is generally sensitive to WSL, extending the high-stage flow option to flood-stage generally results in intensified outflow under extreme-high water scenarios, which is consistent with real-world operations. The majority of reservoirs use a fixed value drought-stage flow. These are largely ecological minima specified by the operating bodies' governing rules enforced/imposed by regulatory bodies. The diversion flow from SIL uses a fixed maximum to simulate the maximum allowable flow through the Notigi CS of 961 $m^3 s^{-1}$.

2.3.3.3 Outflow functions available to specific outlets

Within the OCBD sub-routine, reservoirs can have one or two outlets. These are used (two outlets) for reservoirs with diversions or bifurcated reservoirs. OCBD reservoirs can also be used for complex routines (single outlet) that are not available in the InLine sub-routine. Two additional options for the operations-stage of the primary outlet, and one additional option for the high-stage of the secondary outlet are described below.

Equations A-13 and A-14 (Table A-6) are used to determine the daily outflow (i.e., operations-stage for primary outlets only) based on the ideal daily storage ("*Ideal S*" in Table 2-6). This method calculates the outflow necessary to reach ideal storage (specified by the center line of the operations-stage, $WSL_{avg, i}$), and provides a realistic rate of change in WSL that is scaled by the distance between the current day WSL and the WSL associated with ideal storage. From these, the desired outflow is calculated based on storage change over the past two weeks and outflow records. This option is employed in reservoirs with limited outflow records and is also useful for limiting the parameterization of a reservoir. No additional parameters are used in this option, as all calculations are done using specified limits of the operations-stage.

Equation A-15 (Table A-6) is used to calculate the daily outflow (high-stage for secondary outlets only) based on the past week of inflow and outflow records from the primary outlet ("*S Comp.*" in Table 2-6). This method uses only a seven-day record (rather than the 14-day record used for the ideal storage method) to be able to respond to shorter, more intense high-inflow events. The method determines the difference between the recent volumes of water entering and leaving the reservoir, and determines how much should be released to compensate the primary outflow back to the ideal storage range. It is only used in high-stage scenarios, where the volume entering the reservoir exceeds that leaving the reservoir. This option also self-corrects to only release the calculated flow if it is greater than the low-stage secondary outflow calculated for that day. This prevents negative outflows or unrealistically low outflows. This option is used to simulate secondary outlets operated to gradually empty a reservoir whose stage is rising and approaching a dangerous level (i.e. where the flow in the secondary outlet is not heavily governed, but used to protect reservoir levels). The ideal storage and storage compensation functions both rely on the daily storage, so they can only be applied to separate stages and separate outlets (in development, these methods made the model unstable if jointly applied).

Equation A-16 (Table A-7) is used to calculate the daily outflow based on the discharge at another sub-basin within the model ("*Cond.*" in Table 2-6). Conditioned flow is only available to be applied to the primary outlet, and is used in conjunction with the record (previous 14 days of streamflow) of another location within the model (user-specified). This option is used where the outflow of a reservoir needs to be limited based on upstream or downstream conditions. This method uses a four-parameter curve to relate the calculated outflow for a reservoir to another sub-basin's discharge. Two reservoirs use the conditioning flow option (Reindeer Lake and Lake St. Joseph). Outflow from Reindeer Lake is conditioned by the total flow at Otter Rapids (i.e., the Upper Churchill River before it joins Reindeer River). Reindeer Lake is used to compensate the natural inflow to the local generating station (GS), Island Falls downstream of the Reindeer River junction. Similarly, streamflow at a downstream GS is used to condition the diversion flow from Lake St. Joseph into Lac Seul.

Equations A-17 through A-22 (Table A-8) are used to determine which stage's computed outflow will be used daily (Equation A-17), and then to run automatic, logical corrections (Equations A-18) and user-specified, operational corrections (Equations A-19 through A-22) on the outflow. These operational restrictions within the routine are used as restrictions and correction factors to create outflows that are more realistic. Weekly and daily change restrictions are used to limit potential damage to reservoir infrastructure or downstream municipalities. These also help eliminate situations within the regulation routine that generate unrealistically large flow-changes between days.

Table 2-6: *Type of outflow equations used for each stage in NCRB reservoirs. Available options for each stage are listed above the reservoirs. Note that the ideal storage method ("Ideal S") and flow conditioning are only available for primary outlets and the storage compensation method (S Comp) is only available for secondary outlets.*

Reservoir Name	Model Type	Outlet	Stage				
			Drought	Low	Operations	High	Flood
			Ecolog. / Perc.	ABCD / Monthly / Perc.	Monthly / ABCD / Ideal S / Cond. / Perc.	ABCD / S Comp. / Perc.	Fixed Max. / Extend / Perc.
Lac la Ronge	InLine	Single Outlet	Ecolog.	Monthly	Ideal S	ABCD	Extend
Wollaston Lake	OCBD	Cochrane River	Ecolog.	ABCD	ABCD	ABCD	Extend
		Fond du Lac River	Ecolog.	ABCD	ABCD	ABCD	Extend
Reindeer Lake	OCBD	Single Outlet	Ecolog.	ABCD	Cond.	ABCD	Extend
S. Indian Lake	OCBD	Missi Falls CS	Ecolog.	Perc.	Perc.	S Comp.	Extend
		Notigi CS	Ecolog.	Monthly	Monthly	ABCD	Fixed Max.
Lake Diefenbaker	InLine	Single Outlet	Ecolog.	Monthly	Monthly	ABCD	Extend
Tobin Lake	InLine	Single Outlet	Perc.	ABCD	Ideal S	ABCD	Extend
Cedar Lake	InLine	Single Outlet	Ecolog.	Monthly	Monthly	ABCD	Extend
Lake Manitoba	InLine	Single Outlet	Ecolog.	Monthly	Ideal S	ABCD	Extend
Lake Winnipeg	OCBD	Jenpeg GS	Ecolog.	ABCD	Monthly	ABCD	Extend
		East Channel	Ecolog.	ABCD	Monthly	S Comp.	Perc.
Namakan/Rainy Lake	InLine	Single Outlet	Perc.	ABCD	Ideal S	ABCD	Extend
Lake of the Woods	InLine	Single Outlet	Ecolog.	Monthly	Monthly	ABCD	Extend
Lake St. Joseph	OCBD	Albany River	Ecolog.	Monthly	Monthly	ABCD	Perc.
		Root River Div.	Ecolog.	Monthly	Cond.	ABCD	Extend
Lac Seul	InLine	Single Outlet	Ecolog.	Monthly	Monthly	ABCD	Extend

2.3.4 Model calibration

The following discusses the rationale and methods used in calibration, Figure 2-6 summarizes the comprehensive calibration methodology used in this research.

The new regulation model was calibrated to improve seasonal bias by reapportioning flow volume throughout the year. Where there were two outlets, this entailed optimizing the sum of biases for all seasons and outlets. Reapportionment of outflow to other seasons was done using the limits of the operational range WSL (WSL_{op-} and WSL_{op+}), which were initialized by the daily 25th and 75th percentile WSL levels (for reservoirs with no operational guideline data). These limits dictate when the reservoir will hold or release water preferentially. Reservoirs with extensive operational data (those modelled in the original MH spreadsheet models) were calibrated with operational insight (special considerations in Figure 2-6). Those without operational data (e.g., Lake Manitoba, Lac la Ronge, Tobin Lake, Wollaston Lake) were calibrated using only the available outflow and WSL records.

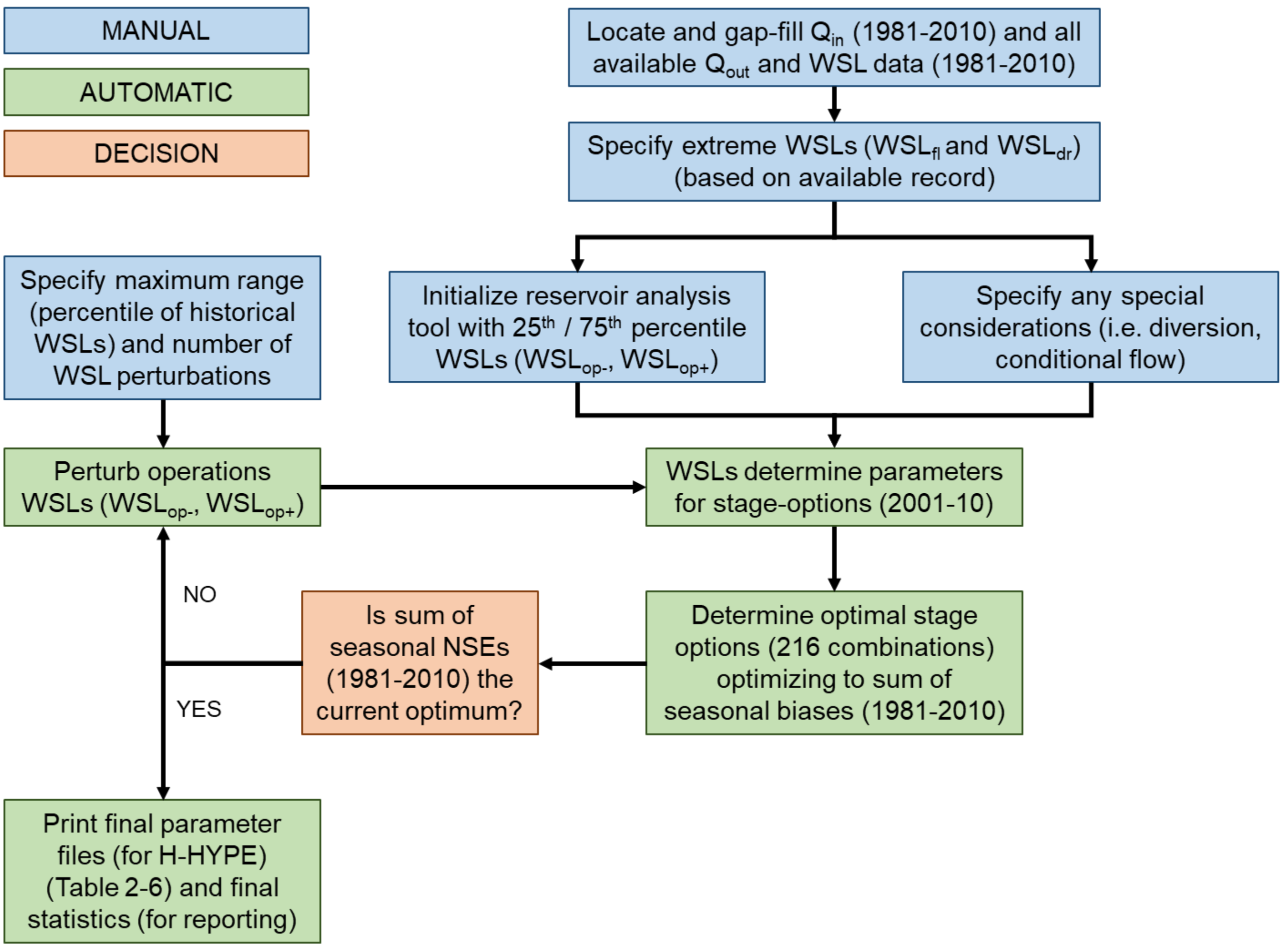


Figure 2-6: *Schematic of calibration methodology within the RAT*

Operational WSLs (WSL_{op-} and WSL_{op+} in Figure 2-5) were adjusted within a range of WSLs and for a number of perturbations. These new WSLs result in new parameters being generated (automatically) for each stage-option. A stage-option is the type of outflow algorithm selected for each stage (see Table 2-6). The ideal combination of stage-options (for the current set of operational

WSLs) is computed based on absolute sum of seasonal biases. If a known stage-option (for reservoirs with operational records) is available, it is locked (fewer combinations tested). Using that current best set of stage options, the sum of seasonal NSEs (computed from daily data) is checked against a previous, stored best value. The highest composite NSE is carried through (as well as the parameters, which are stored in text files) to be compared against the next iteration of WSLs.

Seasonal NSE is used rather than KGE due to the NSE being more sensitive in calibration of reservoir regulation in HYPE (MacDonald et al., submitted). Seasonal statistics used standard hydrological seasons (Winter: DJF, Spring: MAM, Summer: JJA, Autumn: SON). The final seasonal statistics (H-HYPE results for NSE, percent bias of mean outflow) for each reservoir are shown in Figure 2-7 for the validation period (1981 to 2010, daily time-step) with calibration statistics provided in Appendix C (monthly distribution) and Appendix D (seasonal final calibration values).

2.4 Results

The H-HYPE routine performs consistently better than A-HYPE during the 1981 to 2010 validation period. Figure 2-7 shows the final seasonal H-HYPE values for outflow NSE and the absolute value of the percent bias of mean outflow.

$$\Delta_{NSE,i,j} = NSE_{H-HYPE,i,j} - NSE_{A-HYPE,i,j}$$ [Equation 2-2a]

$$\Delta_{Bias,i,j} = |PBias_{H-HYPE,i,j}| - |PBias_{A-HYPE,i,j}|$$ [Equation 2-2b]

$NSE_{mod,i,j}$: NSE value in model *mod*, for reservoir *i*, season *j*

$PBias_{mod,i,j}$: Percent bias value in model *mod*, for reservoir *i*, season *j*

The final H-HYPE values are indicated by the cell colour in Figure 2-7. The improvement (or degradation) in performance achieved by H-HYPE seasonally (Δ_{NSE} and Δ_{Bias}) are calculated using Equations 2-2a and 2-2b. These are indicated by the symbol in each cell. A reduction in NSE shows a degradation in performance. A smaller value of absolute bias (reduction) shows an improved bias (i.e., a reduced overall error).

The NSE and percent bias improve for the H-HYPE routine across all seasons. At a daily time-step, these NSE values reflect the model's strength in predicting peak events. NSE improves in the majority of the seasonal evaluation periods (i.e., 59 of 64 evaluations, see Figure 2-7a). Seasonal NSE scores in the A-HYPE model are relatively poor with 50% for both periods falling below zero (detailed statistical results shown in Appendix D), indicating a simulation poorer than the period mean. With the H-HYPE model, however, only seven seasonal NSE evaluations fell below zero, with 20 over 0.667, where an NSE of 0.65 is considered better than satisfactory performance (Moriasi et al., 2007). The majority of the largest performance improvements in NSE (i.e., improvement of +1 or better (denoted as ">" in Figure 2-7a) are in upstream areas (e.g., Lac la Ronge, Wollaston Lake, Root River diversion), which in long-term simulation, will improve overall model performance by improving the simulated inflow received by downstream reservoirs. Recall that these results use observed inflow at every reservoir, so cascading improvements are not seen.

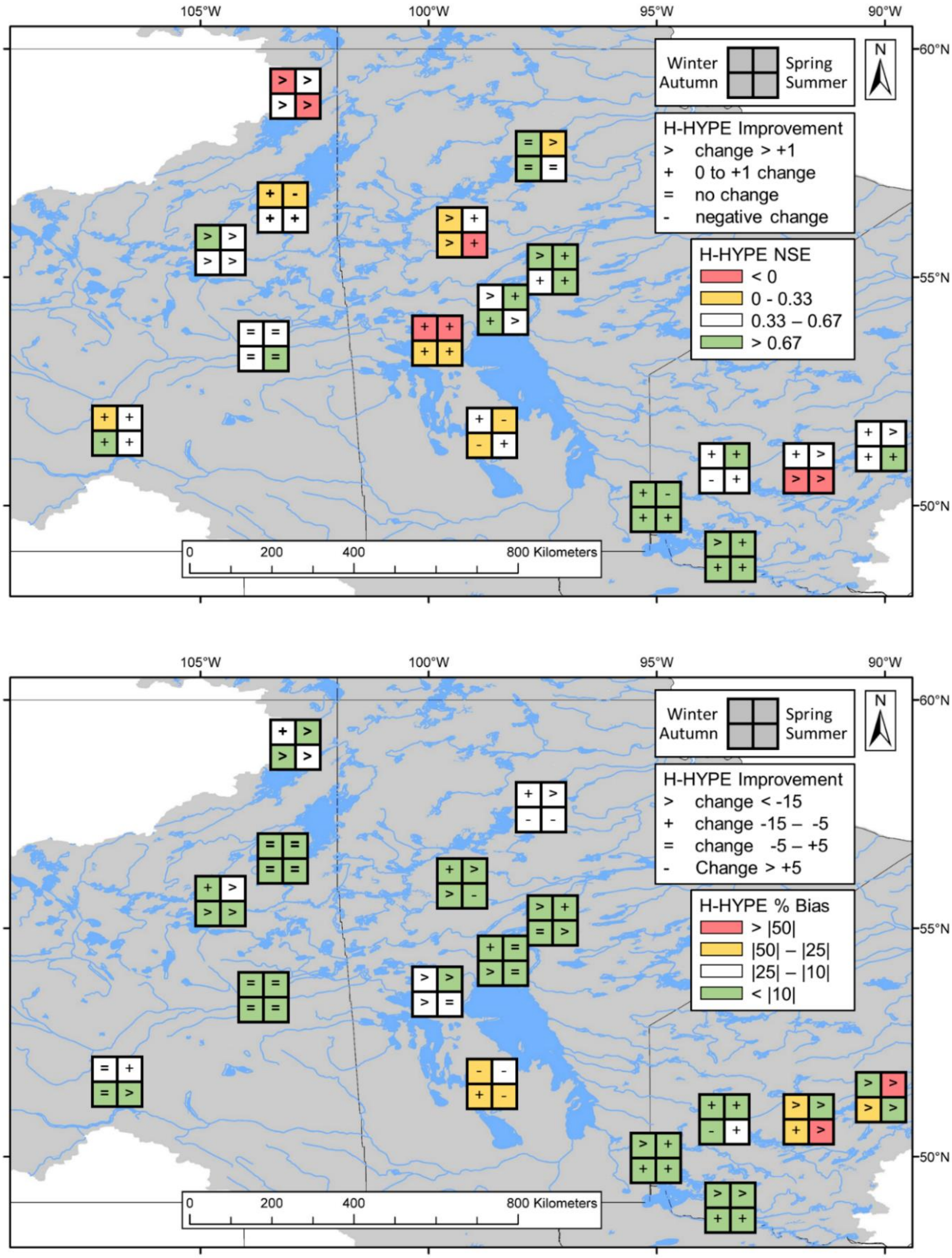


Figure 2-7: *Seasonal (a) NSE and (b) percent bias over the validation period (1981-2010). Cell colour indicates H-HYPE final values and symbol indicates model performance relative to A-HYPE performance (Equations 2-2a, 2-2b).*

Unlike more event-based weighting of NSE scores, seasonal percent bias reflects the overall seasonality of flows predicted by the model; focusing less on regulated response to peak runoff events, and more on the regulation routine's ability to apportion flow throughout the year. This is an important metric for assessing alteration of the seasonality of nival-dominated regimes. Seasonal bias improves when using H-HYPE, with less than a quarter of the seasonal evaluations degrading in performance (49 of 64 improve or are maintained). Additionally, 42 of 64 evaluations from H-HYPE fell between ±10 % bias, a threshold comparable to instrumentation error ("Water Survey of Canada", 2014). This suggests that in two thirds of instances, the model is able to react to inter-annual (climatic) and intra-annual flow (i.e., shorter duration floods) variability to correctly apportion water exiting the reservoir seasonally, without breaching safe reservoir levels. Seasonal bias improvements are strongest for downstream reservoirs (Lake Winnipeg, Southern Indian Lake). In these larger, downstream reservoirs, accurate seasonal volume simulation is crucial for long-term studies as these locations ultimately determine the seasonal flow volume reaching Hudson Bay.

The H-HYPE model yields results that are more consistent with regulated goals and the anthropogenic reality of the system's reservoir operations. Reservoirs with no operational guidelines show varied performance using the new H-HYPE routine (Figure 2-7), however, all but Lake Manitoba outperform A-HYPE in all seasons. This suggests that the H-HYPE routine can be reasonably initialized using only inflow, outflow and WSL records.

2.5 Discussion

The new H-HYPE regulation model is more effective than the current regulation routine in A-HYPE for the NCRB. This is true for all individual reservoirs across all seasons within the regulated system, with minimal exceptions. This can be conclusively stated based on results that are both qualitative (inspection of Figures 2-8 and 2-9), and quantitative (Figure 2-7). Specific examples (Section 2.5.1) and reasoning follow, but the overarching cause of this is the A-HYPE model being fundamentally driven by an ideal outflow (modelled via a sine curve) and restricting flow entirely below a certain level. H-HYPE is driven by an intra-annually varying envelope of WSLs, maintenance of realistic transitions between behavioural stages, and flows that are sensitive to reservoir levels (discussed in Section 2.5.2).

2.5.1 Improvements made by H-HYPE

Over the evaluation period (2001-2010), H-HYPE outperforms A-HYPE at every reservoir, though some outperform A-HYPE by less than others. Smaller reservoirs (closer to run-of-the-river) perform much better than larger reservoirs within the basin, but still show improved performance using H-HYPE. Tobin Lake, Lake of the Woods and Namakan/Rainy Lake all show small improvement to the already strong performance of the A-HYPE model (NSE $\approx$ 0.8). These reservoirs exhibit the small operational ranges (the depth between minimum and maximum allowable depths, governed by Equation 2-1b in A-HYPE), based on heavily legislated annual water levels prescribed by the LWCB and International Joint Commission (IJC) in the cases of Namakan/Rainy and Lake of the Woods (Section 2.3.2.2). The narrow operating range results in less of a sinusoidal influence (Equation 2-1b in A-HYPE) (Figure 2-9a) due to spillway-flow stage (governed by Equation 2-1c in A-HYPE) dictating outflow response most often. The spillway curve in this case is not imitating a spillway or weir, but is based on a shape likely more closely resembling a turbine efficiency curve. Hydroelectric operators are highly familiar with these curves and will maintain (whenever possible) a flow near to peak performance for their turbines, which varies by head (reservoir depth above the turbine). The physical basis of this behaviour and rigid real-life adherence to this curve makes calibrating the fewer parameters of the A-HYPE model more easily automated (using Equation 2-1c), but also allows very accurate calibration of the H-HYPE model with added reliability for all other WSLs.

Conversely, larger reservoirs with greater variability (i.e., greater inter-annual storage or less legislation of allowable water level or outflows) show more noticeable improvement when H-HYPE is used. These reservoirs highlight some of the inherent weaknesses of the A-HYPE model in more variable operational (productions stage in A-HYPE governed by Equation 2-1b) conditions. Cedar Lake (and its GS, Grand Rapids) is a large reservoir with significant operational leeway (depth between its high and low-flow stages, called "regulated depth" in A-HYPE), residing just west of the Lake Winnipeg outlet. As a result and based on observed flow records, Cedar Lake tends to operate on the low-side of operational flow even in high flow years; effectively being used a "swing-station". Out of a desire to control flows into Lake Winnipeg at inopportune times, Cedar Lake flows are often (counterintuitively) held back during wet periods, and (counterintuitively) released during drier periods, in both cases to balance flow into the lower Nelson River generating complex.

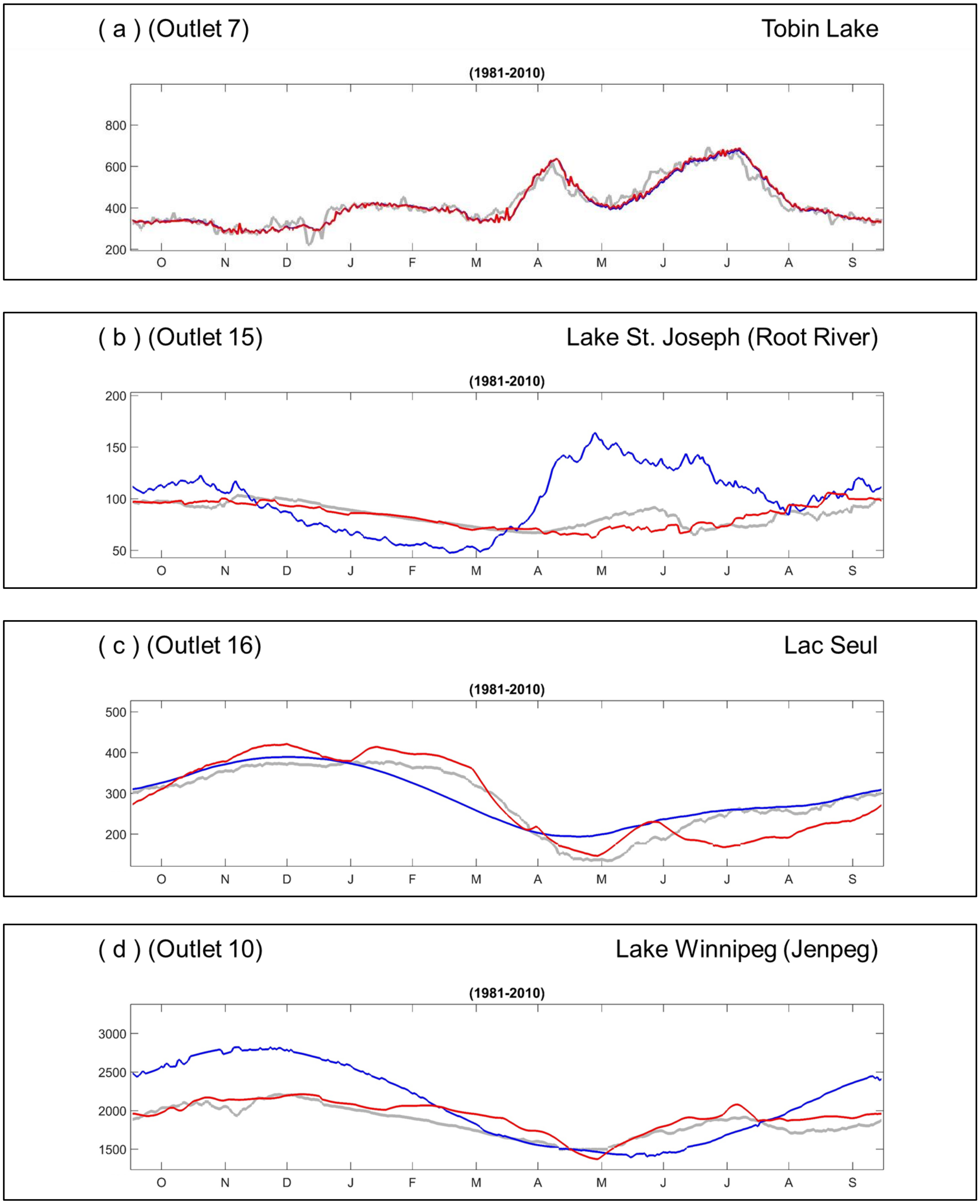


Figure 2-8: *Daily average annual discharge (m^3 s^{-1}) comparison of observed data (grey), existing HYPE regulation routine (A-HYPE; blue), and new HYPE regulation routine for (H-HYPE; red) for the 1981 to 2010 validation period. (a) Tobin Lake, (b) Lake St. Joseph diversion, (c) Lac Seul, (d) Nelson River at Jenpeg (Lake Winnipeg).*

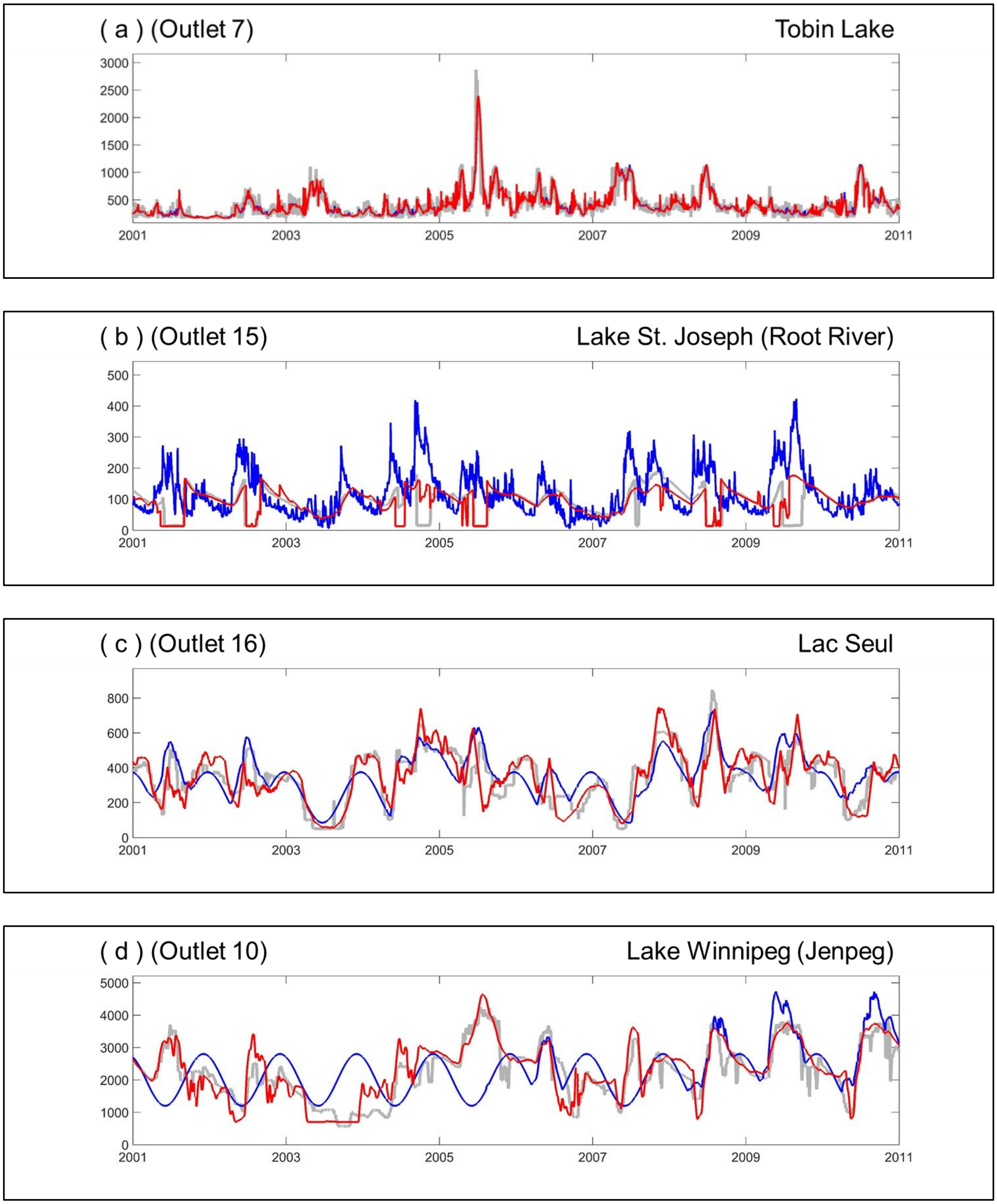


Figure 2-9: *Daily discharge (m^3 s^{-1}) comparison of observed data (grey), existing HYPE regulation routine (A-HYPE; blue), and new HYPE regulation routine for (H-HYPE; red) for the 2001 to 2010 reference period. (a) Tobin Lake, (b) Lake St. Joseph diversion, (c) Lac Seul, (d) Nelson River at Jenpeg (Lake Winnipeg).*

This systematic operation also attempts to benefit its own generating station (Grand Rapids) by preserving high outflows during winter months (i.e., peak seasonal demand due to heating requirements), and low outflows during the summer months (i.e., lower demand). A-HYPE struggles to negotiate the balance between these seemingly contradictory operational philosophies, instead oscillating rapidly between zero-flow (Equation 2-1a in A-HYPE) and the prescribed sine-curve value (Equation 2-1b in A-HYPE) (Figure 2-10) because water levels in Cedar Lake pass above and below the minimum level in rapid succession. This seemingly unrealistic behaviour, with no buffer function or transitional zone, is a detriment to both the statistical performance and overall realism of reservoir release simulated by the A-HYPE model. H-HYPE creates a more consistently realistic relationship between stage and discharge in Cedar Lake using monthly stage-discharge curves (low, operations-stage) and a fixed stage-discharge curve (high-stage), which is reflected in the simulation statistics (Figure 2-7, Appendix C, Appendix D).

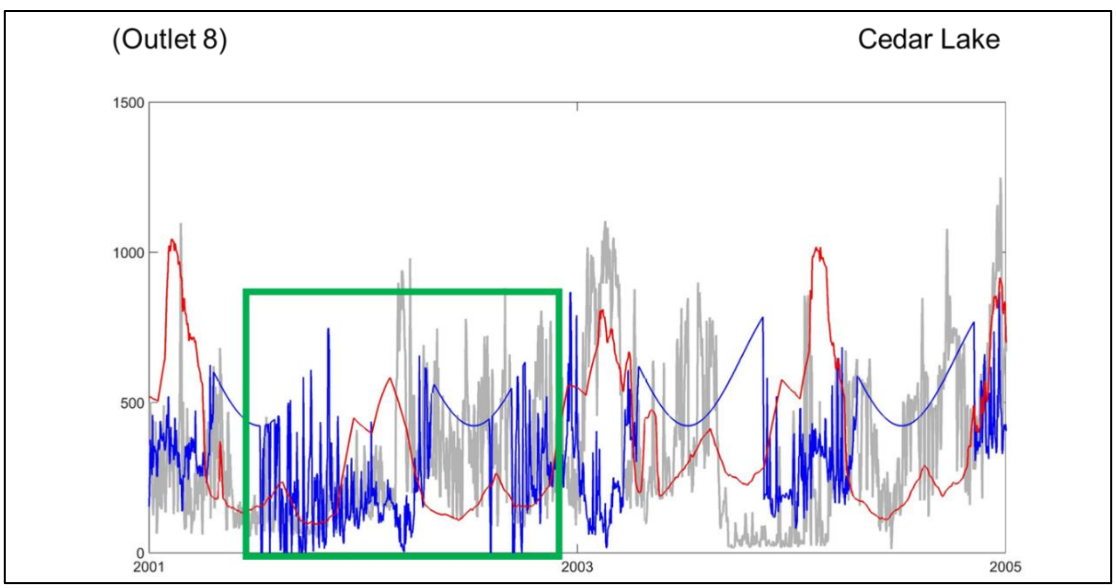


Figure 2-10: *Daily hydrograph comparison for Cedar Lake at Grand Rapids GS of observed data (grey), existing HYPE regulation routine (A-HYPE; blue), new HYPE regulation routine (H-HYPE; red) from 2000 to 2005. Green box highlights low-flow events (early 2001 to late 2002) where A-HYPE routine "shuts down" all flow.*

Other important system reservoirs show similar improvement with the H-HYPE model (both statistical and operational realism). Lake Winnipeg is a dominant land-feature in the prairie ecosystem and an important reservoir for MH operations, specifically the Lower Nelson River generating complex (Limestone GS, Kelsey GS, Kettle GS, Long Spruce GS and Jenpeg GS). Proper forecasting of its regulation affects total energy supply for the Province of Manitoba, but also the validity and realism of projected freshwater exports to Hudson Bay. Figure 2-11 shows the monthly distribution of absolute relative bias (|% bias|) and NSE error (1 – NSE, giving a perfect score of zero). Both are presented in $\log_{10}$ space to highlight changes at the lower end of error (incremental improvement to months with better performance). These metrics both improve as the simulated value is lower (decreased error). H-HYPE shows a consistently lower distribution, with H-HYPE bias (Figure 2-11 ii) median lower than the A-HYPE 25th percentile in eight of 12 months. Box and whisker statistical performance plots of this type for all reservoirs can be found in Appendix C. Using H-HYPE instead of A-HYPE, overall NSE (daily record 1981 to 2010) increases from 0.035 (barely better than using daily average flow) to 0.709 (good performance according to Moriasi et al., 2007) in the validation period. A-HYPE simulated outflow is dominated by a sine curve (Equation 2-1b) (Figures 2-8d and 2-9d), which is an accurate approximation for some years, but can be inaccurate for prolonged periods within the observed record. The A-HYPE model was calibrated to maximize the NSE criterion, which favours the accuracy of peak-flow events (i.e., high-stage outflows). This results in diminished performance during lower flow periods given the model's adherence to an unrealistic sine-curve; that is, the phase of the sine-curve prevents outflows from responding to large inflow events, and the amplitude of the curve prevents proper simulation of wet/dry oscillations (cycling on approximately a seven-year ENSO cycle) affecting reservoir releases.

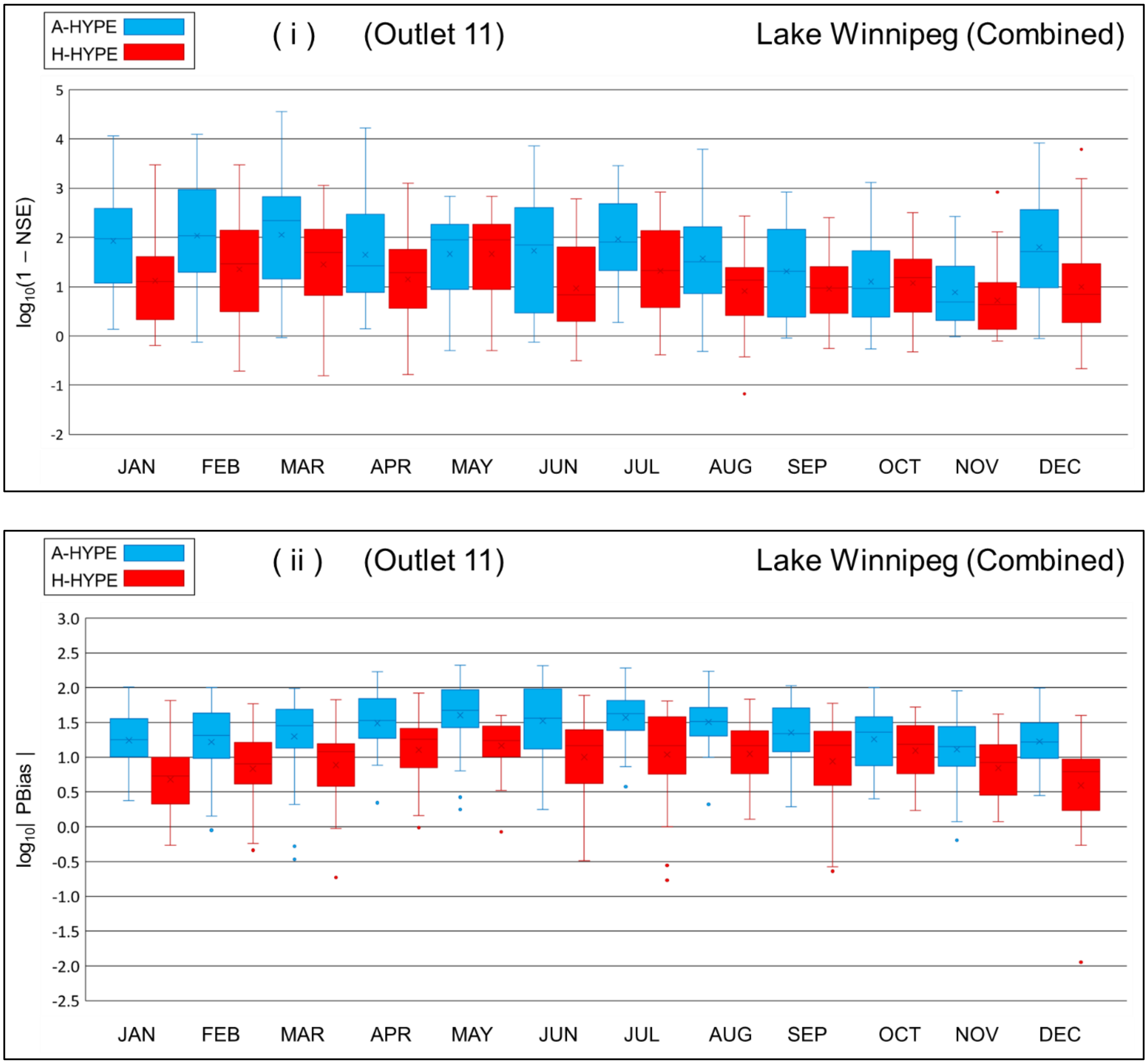


Figure 2-11: *Monthly distributions (1981 to 2010) of (i) NSE error (1 – NSE) and (ii) absolute mean bias (|bias|) for (blue) A-HYPE and (red) H-HYPE at log_{10} base. Box (25/75 percentile), whisker (1.5 x inter-quartile range), divider (median), cross (mean) and dots (outlier). Perfect simulation for both metrics would return negative infinity.*

Lake Winnipeg is the collector for several large sub-basins of the NCRB (i.e., Saskatchewan River, Winnipeg River, Red/Assiniboine River). These basins are highly variable climatically, flowing West-East through semi-arid prairies (Saskatchewan River), East-West through boreal forest (Winnipeg River) and South-North through semi-arid prairies (Red/Assiniboine Rivers). Lake

Winnipeg is affected by climatic trends in those basins either with constructive interference (all experiencing a wet/dry period), or destructive interference (wet/dry periods of the basins offset each other), resulting in a heavily varied inflow profile. A performance tradeoff is seen in the multi-year high flow period from 2005 to 2010, where the A-HYPE model has improved performance in matching observed outflow behavior given the relationship between high flows and WSL in A-HYPE. This period relies heavily on the high-stage flow (Equation 2-1c).

H-HYPE notably outperforms A-HYPE in complex reservoir systems, such as those that are bifurcated by diversions or those whose outflow depends on streamflow at a separate location (i.e. OCBD reservoirs using conditional flow from another reservoir).The Lake St. Joseph diversion to the Root River (Figures 2-8b and 2-9b) is an example of this. A-HYPE simulates a scaled version of outflow from the Albany River outlet of Lake St. Joseph (i.e., increased by a fractional coefficient, specified as a parameter in A-HYPE). In reality, the diversion can be shut off or opened on extremely short notice, based on a series of cascading decision trees involving flow-control structures operated jointly by MH, OPG, the IJC and the LWCB. The new H-HYPE routine models the diversion explicitly, fitting a curve that relates the diversion's operations-stage decisions directly to the outflow at Slave Falls (part of the Winnipeg River generating station complex, downstream of Lake St. Joseph and Lac Seul and downstream of the junction with Lake of the Woods). Once the conditioning option is included (in H-HYPE), the rules of all agencies can be satisfied by relating the data between two sub-basins of the model (in this case, the discharge at the Slave Falls generating station and outflow of the Root River diversion). Using H-HYPE, shut-off events are occasionally over-estimated (early 2004) or under-estimated (late 2008), but most are matched quite closely (early 2005, late 2007), with only ecological flow being passed; events which A-HYPE missed entirely.

2.5.2 Underlying causes of improvement

A large contributor to the success of the H-HYPE routine is the option of monthly stage-discharge curves, which are useful for large, seasonally variant regulation as opposed to a fixed spillway curve (developed more for smaller, run-of-the-river systems that need high reactivity to inflow). The response of releases to water levels can be adjusted month-to-month using stage-discharge curves based on historical records to approximate, safer or more aggressive power generation throughout the year. It is also important to note that a fixed spillway curve can be used year-round, where monthly variations do not affect the operation of the reservoir's high-stage, as is the case in the many reservoirs in the NCRB (Table 2-6).

Another strength of the H-HYPE model is its reactivity to varying climatic conditions. Distinct and lengthy (>5 year) dry and wet cycles are visible in the Lake Winnipeg (Figure 2-9d) and Lac Seul (Figure 2-9c) outflow hydrographs, which are the results of an extended dry (early 2000s) and wet (late 2000s) periods within the Lake Winnipeg basin. A-HYPE shows almost no change in day-of-year outflows over the reference period for the outflows generated, despite the inter-annual variability of the climate. This weakens the A-HYPE performance in the context of climate change analyses with non-stationary inflows. The sine curve deviates only after very prolonged climatic extremes. In these cases, no mitigating steps are taken in A-HYPE until the WSLs have surpassed safe levels on either the high or the low end. This can result in prolonged periods of very low water levels (unsafe for long-term reservoir sustainability), or very high water levels (unsafe for infrastructure) as the sine curve misses intra-annual variability of flow (Déry et al., 2011).

H-HYPE outflows are more directly influenced by daily water level change, meaning that no ideal discharge is targeted, and instead the goal of maintaining a safe water level (within an operating range) for any given day-of-year is prioritized. This allows the model to create more accurate simulations during extended wet and dry cycles, and hence more operationally realistic outflow response under non-stationary climates. In doing so, small steps are taken at each computational time-step (daily for BaySys) to keep the water level within the desired operational range as long as possible. Studies looking at water surface records generated using remote sensing (Mehran et al., 2017, Revilla-Romero et al., 2016) or neural network methods (Shamim et al., 2015) for data-sparse regions have been conducted. With the increased availability of WSL records, the work done in this study will be easier to implement at larger scales for more reservoirs (if new regulated reservoirs are desired in future version of the model).

An assumption for this work is that the safe operations levels derived from 2001 to 2010 (validated between 1981 and 2010) will not change. Realistically, flood and drought levels of reservoirs rarely change as they would require significant infrastructure redesign. The extent of the operations levels within the safe limits (in H-HYPE) are tied indirectly to the seasonality of power demand. Whether a given reservoir will be withholding water from, or supplying water to, the larger river system varies by reservoir but not year-to-year. In this sense, the limits of the operations, flood and drought stages (and by extension, the limits of the low and high stage) will not change dramatically. The only effect that could alter the seasonality of a reservoir would be a reversal of the seasonality of power demand (i.e. theorized -but unlikely- winters requiring lower heating demands, with summers requiring more cooling power), which is climatologically not realistic for the 2021 to 2070 time-scale for which this regulation routine was designed (Stadnyk et al., in press). Another important feature of this routine is that it does not require an optimization algorithm, keeping the routine computationally agile. All calibration can be done off-line from the larger model, saving time and computational demands required for in-model calibration.

2.6 Conclusion

The new, generalized sub-routines (InLine and OCBD) are more efficient than creating a new sub-code for every reservoir, and presents stronger results relative to the default regulation routines available in HYPE (i.e., A-HYPE). This is proven by examining the results from 13 reservoirs within the NCRB, which were calibrated and included in the operational H-HYPE model for the BaySys group of projects. Reservoirs were calibrated using the H-HYPE dam routine with different amounts of available calibration data and operational knowledge, varying both spatially and temporally. An advantage of the H-HYPE regulation routine is that it can, by nature of its design, be structured as simple as necessary or as complex as data-availability allows, with most parameters calibrated automatically before inclusion in the larger hydrological model (using the RAT).

Simulated outflows from the new H-HYPE dam routine outperform those simulated by the default A-HYPE dam routine. This is reflected not only in the statistical improvement of the regulated outflow nodes (monthly distribution and seasonal cumulative), but also in visual analysis of hydrographs (daily and daily average annual), where the H-HYPE routine better adjusts to intra-annual (storm-flood events) and inter-annual (prolonged floods and droughts) hydro-climatic periods in a manner more consistent with the observed record.

Once the new regulation is incorporated, it will be used to quantifiably distinguish the effects of regulation on Hudson Bay freshwater and those effects caused by climate change (Tefs et al., in preparation (b)). These projection studies will be done in conjunction with sensitivity and uncertainty analyses, to quantify the uncertainty envelope to be applied to projected exports (Pokorny et al., in preparation).

2.7 Acknowledgements

Thanks to University of Manitoba, Manitoba Hydro and partners funding through the Natural Sciences and Engineering Research Council of Canada through funding of the BaySys project. Many thanks to Manitoba Hydro for technical and logistical support of regulation system modelling. Many thanks to the Water Survey of Canada (WSC) for the gathering, quality assurance and dissemination of streamflow and WSL data.

Chapter 3

Modelling the relative effects of climate change and hydroelectric development on the changing freshwater exports to Hudson Bay. Tefs, A.; MacDonald, M.K.; Stadnyk, T.A; Koenig, K.; Déry, S.J.; Slota, P.; Guay, C.; Hamilton, M.; Thiemonge, N.; Vieira, M.; Pokorny, S.

3.0 Abstract

Increasing since the 1960s, hydroelectric development has taken place throughout the Hudson Bay Drainage Basin (HBDB), particularly in the Nelson-Churchill River Basin (NCRB) and the La Grande Rivière Complex (LGRC). The areal extents of the watersheds affected by these two regulation complexes spans 1.7 million km^2, which totals 43% of the HBDB or 17% of the total Canadian land-mass. We develop a modified version of the Swedish Meteorological and Hydrological Institute's (SMHI) HYdrological Predictions for the Environment (HYPE) model with a detailed reservoir regulation routine for the Hudson Bay HYPE (H-HYPE) domain. Future scenarios (2021 to 2070 projected by 19 Phase 5 Climate Model Intercomparison Project (CMIP5) scenarios) are compared to a historic baseline period (1981 to 2010), both with regulated and re-naturalized versions of the model. Climate, and subsequently runoff, perturbations through time dominate changes to freshwater export by limiting the capacity of the regulated system to efficiently control flow. Changes in inter-scenario behaviour are most notable where upstream storage is more limited. Monthly analyses of daily climatic input, upstream hydrologic behaviour, and net impact on the freshwater flux (basin discharge) confirm the trend of observed changes to the regime over the past four decades. Further, future changes are quantifiably dictated by different factors at differing time-scales: intra-annually, flow variability is controlled by hydroelectric regulation; inter-annual variability is dominated by climatic variation and the availability of upstream storage; and inter-decadal change is dominated by future and ongoing climate change. This quantifies the driving cause of changes to freshwater fluxes at different time-scales. With this, the effects of human-water interactions and climate change on Hudson Bay's ice cover and associated changes to the marine and estuarine ecosystems can be better predicted and quantified, helping fulfill the BaySys group of projects full scientific potential.

3.0.1 Disclaimer

The results in this thesis present hydrologic modelling of the La Grande Rivière Complex (LGRC) daily net basin supply (NBS) using the HSAMI model. These basin models have been developed for, and calibrated extensively by Hydro-Québec. This HSAMI modelling will be used to produce the best possible representation of the Hydro-Québec regulated response to climate change for general distribution and publication. HSAMI uses the same GCM/RCP forcing as H-HYPE, condensed to single daily forcing values by NBS basin.

These basins represent the headwaters upstream and between major regulation points in the LGRC. These NBS values were generated by Hydro-Québec modellers to compute regulated outflows. This was done to preserve the greatest possible level of skill in regulated modelling. Using the volumes produced by a single hydrological product for the full Hudson Bay drainage basin was preferable due to the sensitivity to hydrostatic forces of the NEMO sea and sea-ice model used by subsequent BaySys projects. To preserve this, the regulated outflows were bias-corrected using equidistant quantile mapping to match H-HYPE volumes.

The final version of the H-HYPE model used in BaySys was calibrated using a balanced calibration. This calibration used an objective function equally weighted over the entire Hudson Bay domain, not optimized regionally (i.e., for areas of interest or importance). This has resulted in a large dry bias (~36%) in the LGRC. Subsequent (journal-published) versions of these results will use LGRC regulated outflows generated from NBS results computed using the HSAMI model. All other elements of the analysis will appear as they do in this work, using the same methodology.

3.1 Introduction

As the climate changes globally, changes are occurring more rapidly in the Arctic and higher latitude regions (Bring et al., 2017; Bring et al., 2016). Here, we focus on northern Canada (Déry et al., 2016; Déry et al., 2011), though the study area also covers large portions of mid-to-southern Canada and portions of the United States. The changing freshwater contributions to Hudson Bay and the need for further inter-disciplinary studies have been documented over the past three decades (St. Laurent et al., 2011; Anctil and Couture, 1994). Over and above the hydrological and anthropogenic effects of these changes (irrigation needs, hydroelectric capacity), these fres]hwater changes have a significant effect on the freshwater-marine coupling system of Hudson Bay itself. Changes in the climate have led to a water-cycle intensification or regime shift (Burn and Whitfield, 2017; Déry et al., 2009) of certain hydrological processes. Changes in snowpack depth, extent, and melt timing have had significant effects on the largely nival regime (DeBeer et al., 2016; Kang et al., 2014; Déry et al., 2007) of the HBDB, which in turn affects the freshwater-marine coupling. Perturbations to the large, spring freshet delivery have resounding impacts across numerous disciplines and for operational management of water resources.

Further complicating the quantification of the hydrological impact of climate change is the increasingly widespread dam-storage capacity and operational hydrograph-attenuation caused by hydroelectric regulation. Hydroelectric regulation strives for reliable discharge year-round, often increasing between late fall and early spring in Canada to produce electric loads consistent with increased demands for winter heating. This, with climate change affecting snowmelt, has led to changes in both the timing and volume of freshwater being exported to Hudson Bay (Déry et al., 2018). The two largest flow-producing river systems in Hudson Bay (NCRB and LGRC) are heavily flooded, regulated and diverted (Dynesius and Nilsson, 1994). Several studies related to climate change and its hydrological impacts without regulation have been undertaken within Hudson Bay limited to the Québec-based drainage areas (Guay et al., 2015), limited to the Nelson Churchill upstream drainage ("Manitoba Hydro Climate Change Report", 2015), and on the pan-Arctic drainage as a whole (Gelfan et al., 2017). To date, studies for the Hudson Bay region have examined the effects of climate change and regulation on the historical discharge record (Déry et al., 2018) *or* projected the effects of climate change on sub-basin runoff without regulation (Guay et al., 2015) *or* projected the future effects of climate change on basin regulation modelling for boreal sub-arctic basins adjacent to the HBDB (Minville et al., 2009). To date, there is a gap in the literature on the combined impact of hydroelectric regulation *and* climate change over the next half a century (to 2070) for the full HBDB. It is also unclear whether the tandem effects are net-additive or net-offsetting. A study was undertaken using the HYPE model (Lindstrom et al., 2010), to examine the impacts of climate change and regulation in Sweden (S-HYPE sub-model), which showed that regulation exerts a greater effect on hydrology than climate change (Arheimer et al., 2017).

Modelling of regulation effects have been cited as a source of error or uncertainty in HYPE simulations in several studies (Donnelly et al., 2016; Bergstrand et al., 2014) and in large-to-continental scale hydrologic modelling as a whole (Wada et al., 2017; Bring et al., 2017; Zhao et al., 2016; Denaro et al., 2017; Pokhrel et al., 2012). A new regulation routine has been developed for HYPE and integrated into the H-HYPE model at 13 reservoir locations in the NCRB (Tefs et al., in preparation). The HYPE model is proven for continental-scale studies (Pechlivanidis and Arheimer, 2015), and H-HYPE has further been extensively calibrated for the HBDB domain (MacDonald et al., in revision).

This study combines regulation and climate change effects to project runoff generation and freshwater export to Hudson Bay. We establish long-term trends attributed to each influencing factor, and quantify the relative contribution of each to the overall variability in projected trends. We use two versions (regulated and re-naturalized) of the H-HYPE model over three time-periods (1981 to 2010, 2021 to 2050 and 2041 to 2070) and a robust ensemble of 19 CMIP5 GCM and associated RCP combinations (Stadnyk et al., in press; MacDonald et al., 2018). Results are presented for overall change over time, trend change, trend significance, and changes due to regulation in the model. The uncertainty associated with climatic simulations plays a large role in future variability. A sister project to this work will be examining the effects of uncertainty and sensitivity in the freshwater results generated by the BaySys group of projects (Pokorny et al., in preparation).

3.2 Model and methodology

The HBDB is a large (3,860,000 km²) basin, extending into four American states, five Canadian provinces and two Canadian territories. The basin is described by the Laurentian, Arctic and Great Continental divides. It also straddles multiple ecosystems, geological regions and climatic regions; ranging from semi-arid prairies in the west, to tundra in the north, to boreal forest in the east. The basin also covers a variety of physiographic conditions, with short, high-relief basins on the eastern side of the bay and (relatively) long, low-relief basins in the west once rivers have moved beyond the Rocky Mountains' foothills. Additional details regarding the basin and its various aspects as represented hydrologically in H-HYPE can be found in MacDonald et al. (in revision).

The regulated basins examined in this work are the NCRB and LGRC hydroelectric complexes. The NCRB comprises the Nelson and Churchill rivers. More than three quarters of the annual flow of the Churchill River is diverted to the Lower Nelson River Basin (LNRB) by way of the Churchill River

Diversion (CRD). The LGRC comprises La Grande Rivière, much of la Rivière Eastmain, much of la Rivière Rupert and the portion of the la Rivière Koksoak upstream of Lac Caniapiscau. A small portion of la Grande Rivière de la Baleine and the upper portions of the Koksoak, Rupert and Eastmain rivers are diverted towards the generating complex on La Grande Rivière through a series of diversions.

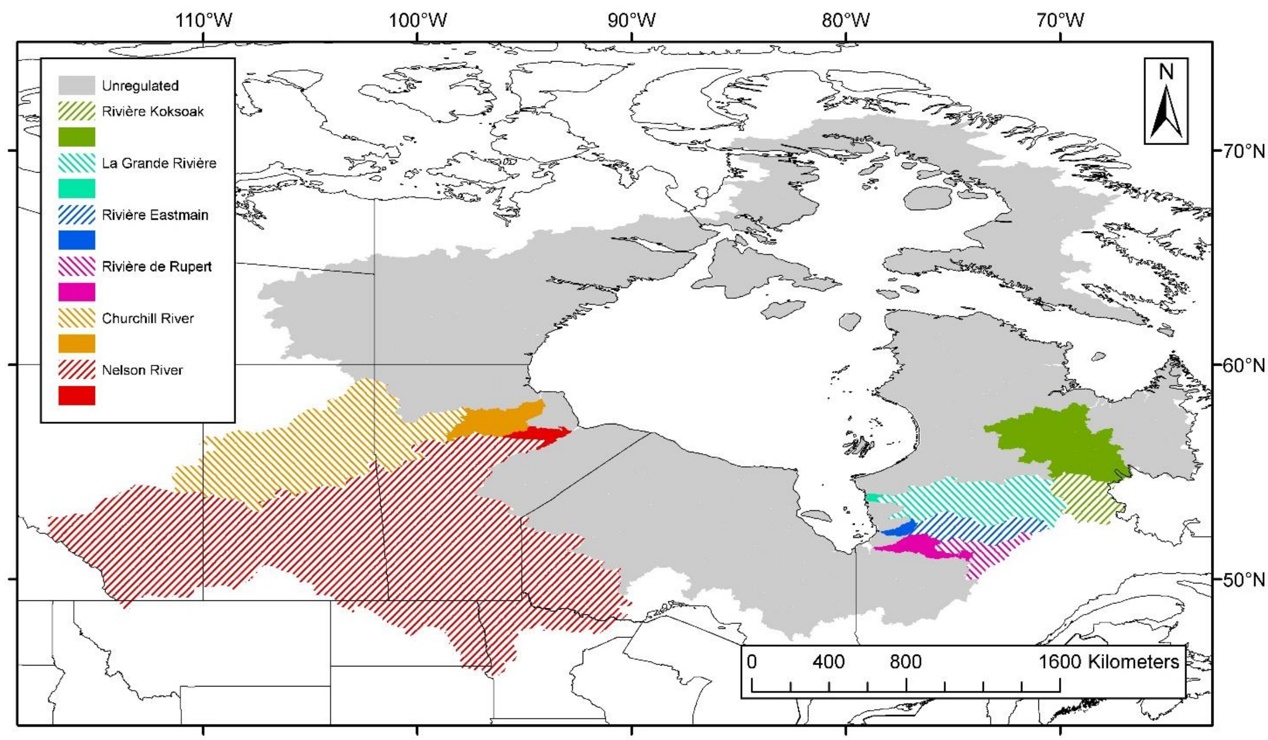


Figure 3-1: *Basins used for NCRB and LGRC composite outlets (NCRB: Nelson River and Churchill River, LGRC: La Grande Rivière, La Rivière Rupert, La Rivière Eastmain and La Rivière Koksoak). Note that regulated areas are those regulated within HYPE (hatched) and may ignore smaller, real-world control structures in the areas downstream of regulation points (solid colour).*

In HYPE, only the NCRB and LGRC have been meaningfully changed from regulated to re-naturalized. Accordingly, they are the only two upstream basins presented. Figure 3-1 shows extents of the basins used for each of these major conjugate outlets. Results have been calculated and presented for multiple variables (separated by their upstream basins) to give context and cause to the ultimate results at the outlets, which are presented in Sections 3.3.1 and 3.3.2.

3.2.1 Hydrologic model and climate data

HYPE was selected and the H-HYPE model developed for the BaySys series of projects because it is computationally efficient (approximately 1 hour per decade of HBDB simulated), with appropriate cold regions hydrologic process representation, and proven at the continental-scale (Pechlivanidis and Arheimer, 2015; Lindstrom et al., 2010). H-HYPE is a sub-basin model of the larger Arctic domain HYPE model (A-HYPE) composed of 6668 sub-basins of the 32600 sub-basins in the circumpolar region, and terminating with 398 outlets throughout Hudson Bay, James Bay, the Foxe Basin and Hudson Strait.

Nineteen climate scenarios for 2021 to 2070 have been selected from the CMIP5 ensemble of climate models. Because some of the selected models include multiple Representative Concentration Pathways (RCPs), which define the anthropogenic carbon scenario applied within the General Circulation Model (GCM) from the same GCM, there are 14 historic scenarios (1981 to 2010) corresponding to these 19 models. Selection was based on k-means clustering (Lloyd, 1957) to represent the greatest possible variability in climate over the HBDB for the 2021 to 2050 and 2041 to 2070 periods. Results indicated that 90% of the variability in projected climate from the ensemble of 154 CMIP5 GCMs was captured by the 19 models selected for the BaySys study (Stadnyk et al., in press). More localized studies within the region have looked at the coupling of climate change models and hydroelectric reservoirs (Irambona et al., 2016). This study utilized fixed climate change scenarios, un-perturbed by the hydrological model's feedbacks. Outflows generated using the Hydro-GFD (Berg et al., 2017) climate data product (1981 to 2010) were calibrated against long-term records for 34 Hudson Bay outlets (provided by Déry et al., personal communication) and upstream streamflow records at selected stations obtained from Manitoba Hydro (MH), Hydro-Québec (HQ) and the Water Survey of Canada (WSC).

3.2.2 Reservoir regulation

The joint effects that climate change and hydroelectric regulation will impose (as an input condition) on the larger freshwater-marine system coupling are the primary focus of this study. Optimal future energy production and hydroelectric generation capacity are not within the scope of the BaySys projects, therefore regulated system modelling targeted safe reservoir operation (calibrated to reservoir water surface levels) and modelled downstream discharge. No energy-demand adaptation strategy or future changes to reservoir operations or capacity are simulated. Adapted energy-demand and regulation modelling strategies have been studied in a basin adjacent to the HBDB (Minville et al., 2009); however, to limit uncertainty and computational demand, static reservoir operation algorithms have been employed for both the NCRB and LGRC. In the NCRB, the static regulation rules (as part of the new H-HYPE regulation routine) have been derived from historical records from 2001 to 2010 and validated over the 1981 to 2010 period. Both the NCRB and LGRC rules are static insofar as the regulation methods applied are those that are currently in operation, though they are based on algorithms that adapt dynamically to the inflow and water levels of the reservoirs. In both basins, the rules are static, the outflows generated by those flows are dynamic depending on reservoir water surface level.

In collaboration with Manitoba-based regulators, NCRB regulation has been embedded directly into the H-HYPE model to improve historical regulation modelling, and to make the model more responsive to changing climatic conditions (Tefs et al., in preparation (a)). LGRC regulated flows have been provided by Hydro-Québec (personal communications, Nathalie Thiemonge) for the furthest downstream regulation points of the Rivière Rupert (daily flow) and La Grande Rivière (weekly average flow) for the periods of 1981 to 2010 and 2021 to 2070. Daily net-basin supply upstream of regulation points was generated in HYPE for 12 basins within the LGRC and provided to Hydro-Québec. Regulated reservoir outflows were calculated using a combination of the Riverware (Zagona et al., 2001) and SimHyd (Wang et al., 2005) software packages.

For the 1981 to 2010 and 2021 to 2040 timeseries, H-HYPE discharges were generated using the regulation algorithms available in HYPE, calibrated for the H-HYPE domain, over the 1981 to 2010 period (MacDonald et al., in revision). Discharges for 2041 to 2070 were also calculated, only to be used for quantile mapping to correct the LGRC flows for 1981 to 2010 and 2021 to 2040. The Equidistant Quantile Mapping (EQM) method (Li et al., 2010b) is employed to correct modelled values from earlier time-periods, because it explicitly considers the non-stationarity between data-samples of differing time-periods. EQM is performed using the H-HYPE values as the 'modelled' values and the HQ regulated values as the 'observation' data. Corrected, regulated outflows were used to force the H-HYPE model at the appropriate nodes (directly upstream of solid areas in Figure 3-1).

3.2.3 Re-naturalization

To distinguish the effects of climate change from regulation in future scenarios, a set of corresponding 'natural' scenarios was needed that removed any anthropogenic influence on watershed outflow. Re-naturalization of the regulated H-HYPE model to a naturogenic state had two steps: 1) removal of infrastructure, and 2) reverting land-use to its pre-flooding condition.

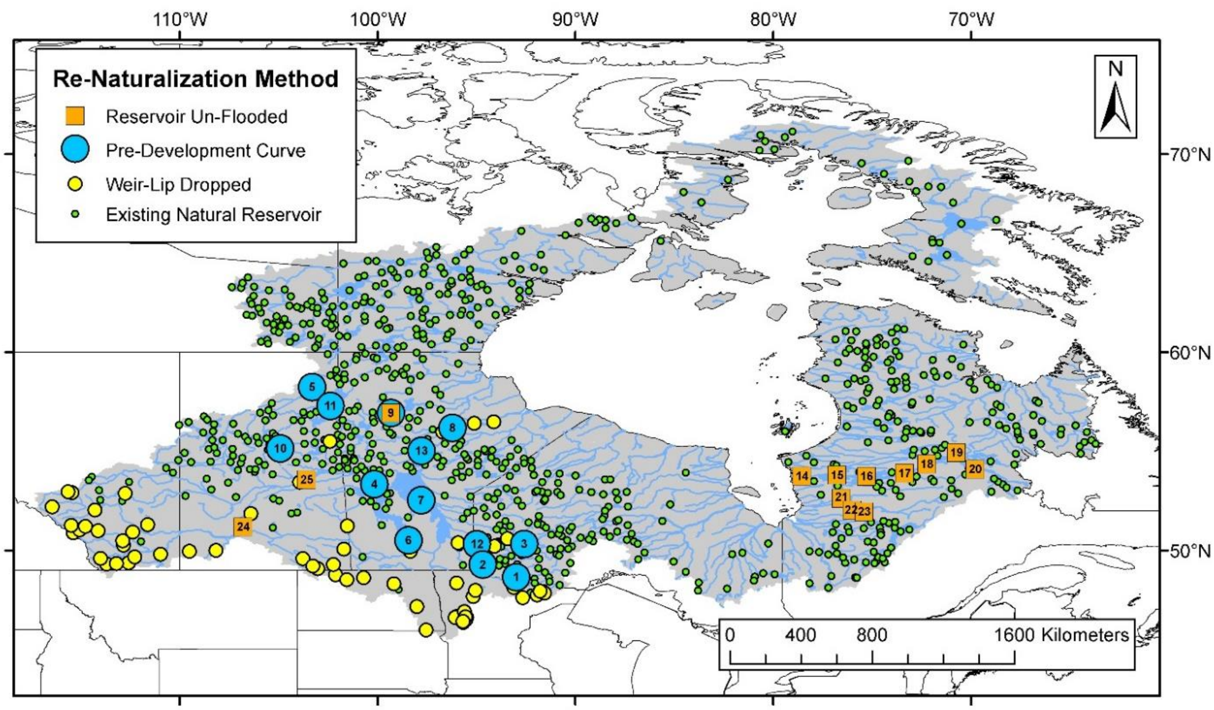


Figure 3-2: *Re-naturalization methods applied to reservoirs in the HYPE model. Note that labelled numbers correspond to entries in Tables 3-2 and 3-3.*

Anthropogenic, flooded reservoirs created for flow regulation are removed and returned to their pre-flooded riverine conditions. The following section describes the methods used to revert the H-HYPE model's land-cover components and reservoir parameters to mimic natural-state behaviour.

3.2.3.1 Re-naturalizing reservoirs to lakes

Changing reservoirs from regulated (dams) to unregulated (lakes) was done using historic stage-discharge data obtained from Manitoba Hydro (MH) by fitting stage-discharge curves using two parameters (α and β) of the HYPE reservoir-outflow routine (see Equations 3-1a and 3-1b). Lake outflow (at all depths) is dictated by a single equation (Equation 3-1a). Dam outflow above the height of the dam lip is governed by a weir equation (Equation 3-1b). Below this depth, algorithms can be specified for simulating hydroelectric regulation, water supply, irrigation operations, or flood control. All equations are taken from the HYPE documentation on reservoir-outflow calculation (“Rivers and Lakes”, 2018), which can be obtained or browsed online for further reference. Further details explaining the routines used in A-HYPE for regulating reservoirs within the NCRB and the new regulation routine can be found in previous work produced by BaySys (MacDonald et al., in revision; Tefs et al., in preparation (a)).

$$Outflow_i = \alpha \times (Depth_i - Sill\ Height)^{\beta}$$ [Equation 3-1a]

$$Outflow_i = \alpha \times (Depth_i - Sill\ Height - Dam\ Depth)^{\beta}$$ [Equation 3-1b]

A summary of the re-calibrated reservoirs and the accuracy of their re-calibration (when compared to historic stage-discharge records) is presented in Table 3-2. Where no accurate stage-discharge data were available to re-calibrate the outflow equation, the lip of the dam was dropped to match the level of the natural lake outlet, with parameters (α and β) kept as their post-development values. In practical terms, this entails removing *Dam Depth* from Equation 3-1b, but retaining all other parameters. Locations where re-calibration and lowering of the dam-lip are employed are shown on Figure 3-2.

Table 3-2: *Reservoirs with available pre-development stage-discharge data, simulated to fit historical data (R^2 and p-value from two-tailed t-test). Numbers correspond to Figure 3-2.*

Reservoir Name		Years Used (Historic Record)	Pre-Development Stage-Discharge Curve		
			R^2 value	p value	Paired data count
1	Rainy Lake	1912 - 1913	0.994	0.5113	128
2	Lake of the Woods	1913 - 1924	0.954	0.0000	2888
3	Lac Seul	1918 - 1919	0.948	0.7815	336
4	Cedar Lake	1951 - 1963	0.898	0.0240	1867
5	Wollaston Lake	1952 - 1954	0.990	0.9880	18
6	Lake Manitoba	1955 - 1957	0.989	0.9628	153
7	Lake Winnipeg	1959 - 1966	0.912	0.1542	552
8	Split Lake	1960 - 1966	0.823	0.0424	1055
9	S. Indian Lake	1960 - 1976	0.963	0.6781	2409
10	Lac la Ronge	1967 - 1967	0.818	0.0858	26
11	Reindeer Lake	1971 - 1972	0.744	0.0000	307
12	Umfreville Lake	1981 - 1985	0.645	0.1258	870
13	Sipiwesk Lake	2005 - 2015	0.888	0.0228	1993

In HYPE, the DamData.txt, MgmtData.txt and BranchData.txt files are removed entirely, preventing the model from accessing any data related to regulation (DamData), irrigation (MgmtData) or diversions (BranchData). Adjustments to LakeData.txt are made to remove any effect of the reservoirs or dams and GeoData.txt to remove their DamID and change any necessary land-cover fractions (Section 3.2.3.2) in the case of flooded or otherwise anthropogenic, flooded reservoirs.

Pre-development areas listed as "River" in Table 3-3 denote reservoirs whose pre-development reservoirs area was zero, but which have a surface area defined by the river extents in HYPE. Least-squares regression of stage-discharge data yields relatively strong average performance (R^2) and capture the overall behaviour of the unregulated reservoirs (visual fit) (Appendix E). These models exhibit poor performance when comparing distributions (p-value) since the re-naturalized curves ignore natural variability (i.e., due to upstream and downstream hydraulic effects). Note that very different discharge values are possible for the same depth, which is mathematically impossible using a fitted curve.

3.2.3.2 Re-naturalizing land-cover properties

The HYPE model dictates sub-basin properties by their Soil and Land-use Classes (SLC) fractions. Previous sub-basin-specific studies have examined the effects of land-cover non-stationarity in hydrologic modelling (Wruth et al., 2014; Murray et al., 2012; Li et al., 2011; Gerten et al., 2004). In this study, Soil and Land-use Combinations (SLCs) have been assumed static through time such that we can isolate changes directly attributed to the GCM inputs or regulation of flow; though SLCs do vary between the regulated and re-naturalized models. This is also consistent with other studies using HYPE (Arheimer et al., 2017; Donnelly et al., 2016; Pechlivanidis and Arheimer 2015; Bergstrand et al., 2014).

Table 3-3: *Reservoirs re-naturalized by reverting to pre-development land-soil combination (un-flooded). Numbers correspond to Figure 3-2. Note that S. Indian Lake appears here and in Table 3-2 (both un-flooded and reverted to a historical outflow).*

Reservoir Name		Surface Area [km²]			Source
		Post-Development		Pre-Dev.	
		HYPE	Source Varies		
14	Réservoir La Grande 1	68	71	25	Personal communication with Hydro-Québec
15	Réservoir La Grande 2	3634	2905	444	
16	Réservoir La Grande 3	2818	2452	477	
17	Réservoir La Grande 4	541	836	126	
18	Réservoir Laforge 1	314	1240	481	
19	Réservoir Laforge 2	2236	346	12	
20	Lac Caniapiscau	1735	4378	1748	
21	Lac Opinaca	1253	998	443	
22	Réservoir Eastmain 01	362	589	114	
23	Bief Rupert Aval	2495	690	156	
25	Tobin Lake	226	298	River	Hammer, 1988
24	Lake Diefenbaker	458	430	River	Smith and Kells, 1993
9	Southern Indian Lake	2227	2415	2033	Newbury et al., 1984

To return sub-basins to their pre-flooding (re-naturalized) state, non-lake SLC fractions are scaled up based on the post-flooding land composition (surrounding the reservoir) and pre-flooding lake coverage, calculated on the scale of HYPE sub-basins. The method used applies Equations 3-2a, 3-2b and 3-2c to every sub-basin containing a part or the whole of a flooded reservoir, to every SLC i (30 total SLC combinations in H-HYPE). The area of the reservoirs contained within each sub-basin was calculated from the sources listed in Table 3-3. All SLC fractions post-development are known for every sub-basin as they exist in the data provided for the H-HYPE model. These were originally generated using the European Space Agency (ESA) Climate Change Initiative Land-Cover Project (Version 1.4).

$$FracScaleUp = {Area_{H_2O}^{Pre-Dev}} \Big/ {Area_{H_2O}^{Post-Dev}} \qquad \text{[Equation 3-2a]}$$

$$SLC_{H_2O}^{Pre-Dev} = SLC_{H_2O}^{Post-Dev} \times FracScaleUp \qquad \text{[Equation 3-2b]}$$

$$SLC_{i}^{Pre-Dev} = SLC_{i}^{Post-Dev} \times \left({1 - SLC_{H_2O}^{Pre-Dev}} \Big/ {1 - SLC_{H_2O}^{Post-Dev}} \right) \qquad \text{[Equation 3-2c]}$$

3.2.4 Climate/regulation intercomparison methodology

To compare the relative effects of climate change and regulation over various time periods, nine intercomparisons were made (Table 3-4). Horizontal arrows represent direct comparison (same time period and therefore climatic ensemble forcing) of model configurations (regulated or re-naturalized). These analyses explain the differing response from the two model configurations to varying climatic conditions. Vertical arrows compare the same model configuration (regulated or re-naturalized) between different time periods (1981 to 2010 compared to 2021 to 2050 and 2041 to 2070), evaluating the effect climate change has on a static model configuration. Vertical arrows originating from the “HydroGFD” panels describe the ensemble bias in the GCM historical climate, relative to the calibration re-analysis product.

Table 3-4: *Schematic of intercomparison periods and models*

(1981-2010) (HydroGFD) Regulated	**(1981-2010) (HydroGFD) Re-Naturalized**
(1981-2010) Regulated	**(1981-2010) Re-Naturalized**
(2021-2050) Regulated	**(2021-2050) Re-Naturalized**
(2041-2070) Regulated	**(2041-2070) Re-Naturalized**

Intercomparison of these results indicates changes in different behavioural patterns and trends among different periods and models. Comparisons were done on model input (total precipitation, liquid precipitation, solid precipitation and air temperature), the model’s hydrological responses (evapotranspiration, snow-water equivalent, runoff), and the net effect at the outlet (basin discharge).

3.2.5 Statistical treatment of data

3.2.5.1 Intercomparison of upstream basins

Daily results were generated for both models from 1981 to 2070 for all 19 climate scenarios, producing a variety of hydrologic and climatic variables (Table 3-5). Owing to the size of the region and number of scenarios run, daily results were reduced (summed or averaged depending on the variable) to monthly values to examine shifts in magnitude and timing. Using all sub-basins (2883 sub-basins for the NCRB and 567 for the LGRC) upstream of basin outlets, monthly basin averages (*Val* for month *j*) were generated using an area-weighted average of monthly values.

$$Val_j = {(\sum_i^{basins} Var_{j,i} \times Area_i)} \Big/ {\sum_i^{basins} Area_i} \quad \text{[Equation 3-3]}$$

Table 3-5: *Variables computed in HYPE presented for upstream basin analysis.*

Variable Description	HYPE Variable	Unit	Aggregation
Total Precipitation	CPRC	mm	Sum
Liquid Precipitation	CPRF		
Solid Precipitation	CPSF		
Actual Evapotranspiration	EVAP		
Runoff	CRUN		
Snow-Water Equivalent	SNOW		Mean
Air Temperature	CTMP	°C	
Basin Discharge	COUT	$m^3 s^{-1}$	

A monthly anomaly analysis was performed and is shown for the input variables (air temperature, total precipitation, liquid precipitation, solid precipitation). From the monthly GCM-mean values for each major basin and model configuration, a monthly mean was created including all years analysed in the study period (1981 to 2010 and 2021 to 2070). For the NCRB and LGRC, regulated and re-naturalized values for each month for every year were compared to their respective monthly mean and the monthly anomaly was computed. Decomposing the monthly GCM-mean values to their component parts, the standard deviation was calculated between the GCM members for each month. These are shown as the coefficient of variation (COV) value (Equation 3-4b), indicating the relative variability between the climate models for that particular month within the timeseries.

A monthly period mean analysis was done and is shown for the hydrologic response variables. For each of the months (for the NCRB and LGRC and for regulated and re-naturalized) a 30-year period-mean (μ) of the GCM-mean values were calculated. The standard deviation between each monthly value for the 30-year period was calculated ($\sigma_{inter\text{-}annual}$) and used to compute the $COV_{inter\text{-}annual}$

(Equation 3-4a). The standard deviation for month of the year was taken between the 19 climate scenarios ($\sigma_{\text{inter-scenario}}$) to compute the $COV_{\text{inter-scenario}}$ (Equation 3-4b).

$$COV_{inter-annual} = {}^{\sigma_{inter-annual}}/_{\mu} \times 100\% \qquad \text{[Equation 3-4a]}$$

$$COV_{inter-scenario} = {}^{\sigma_{inter-scenario}}/_{\mu} \times 100\% \qquad \text{[Equation 3-4b]}$$

Seasonal values for each period were aggregated from monthly values using literature-typical hydrologic seasons: Winter (DJF), Spring (MAM), Summer (JJA), and Autumn (SON). Given the size and latitudinal gradient of the HBDB, it is acknowledged that there will be a shift in seasonality from lower to higher-latitude sub-basins. The standard seasonal definition was chosen to be most consistent with the literature and the southern headwater extents of the HBDB. Seasonal values calculated annually were used to determine seasonal mean values per period, seasonal trends within periods (as well the significance of those trends) and the percent differences (percent and absolute) between models and periods. The significance of trends for each period and model configuration was calculated using the Mann-Kendall (Kendall, 1975) test following pre-whitening at a 95% significance level ($\alpha = 0.05$).

3.2.5.2 Intercomparison at outlets of regulated basins

Daily estuary discharges were aggregated by major drainage basin (NCRB: sum of Nelson and Churchill Rivers; LGRC: sum of La Grande, Eastmain, Rupert and Koksoak Rivers) to generate daily average annual hydrographs. A daily average annual hydrograph was computed for each of the 19 GCMs, with the ensemble mean for both model configurations and three time-periods used for comparison as well as for the historical period using the re-analysis product and observed record. Inter-annual and inter-scenario COV values were developed using Equations 3-4a and 3-4b, though in this case using daily data, not monthly. Average and standard deviation for leap year days (DOY = 366) were calculated only on those years with data present (fewer data points).

3.3 Results and discussion

3.3.1 Upstream basins under climate change

Heat maps are used to show the monthly anomaly analysis for total precipitation, liquid precipitation, solid precipitation and air temperature (Figures 3-3a, 3-3b, 3-3c and 3-3d). Monthly values below the heat maps report the mean used to calculate the monthly anomalies. The anomaly of each month is dependent only on that month's mean and independent of all other months. Units and scale change for every figure and are listed next to the colour scale (units and aggregation method from Table 3-5). Radial plots are used to analyse mean monthly evapotranspiration, snow-water equivalent and runoff (Figures 3-4a, 3-4b and 3-4c). All radial plots share the legend from Figure 3-4a (units and aggregation method change by variable and are consistent with Table 3-5). Figure 3-5 presents the discharge in the same format as Figure 3-3. Inter-scenario COV is shown for discharge using a heat map (Figure 3-6).

Table 3-6: *30-year period-mean value and trend by season, model configuration and time period. Bold values indicate significance (Mann-Kendall, α = 5%); green cells indicate increasing (positive) trends, red for decreasing (negative) trends, and blue indicates no (negligible) trend).*

(a) Total Precipitation [mm]

Value [mm]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	56	99	218	115	488	124	128	269	231	752
CalibNat		Re-Naturalized		56	99	218	115	488	124	128	269	231	752
HistReg	GCM Ensemble	Regulated		61	97	208	129	494	84	95	197	163	538
HistNat		Re-Naturalized		61	97	208	129	494	84	95	197	163	538
Fut1Reg		Regulated	2021-2050	65	109	213	136	524	93	104	207	177	582
Fut1Nat		Re-Naturalized		65	109	213	136	524	93	104	207	177	582
Fut2Reg		Regulated	2041-2070	72	116	212	142	542	105	114	214	187	620
Fut2Nat		Re-Naturalized		72	116	212	142	542	105	114	214	187	620

Trend [mm/yr]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0.3	0.6	0.5	0.0	1.3	-0.2	**-0.9**	1.1	-0.1	0.0
CalibNat		Re-Naturalized		0.3	0.6	0.5	0.0	1.3	-0.2	**-0.9**	1.1	-0.1	0.0
HistReg	GCM Ensemble	Regulated		**0.1**	**0.3**	**0.4**	**0.2**	**1.1**	**0.3**	**0.3**	**0.3**	**0.4**	**1.3**
HistNat		Re-Naturalized		**0.1**	**0.3**	**0.4**	**0.2**	**1.1**	**0.3**	**0.3**	**0.3**	**0.4**	**1.3**
Fut1Reg		Regulated	2021-2050	**0.2**	**0.5**	0.0	**0.2**	**0.9**	**0.5**	**0.4**	**0.4**	**0.5**	**1.7**
Fut1Nat		Re-Naturalized		**0.2**	**0.5**	0.0	**0.2**	**0.9**	**0.5**	**0.4**	**0.4**	**0.5**	**1.7**
Fut2Reg		Regulated	2041-2070	**0.4**	**0.4**	0.1	**0.5**	**1.4**	**0.6**	**0.6**	0.3	**0.8**	**2.2**
Fut2Nat		Re-Naturalized		**0.4**	**0.4**	0.1	**0.5**	**1.4**	**0.6**	**0.6**	0.3	**0.8**	**2.2**

(b) Rainfall [mm]

Value [mm]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	1	70	217	81	370	1	44	267	144	456
CalibNat		Re-Naturalized		1	70	217	81	370	1	44	267	144	456
HistReg	GCM Ensemble	Regulated		0	58	208	83	350	0	23	195	81	299
HistNat		Re-Naturalized		0	58	208	83	350	0	23	195	81	299
Fut1Reg		Regulated	2021-2050	1	75	213	95	384	0	35	206	102	344
Fut1Nat		Re-Naturalized		1	75	213	95	384	0	35	206	102	344
Fut2Reg		Regulated	2041-2070	2	83	212	103	399	1	43	213	115	372
Fut2Nat		Re-Naturalized		2	83	212	103	399	1	43	213	115	372

Trend [mm/yr]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0.0	0.6	0.5	0.1	1.2	0.0	0.0	1.2	0.5	1.7
CalibNat		Re-Naturalized		0.0	0.6	0.5	0.1	1.2	0.0	0.0	1.2	0.5	1.7
HistReg	GCM Ensemble	Regulated		0.0	**0.4**	**0.4**	**0.4**	**1.1**	0.0	**0.3**	**0.3**	**0.5**	**1.1**
HistNat		Re-Naturalized		0.0	**0.4**	**0.4**	**0.4**	**1.1**	0.0	**0.3**	**0.3**	**0.5**	**1.1**
Fut1Reg		Regulated	2021-2050	**0.0**	**0.5**	0.0	**0.3**	**0.7**	0.0	**0.3**	**0.4**	**0.7**	**1.4**
Fut1Nat		Re-Naturalized		**0.0**	**0.5**	0.0	**0.3**	**0.7**	0.0	**0.3**	**0.4**	**0.7**	**1.4**
Fut2Reg		Regulated	2041-2070	**0.1**	**0.4**	0.1	**0.6**	**1.2**	**0.0**	**0.5**	**0.3**	**1.0**	**1.8**
Fut2Nat		Re-Naturalized		**0.1**	**0.4**	0.1	**0.6**	**1.2**	**0.0**	**0.5**	**0.3**	**1.0**	**1.8**

(c) Snowfall [mm]				NCRB					LGRC				
Value [mm]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	55	29	0	34	118	123	84	2	87	296
CalibNat		Re-Naturalized		55	29	0	34	118	123	84	2	87	296
HistReg	GCM Ensemble	Regulated		60	38	0	46	145	83	71	2	82	239
HistNat		Re-Naturalized		60	38	0	46	145	83	71	2	82	239
Fut1Reg		Regulated	2021-2050	65	33	0	41	139	93	70	1	75	239
Fut1Nat		Re-Naturalized		65	33	0	41	139	93	70	1	75	239
Fut2Reg		Regulated	2041-2070	70	33	0	39	143	104	71	1	72	248
Fut2Nat		Re-Naturalized		70	33	0	39	143	104	71	1	72	248

Trend [mm/yr]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0.3	0.0	0.0	-0.1	0.2	-0.3	-0.9	0.0	-0.6	-1.7
CalibNat		Re-Naturalized		0.3	0.0	0.0	-0.1	0.2	-0.3	-0.9	0.0	-0.6	-1.7
HistReg	GCM Ensemble	Regulated		0.1	0.0	0.0	-0.1	-0.1	0.3	0.0	0.0	-0.2	0.2
HistNat		Re-Naturalized		0.1	0.0	0.0	-0.1	-0.1	0.3	0.0	0.0	-0.2	0.2
Fut1Reg		Regulated	2021-2050	0.2	0.0	0.0	-0.1	0.2	0.5	0.1	0.0	-0.1	0.4
Fut1Nat		Re-Naturalized		0.2	0.0	0.0	-0.1	0.2	0.5	0.1	0.0	-0.1	0.4
Fut2Reg		Regulated	2041-2070	0.3	0.0	0.0	-0.1	0.2	0.6	0.1	0.0	-0.2	0.5
Fut2Nat		Re-Naturalized		0.3	0.0	0.0	-0.1	0.2	0.6	0.1	0.0	-0.2	0.5

(d) Air Temperature [°C]				NCRB					LGRC				
Value [°C]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	-15	2	16	3	1	-21	-6	12	1	-3
CalibNat		Re-Naturalized		-15	2	16	3	1	-21	-6	12	1	-3
HistReg	GCM Ensemble	Regulated		-17	-1	15	1	-1	-22	-9	10	-2	-6
HistNat		Re-Naturalized		-17	-1	15	1	-1	-22	-9	10	-2	-6
Fut1Reg		Regulated	2021-2050	-15	1	17	3	1	-19	-6	11	-1	-4
Fut1Nat		Re-Naturalized		-15	1	17	3	1	-19	-6	11	-1	-4
Fut2Reg		Regulated	2041-2070	-13	2	18	4	3	-17	-5	12	1	-2
Fut2Nat		Re-Naturalized		-13	2	18	4	3	-17	-5	12	1	-2

Trend [°C/yr]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.0	0.1	0.1
CalibNat		Re-Naturalized		0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.0	0.1	0.1
HistReg	GCM Ensemble	Regulated		0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.1
HistNat		Re-Naturalized		0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.1
Fut1Reg		Regulated	2021-2050	0.1	0.1	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.1
Fut1Nat		Re-Naturalized		0.1	0.1	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.1
Fut2Reg		Regulated	2041-2070	0.1	0.0	0.1	0.0	0.1	0.1	0.1	0.0	0.1	0.1
Fut2Nat		Re-Naturalized		0.1	0.0	0.1	0.0	0.1	0.1	0.1	0.0	0.1	0.1

(e) Actual Evapotranspiration [mm]				NCRB					LGRC				
Value [mm]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	4	98	251	52	405	2	48	240	54	343
CalibNat		Re-Naturalized		4	98	251	52	405	2	48	240	54	343
HistReg	GCM Ensemble	Regulated		4	89	261	56	410	2	41	189	44	276
HistNat		Re-Naturalized		4	89	261	56	410	2	41	189	44	275
Fut1Reg		Regulated	2021-2050	5	109	270	59	443	2	52	208	49	311
Fut1Nat		Re-Naturalized		5	109	270	59	443	2	52	208	49	311
Fut2Reg		Regulated	2041-2070	5	119	273	61	458	2	60	218	52	332
Fut2Nat		Re-Naturalized		5	119	273	61	458	2	60	218	52	332

Trend [mm/yr]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0.0	0.0	0.2	0.2	0.3	0.0	0.4	0.8	0.3	1.5
CalibNat		Re-Naturalized		0.0	0.0	0.2	0.2	0.3	0.0	0.4	0.8	0.3	1.5
HistReg	GCM Ensemble	Regulated		0.0	0.4	0.4	0.1	0.9	0.0	0.2	0.5	0.1	0.9
HistNat		Re-Naturalized		0.0	0.4	0.4	0.1	0.9	0.0	0.2	0.5	0.1	0.9
Fut1Reg		Regulated	2021-2050	0.0	0.5	0.1	0.1	0.7	0.0	0.4	0.4	0.1	1.0
Fut1Nat		Re-Naturalized		0.0	0.5	0.1	0.1	0.7	0.0	0.4	0.4	0.1	1.0
Fut2Reg		Regulated	2041-2070	0.0	0.5	0.3	0.1	0.9	0.0	0.4	0.5	0.2	1.1
Fut2Nat		Re-Naturalized		0.0	0.5	0.3	0.1	0.9	0.0	0.4	0.5	0.2	1.1

(f) Snow-Water Equivalent [mm]

Value [mm]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	47	32	0	6	21	129	168	5	15	79
CalibNat		Re-Naturalized		47	32	0	6	21	129	168	5	15	79
HistReg	GCM Ensemble	Regulated		65	53	0	9	32	113	148	10	21	73
HistNat		Re-Naturalized		65	53	0	9	32	113	148	10	21	73
Fut1Reg		Regulated	2021-2050	63	45	0	7	29	111	141	7	17	69
Fut1Nat		Re-Naturalized		63	45	0	7	29	111	141	7	17	69
Fut2Reg		Regulated	2041-2070	63	45	0	7	29	112	143	6	15	69
Fut2Nat		Re-Naturalized		63	45	0	7	29	112	143	6	15	69

Trend [mm/yr]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0.0	0.1	**0.0**	0.0	0.0	-0.7	**-1.7**	-0.1	-0.2	**-0.7**
CalibNat		Re-Naturalized		0.0	0.1	**0.0**	0.0	0.0	-0.7	**-1.7**	-0.1	-0.2	**-0.7**
HistReg	GCM Ensemble	Regulated		-0.1	-0.1	0.0	**-0.1**	-0.1	0.1	0.1	-0.1	**-0.1**	0.0
HistNat		Re-Naturalized		-0.1	-0.1	0.0	**-0.1**	-0.1	0.1	0.1	-0.1	**-0.1**	0.0
Fut1Reg		Regulated	2021-2050	0.0	0.0	0.0	0.0	0.0	**0.1**	0.1	0.0	**-0.1**	0.0
Fut1Nat		Re-Naturalized		0.0	0.0	0.0	0.0	0.0	**0.1**	0.1	0.0	**-0.1**	0.0
Fut2Reg		Regulated	2041-2070	-0.1	0.0	0.0	**0.0**	0.0	0.0	0.0	0.0	**-0.1**	0.0
Fut2Nat		Re-Naturalized		-0.1	0.0	0.0	**0.0**	0.0	0.0	0.0	0.0	**-0.1**	0.0

(g) Runoff [mm]

Value [mm]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	4	49	31	17	100	11	173	136	95	415
CalibNat		Re-Naturalized		4	49	31	17	100	11	173	136	95	415
HistReg	GCM Ensemble	Regulated		2	49	35	11	97	3	86	140	37	267
HistNat		Re-Naturalized		2	49	35	11	97	3	86	140	37	267
Fut1Reg		Regulated	2021-2050	3	52	27	12	95	5	112	113	47	277
Fut1Nat		Re-Naturalized		3	52	27	12	95	5	112	113	47	277
Fut2Reg		Regulated	2041-2070	4	55	27	13	99	7	128	106	53	294
Fut2Nat		Re-Naturalized		4	55	27	13	99	7	128	106	53	294

Trend [mm/yr]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0.0	0.2	0.3	0.2	0.7	0.1	-0.3	**-1.8**	0.2	-1.7
CalibNat		Re-Naturalized		0.0	0.2	0.3	0.2	0.7	0.1	-0.3	**-1.8**	0.2	-1.7
HistReg	GCM Ensemble	Regulated		**0.0**	**0.2**	0.0	**0.1**	0.3	**0.0**	**0.6**	**-0.4**	**0.2**	**0.5**
HistNat		Re-Naturalized		**0.0**	**0.2**	0.0	**0.1**	0.3	**0.0**	**0.6**	**-0.4**	**0.2**	**0.5**
Fut1Reg		Regulated	2021-2050	**0.0**	**0.2**	-0.1	0.0	0.1	**0.1**	**0.8**	**-0.4**	**0.3**	**0.8**
Fut1Nat		Re-Naturalized		**0.0**	**0.2**	-0.1	0.0	0.1	**0.1**	**0.8**	**-0.4**	**0.3**	**0.8**
Fut2Reg		Regulated	2041-2070	**0.1**	**0.2**	0.0	**0.1**	**0.5**	**0.1**	**0.8**	**-0.4**	**0.5**	**1.1**
Fut2Nat		Re-Naturalized		**0.1**	**0.2**	0.0	**0.1**	**0.5**	**0.1**	**0.8**	**-0.4**	**0.5**	**1.1**

(i) Discharge [m^3/s]

Value [m^3/s]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	3350	3597	3604	3297	3462	4386	4654	4488	4020	4387
CalibNat		Re-Naturalized		3191	3199	3620	3472	3371	3299	4225	5430	4205	4290
HistReg	GCM Ensemble	Regulated		3352	3488	3757	3361	3490	3142	2624	3193	2254	2803
HistNat		Re-Naturalized		3314	3187	3652	3508	3415	2074	2316	3988	2590	2742
Fut1Reg		Regulated	2021-2050	3192	3433	3582	3192	3350	3166	2986	3030	2384	2891
Fut1Nat		Re-Naturalized		3164	3116	3454	3339	3268	2173	2651	3827	2661	2828
Fut2Reg		Regulated	2041-2070	3320	3591	3765	3357	3508	3282	3308	3072	2527	3047
Fut2Nat		Re-Naturalized		3290	3257	3588	3483	3404	2312	2956	3904	2813	2996

Trend [$m^3/s/yr$]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	18	16	15	25	19	-15	-2	-35	-11	-16
CalibNat		Re-Naturalized		24	22	22	34	25	-9	-1	**-38**	-11	-15
HistReg	GCM Ensemble	Regulated		**19**	**19**	**18**	**18**	**18**	1	5	0	**4**	3
HistNat		Re-Naturalized		**15**	**16**	**14**	**14**	**15**	**4**	**9**	3	**4**	**5**
Fut1Reg		Regulated	2021-2050	**8**	**9**	**9**	**8**	**9**	3	**11**	0	**6**	**5**
Fut1Nat		Re-Naturalized		**5**	**6**	5	**5**	**5**	**6**	**14**	3	**7**	**8**
Fut2Reg		Regulated	2041-2070	**12**	**13**	**16**	**16**	**14**	**10**	**21**	2	**10**	**11**
Fut2Nat		Re-Naturalized		**14**	**14**	**15**	**16**	**15**	**9**	**17**	4	**11**	**10**

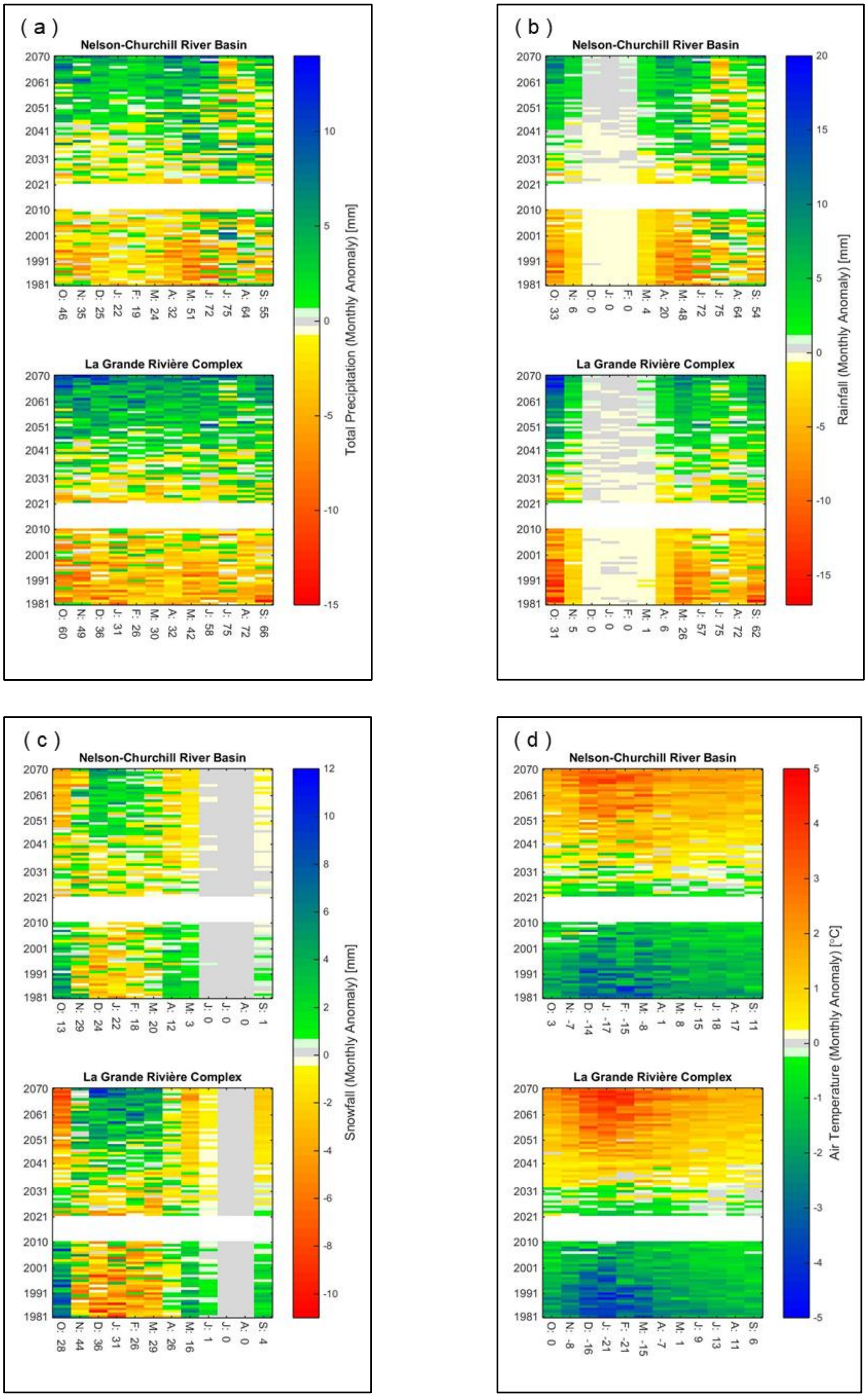
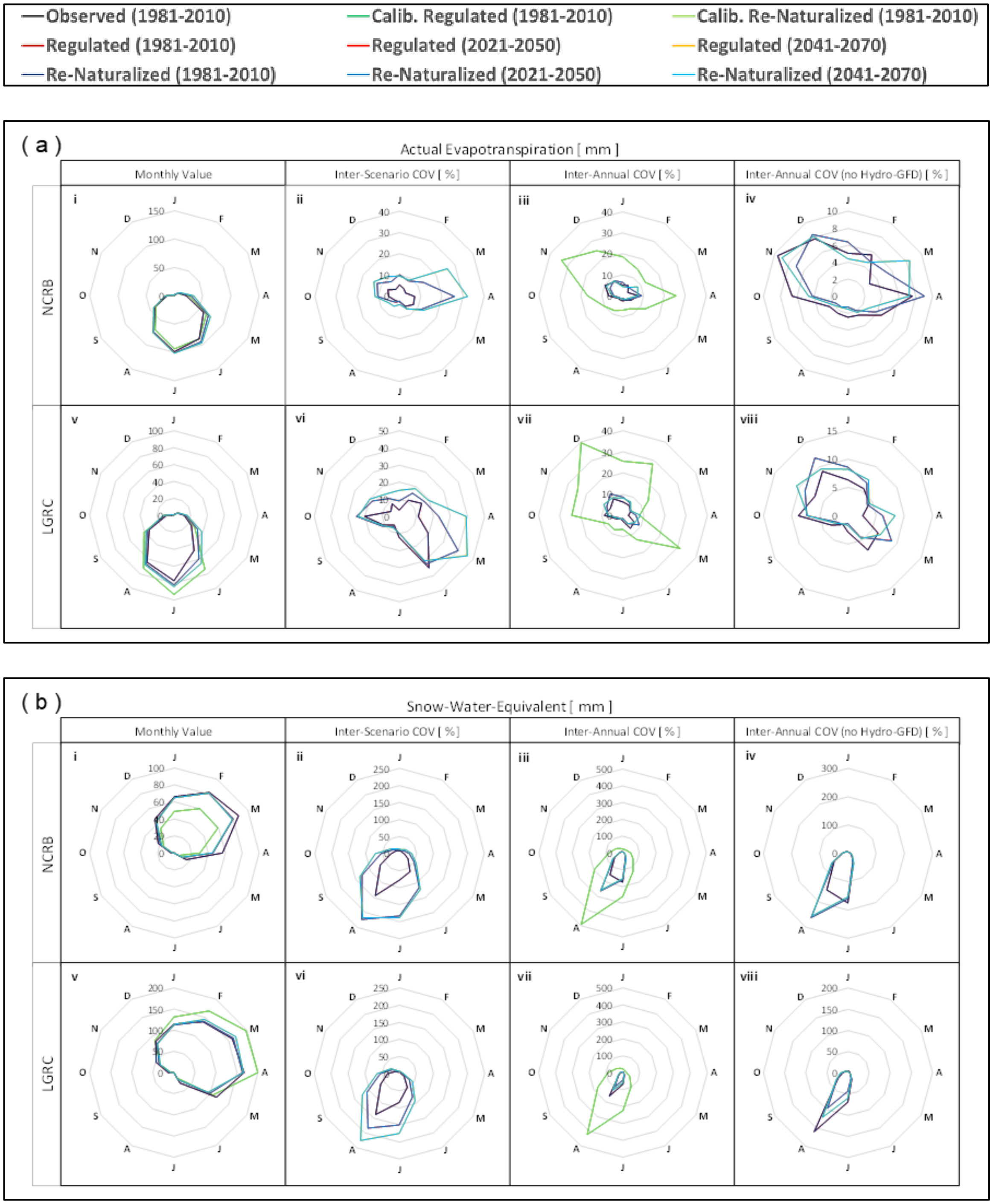


Figure 3-3: *Anomaly maps by year and month for NCRB (top) and LGRC (bottom) by model variable; anomaly relative to monthly average (1981-2010, 2021-2070), shown below each month. Variable and units are listed at right.*


Observed (1981-2010)
Calib. Regulated (1981-2010)
Calib. Re-Naturalized (1981-2010)
Regulated (1981-2010)
Regulated (2021-2050)
Regulated (2041-2070)
Re-Naturalized (1981-2010)
Re-Naturalized (2021-2050)
Re-Naturalized (2041-2070)
(a)
Actual Evapotranspiration [mm]
Monthly Value
Inter-Scenario COV [%]
Inter-Annual COV [%]
Inter-Annual COV (no Hydro-GFD) [%]
NCRB
LGRC
(b)
Snow-Water-Equivalent [mm]
Monthly Value
Inter-Scenario COV [%]
Inter-Annual COV [%]
Inter-Annual COV (no Hydro-GFD) [%]
NCRB
LGRC

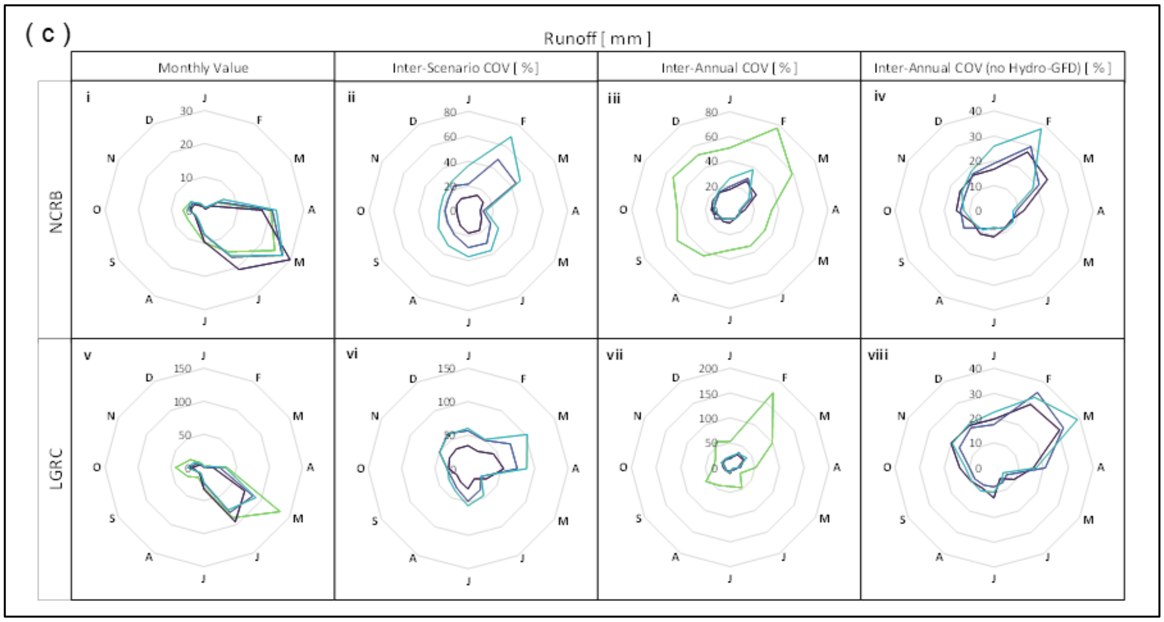


Figure 3-4: *Monthly radial plots by period/model configuration for (i, ii, iii, iv) NCRB and (v, vi, vii, viii) LGRC for (i, v) 30-year ensemble average value, (ii, vi) inter-scenario COV, (iii, vii) inter-annual COV, and (iv, viii) inter-annual COV with reanalysis products excluded.*

Results show the basins are expected to receive more rainfall across all months (Figure 3-3b) with decreasing snowfall at the beginning and end of the snow season (September, October, May, June) and increasing snowfall over the winter and early spring (December to March) (Figure 3-3c). These trends are generally significant for liquid (Table 3-6b) and solid precipitation (Table 3-6c) and occur simultaneously with increasing temperature in all months through time (Figure 3-3d) and an overall increasing total precipitation (Table 3-6a). ET subsequently increases through time (i.e., progression outwards of radial lines, Figure 3-4a) with a statistically significant trend (Table 3-6e). In summer, increasing ET appears to be outpacing increasing precipitation, which results in an overall trend toward decreasing summer runoff for both basins (Table 3-6g), with spring and autumn runoff increasing for both the NCRB and LGRC (Figure 3-4c). Inter-annual variability of runoff changes only slightly (Figure 3-4c), with significant increasing trends in runoff for the NCRB and the LGRC, except in summer where there are significant trends towards runoff loss in the LGRC and non-significant trends in the NCRB (Table 3-6g).

The loss of static water storage on the ground through the winter (SWE) (Figure 3-4b) is due to slowly increasing (or static) overall snowfall, and more efficient snowpack sublimation from increased ET during shoulder seasons (Figure 3-4a). Increased sublimation is coupled with higher temperatures that produce more mid-winter melt events and increasing DJF runoff trends for both the NCRB and LGRC (Figure 3-4c). The net result is decreased snow depth over a shorter portion of the year. This aligns with the observed trend towards a reduced nival regime in basins draining into Hudson Bay (MacDonald et al., 2018) and the Arctic Sea (Mackenzie River; Kang et al., 2014) and in northern Canada overall (Burn and Whitfield, 2017).

Importantly, these results confirm no (i.e., negligibly small) changes between the regulated and re-naturalized model configurations, for any given period. All variables were tested for differences between the regulated and re-naturalized models, only basin discharge showed any variation between ensemble members greater than 0.5% for any given month. This suggests, as one would intuitively guess, that basin-wide precipitation, temperature, transpiration and depth of snowpack are not affected by hydroelectric regulation or flooding. Small changes in evaporation are noted due to the differences between evapotranspiration from land and free-water evaporation off of flooded reservoirs. The only notable change caused by switching between regulated and re-naturalized models was seen in discharge values (Figure 3-5, particularly Figure 3-5i, iv).

3.3.2 Basin outlets under climate change and regulation

An analysis of the daily average annual discharge and inter-scenario and inter-annual coefficients of variation for both the NCRB and LGRC is provided in Figure 3-8. Figures 3-8e and 3-8f include the inter-annual variation of the re-analysis product used for calibration and observed data; Figures 3-8g and 3-8h focus exclusively on the GCM-generated results (re-analysis product removed). Differences from regulated to natural flow regimes impact the timing of yearly fluxes and are more noticeable in the LGRC combined outlet (Figures 3-5i and 3-5iv, Figures 3-7i and 3-7v). The driver between the differing LGRC and NCRB responses to climate change *may* be upstream storage availability *or* climate variability (particularly the effect of temperature on ET, and snowmelt timing).

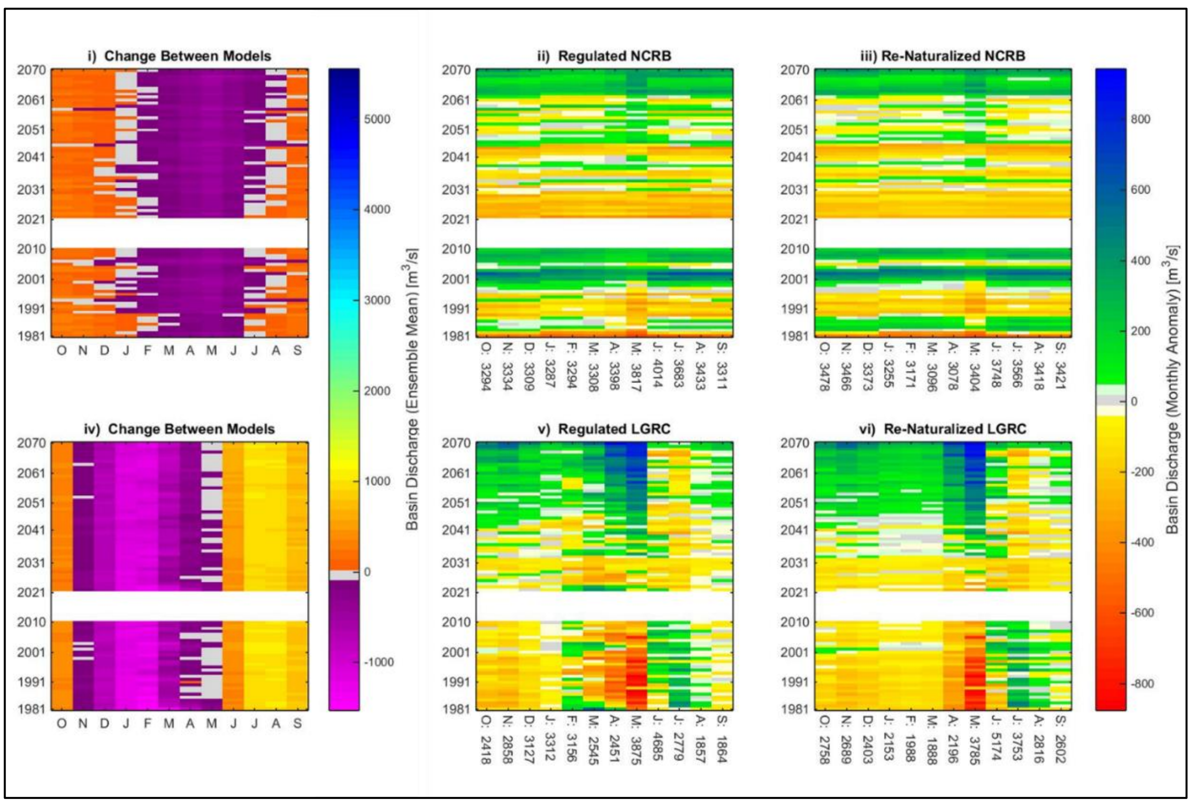


Figure 3-5: *Anomaly maps by year and month for (i, ii, iii) NCRB and (iv, v, vi) LGRC, (ii, iv) regulated model and (iii, vi) re-naturalized model and (i, iv) the difference (Δ = Nat. – Reg.). Anomaly is relative to monthly average (1981-2070), listed below each map.*

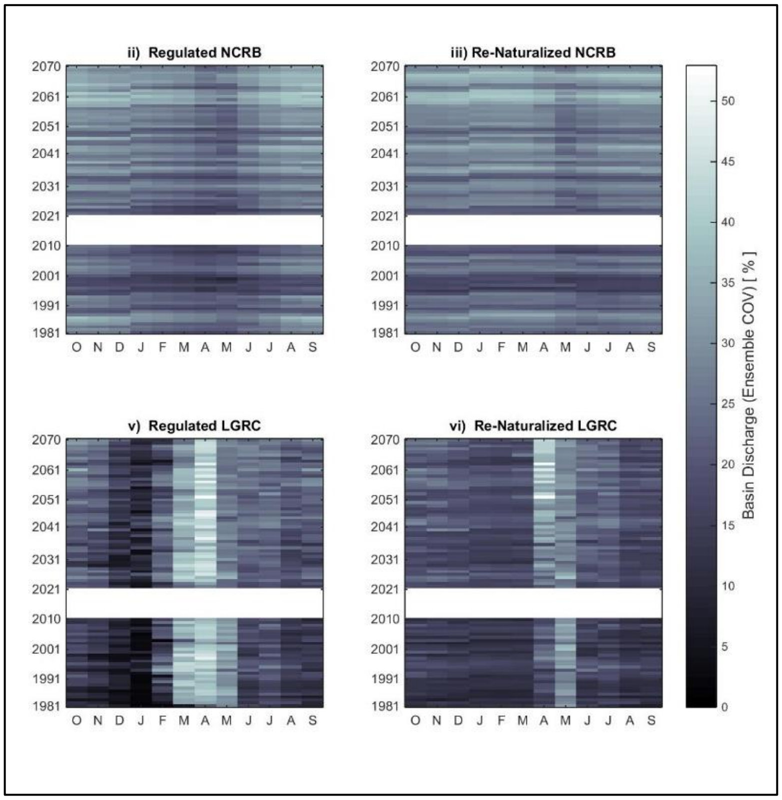


Figure 3-6: *Inter-scenario COV maps by year and month for (ii, iii) NCRB and (v, vi) LGRC, (ii, iv) regulated model and (iii, vi) re-naturalized model.*

Increasing ET may account for the consistently (throughout the year) higher inter-scenario variability of flow in the NCRB (Figures 3-6, 3-7ii, 3-7vi, 3-8g, and 3-8h). In a water-limited or semi-arid basin, increased precipitation can lead to increased runoff (and discharge), but significant water can also be lost along the flow-path due to evaporation if temperature increases are great enough. Even marginal inter-scenario disagreement in precipitation and/or temperature will propagate to disagreement in runoff and discharge values (Stadnyk et al., in press; Bring et al., 2017).

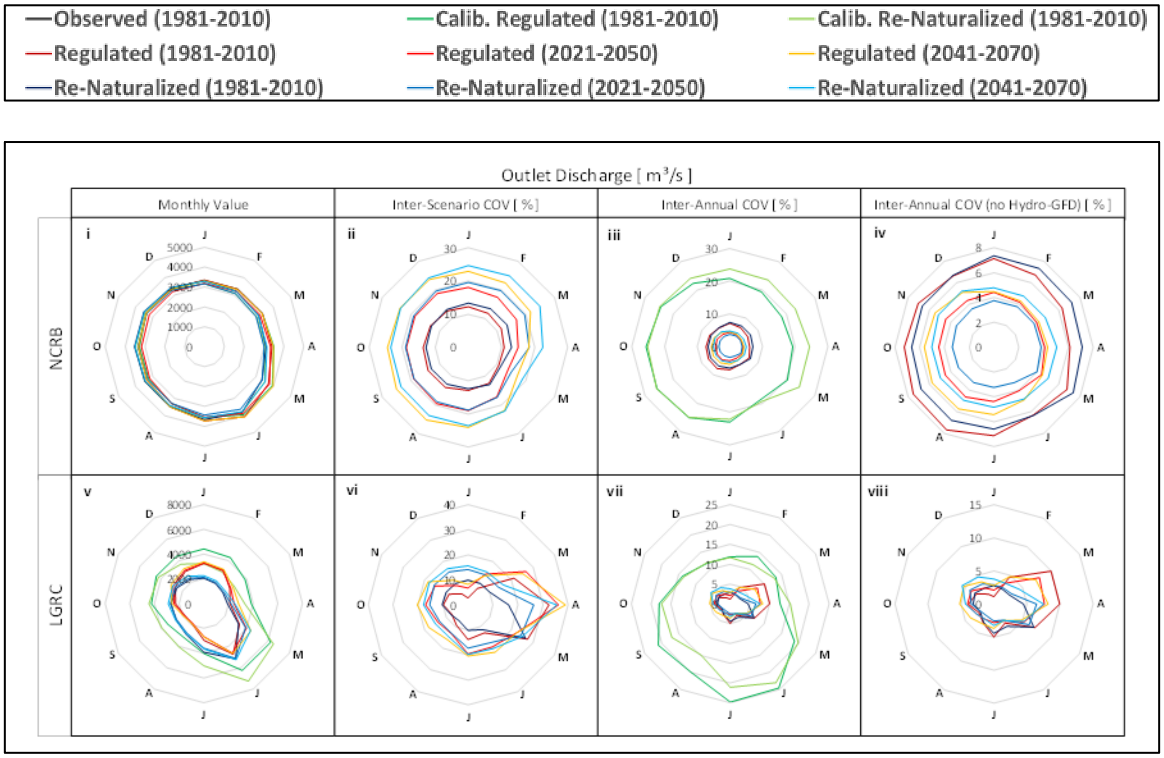


Figure 3-7: *Monthly radial plots by period/model configuration for (i, ii, iii, iv) NCRB and (v, vi, vii, viii) LGRC for (i, v) 30-year ensemble average value, (ii, vi) inter-scenario COV, (iii, vii) inter-annual COV, and (iv, viii) inter-annual COV with reanalysis products excluded.*

Climatic variability being the main driver of inter-annual variability differences between the NCRB and LGRC is not supported by the inter-scenario and inter-annual variability in ET and runoff, comparing the NCRB to the LGRC (Figures 3-4a and 3-4c and Table 3-6e). For both ET and runoff, the LGRC shows consistently larger inter-scenario COV than the NCRB, suggesting that even under equally or more variable runoff and more variable ET, the LGRC is still terminating with less variable flow for both regulated and re-naturalized model configurations. The explanation for this is likely the disparity between the NCRB and LGRC in available upstream storage relative to the flow being passed.

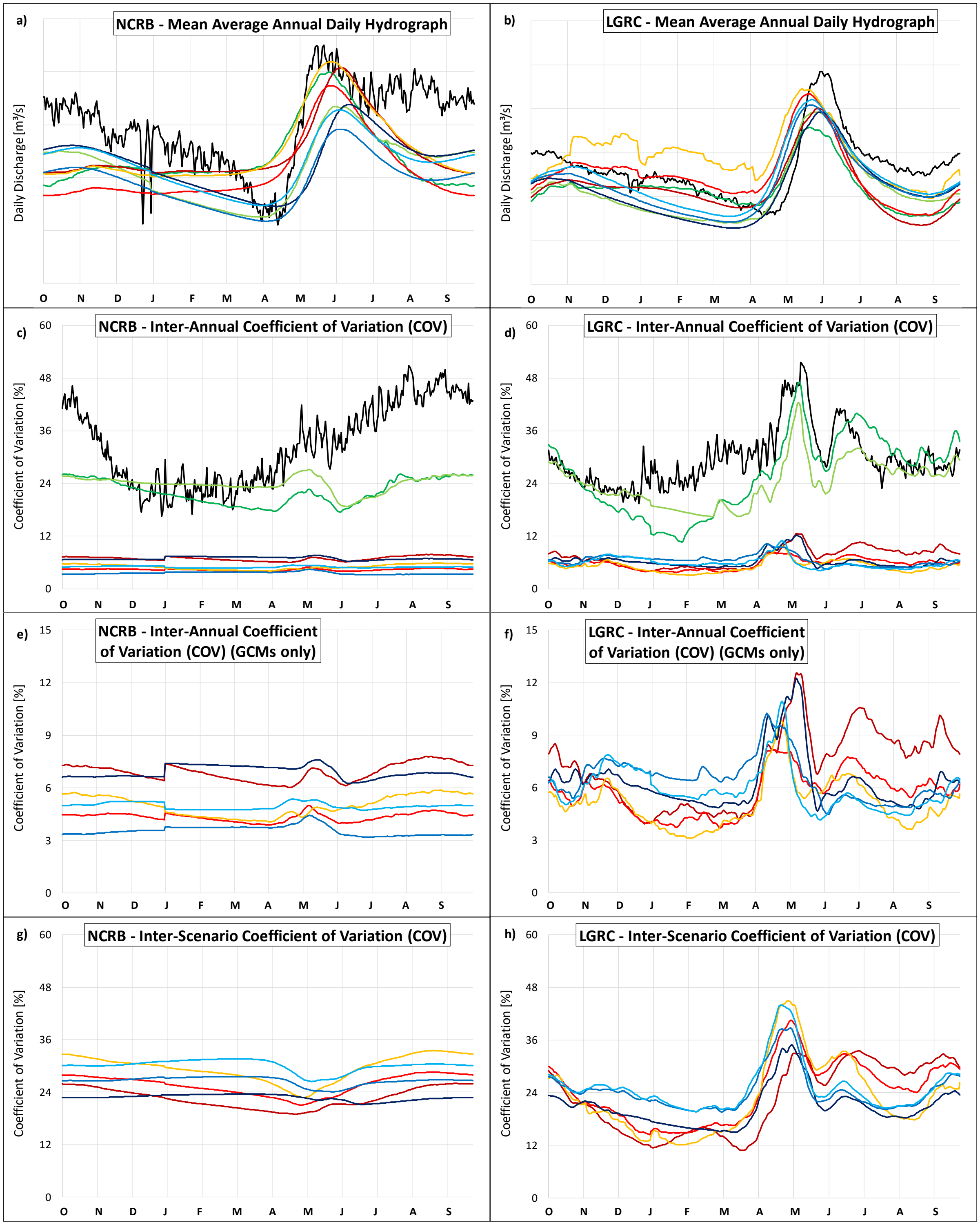


Figure 3-8: *(a, b) Average annual daily discharge, (c, d, e, f) inter-annual COV and (g, h) inter-scenario COV. Charts shown for the combined (b, d, f, h) LGRC and (a, c, e, g) NCRB outlets. Regulated models (reds), re-naturalized models (blues), shown for different time-periods (darkest: 1981-2010, lightest: 2041-2070, mid-time: 2021-2050). Re-analysis products (regulated: light green, re-naturalized: light green) and observed data (black).*

3.3.3 Effects of storage capacity and regulation

Upstream storage in regulated systems has previously been shown to limit the effectiveness of dams in reducing climate change effects on water availability (Ehsani et al., 2017). The NCRB regulated system has relatively limited storage (compared to mean annual flow) and is more heavily governed, meaning that under circumstances of increased runoff (and therefore increased upstream discharge) outflows may begin mimicking natural outflows (i.e., reservoirs are forced to spill reactively to large inflow events). Conversely, the LGRC has extensive storage-added (by flooding land), enabling it to respond more consistently to extreme (high or low) inflows year-by-year regardless of the climate forcing applied (i.e., greater operational leeway), resulting in lower inter-scenario and inter-annual variability (Figures 3-7 and 3-9).

Noticeable differences between the NCRB and LGRC basins, and the impact of regulation on their average annual discharge, are evident for both the observed and modelled results. The LGRC includes flooded reservoirs, which were reverted to their original storage volume in the re-naturalized model with regulation also removed (Figure 3-2). The headwaters of the NCRB combined outlet have more natural lakes to begin with (i.e. present in both the regulated and re-naturalized models), and virtually all the re-naturalized reservoirs retain their regulated storage in H-HYPE due to power generation being predominantly run-of-the-river in the NCRB. The regulated NCRB has a theoretical maximum detention time ($\tau = [\Sigma S_{upstream}] / \mu_Q$) of 285 days, where the LGRC has one of 422 days (based on storage and discharge values from Déry et al., 2011). Returning to Figures 2-3 and 3-2, the distribution of the upstream storage is also notably different. The NCRB regulated reservoirs with the largest ratio of live storage to inflow (Reindeer Lake, Lake of the Woods, and Cedar Lake) are further upstream. The last points of major regulation (Lake Winnipeg and S. Indian Lake) are well upstream (approximately 600 and 375 km, respectively) and have lower theoretical detention times

(Table 2-2). On the other hand, the LGRC reservoirs are spread out linearly and grow in size as they approach La Grande 2 (Réservoir Robert Bourassa) which is near to the outlet (approximately 125 km), leaving less intervening land-mass to contribute unregulated runoff. This is reflected in the relative degrees of control over outflow.

The potential of the LGRC system to store more than one year's worth of flow is reflected in the lower overall inter-scenario variability in the LGRC (Figures 3-6 and 3-7). With more storage capacity, the LGRC system is capable of adapting to disparate climate situations (i.e., such as an ensemble of GCMs or an increasingly variable inter-annual climate) by using the large reservoirs to buffer shorter-term alteration of inflows to achieve desired flows in different seasons. In contrast, variability at the outlet of the NCRB has the potential to be higher, even under less variable runoff. Consequently, the NCRB is prone to having an entire year affected by extreme flows. Inter-scenario COV for the NCRB shows a heat-map pattern that is more prominent horizontally (year-to-year), where extreme years (wet or dry) dominate variability across an entire year (e.g., Figure 3-6). Conversely, the LGRC shows months that consistently have higher (spring) and lower (winter) COV across the 90 years of study. Both the LGRC and NCRB show changes in their COVs between regulated and re-naturalized scenarios. This implies that the regulation of these basins not only affects the ensemble mean discharge, but the degree of variation between possible discharge scenarios in the ensemble of GCMs.

The effect of regulation is seen most prominently in the COV (inter-annual and inter-scenario) of the two basins, with both exhibiting a shift in behaviour between regulated and re-naturalized scenarios. Both regulated systems show decreasing inter-annual COV (greater agreement, year-to-year) over winter (Figure 3-8c through 3-8h). Hydroelectric companies strive for greater reliability of flows year-round, which is largely being achieved (evidenced by smaller COVs) in both the LGRC and NCRB. Regulated rings are generally tighter than their corresponding re-naturalized rings in the radial COV plots (with the exception of LGRC 1981-2010, Figure 3-7), despite far more consistent (compared to discharge) COVs for runoff between regulated and re-naturalized scenarios (Figure 3-4c). Regulation also produces large changes intra-annually (i.e., not seen in any of the upstream variables) by re-allocating flow throughout the year (Figure 3-5i, iv). Additionally, by retaining stationary regulation rules, the effect of concentrating the variability in certain times of year is seen. Seen more clearly in the LGRC (Figure 3-7 viii), this re-allocation of the time of year with the greatest variability is largely due to static regulation. By prescribing the day (or week or month) where spills are allowable, the regulation methods used may focus variability over a shorter period of time in exchange for longer periods of improved flow reliability. This may seem unrealistic at first glance, but at its core, this is the basic principle of hydroelectric regulation, reflected by the seasonal nature of the observed COV plots (Figure 3-8c and 3-8d).

These results stand contrary to the results of a study using the same model and a similar methodology, but studying the Swedish hydroelectric system (Arheimer et al., 2017). This study showed that regulation exerts a greater effect than climate change on snow-fed rivers. The exact reason for these studies reaching opposing conclusions is not singular or conclusive, but is likely due to the alignment and size of the basins themselves. In the case of the NCRB, long rivers converge (naturally or through diversions) towards hydroelectric generation points separated by significant space. The upstream area covers zones of varying climate, land-cover and soil-type over an area more than three times the size of Sweden (1,400,000 km^2 versus 425,000 km^2). Because of the relative density of hydroelectric regulation in Sweden, over a smaller area, it is not surprising that regulation effects will dominate. This is supported by the LGRC results being more comparable to the results of the SMHI study, but still having significant effects of climate change because of the large basin area relative to the number hydroelectric installations (regulation density).

3.4 Conclusion

In the context of the larger BaySys question, "Is climate change or hydroelectric regulation playing the larger role in changes to freshwater export into Hudson Bay?", the main driver of changes in the freshwater flux appears to be upstream storage capacity, and by extension, reservoir capability to control floods and ride out droughts. The degree of hydrograph flattening and decrease of inter-scenario variability among regulated scenarios differs between the two basins examined in this study under a changing climate. Namely, the degree of flattening and the scenario agreement are determined by the regulated system's capacity to absorb greater climate (i.e., inflow) variability. The changes in the freshwater flux into Hudson Bay cannot be entirely attributed to one or the other of climate change or hydroelectric regulation; however, by separating the analysis into time-scales, more distinct conclusions can be drawn.

Intra-annually, changes are driven by hydroelectric operations. By examining changes between the regulated and re-naturalized models across all variables, no significant changes in either the input (volume and type of precipitation, temperature) nor the response variables (ET, SWE, and runoff) is observed. If changes in runoff timing do not correlate to the changes in timing of the discharge, only hydroelectric regulation can be causing this intra-annual variation.

Inter-annually, changes in the flow regime are partly attributable to climate variability, but are also influenced by the differences in upstream storage availability between the two basins (a corollary of regulation). The NCRB COV and discharge anomaly indicate the basin is more prone to persistent wet or dry periods than the LGRC. The LGRC, in contrast, is more likely to have consistent seasonal patterning between years. Between the re-naturalized and regulated models, the COV changes indicate a system without regulation would be as or more subject to inter-annual variability. The overall variability within any given year is similar with and without regulation, but the timing will be dictated by the presence and extent of regulation.

Examination of inter-period (or inter-decadal) trends reveals the most significant driving factor appears to be climate change. Large increases in precipitation, changes in the type of precipitation (i.e., liquid vs. solid), and increasing temperatures (and subsequent impacts on both SWE and ET) begin to dominate the downstream flux, independent of whether the model is regulated or re-naturalized.

These projection studies will be done in conjunction with sensitivity and uncertainty analyses, to quantify the uncertainty envelope to be applied to projected exports (Pokorny et al., in preparation).

The HBDB has seen significant change over the past five decades, between climate change and hydroelectric development. The fate of the freshwater flux to the Bay from its two largest river systems (Nelson-Churchill River Basin and La Grande Rivière Complex) is in question due to anthropogenic hydroelectric demands and the changing climate. What is more apparent now, however, is that short-term (intra-annual) variation in freshwater export to the Bay is driven by hydroelectric regulation, mid-term variation is due to climate variability and storage capacity, and long-term changes are the result of climate change.

3.5 Acknowledgements

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4 Conclusion

4.1 Summary of major findings

4.1.1 Integration of a generalized reservoir regulation routine to the NCRB in H-HYPE

The foundation of this work is the regulation of hydroelectric reservoirs in the NCRB. Without robust modelling of the regulated reservoirs in the HBDB, the intercomparison of the relative contributions of climate change and regulation to changes in the freshwater system is not feasible.

Chapter 2 describes the development of the reservoir regulation routine applied in HYPE. This routine is generalized, where a set of operational procedures were developed to represent different methods of reservoir management. These operational types and the parameters that govern them can be modified for calibration or sensitivity studies. This generalized model can be applied to any reservoir (algorithms used are not specific to a given spatio-temporal location, operational philosophy, or particular reservoir), while also bypassing the computational demand of a dynamically optimized reservoir operations model.

Sensitivity to the daily WSL simulates outflows with better statistical performance in reservoirs than the default A-HYPE routines, based on historical records in the NCRB. It also creates a more robust and reliable reservoir model because it simulates implicitly the real-world safety precautions in the operation of reservoirs. The daily flow decisions of reservoirs in real-world operations are generally sensitive to WSL based on the fixed stages (hold water, production, release water), but also sensitive *within* these stages. This was the guiding principle in the development of a new regulation routine incorporated into the H-HYPE model.

This new routine divides reservoirs into seven stages, separated by six WSLs, which are variable throughout the year. These WSLs are not dynamically optimized, but are set for each day of the year over the simulation period. There are varieties of outflow-options for each stage, which are selected (where operational reports are available) or can be calibrated (where no operational data is available) by reservoir. These will react to the reservoir conditions differently and help model different types of reservoir (small reservoirs, large reservoirs, small throughflow, large throughflow, etc.). These options are used to make the daily computed discharge more or less sensitive to daily WSL. By tying the computation of the reservoir outflow more closely to real-world operational philosophy, the performance (i.e., short-term) and reliability (i.e., long-term) of these reservoirs is improved.

This model also has the strength of requiring only hydraulic data to be calibrated (i.e., inflow, outflow, water level records). Operational characteristics (i.e., spillway design, turbine efficiency, gate operations) can be used (if known) to calibrate manually. With only the hydraulic data listed above, however, the model can be automatically calibrated using a RAT developed as part of this work. Thirteen reservoirs in the NCRB are modelled using this routine, of which, nine are modelled guided by existing operational data, and four are modelled using only their hydraulic data records.

The performance of this reservoir routine is evaluated at 16 outlets (3 of the 13 reservoirs have two outlets) at monthly and seasonal resolutions and found to improve all A-HYPE results. For the validation period (1981 to 2010), NSE for seasonal discharge improves in all but four instances (out of 16 outlets times 4 seasons gives 64 evaluations), yielding a net seasonal improvement of 93%. In 78% of evaluations (50 of 64 total seasons), mean bias is improved. NSE evaluations point to short-term (i.e. event-based) improvement of daily outflow simulations, as NSE is more heavily weighted to high-flow events. Seasonal bias improvements show that the H-HYPE regulation routine is more efficient at apportioning flow throughout the year, improving long-term reliability of this routine.

Overall, the performance and reliability of outflows generated by the H-HYPE regulation routine improve on those generated by A-HYPE, for the overall time series and seasonally. This is important, as the main function of hydroelectric regulation in predominately nival regimes is intra-annual detention of spring freshets and re-apportioning this flow throughout the year. With an improved regulation routine in place, the results of long-term hydrologic simulation can more accurately distinguish the effects of climate change in a regulated system.

4.1.2 Comparison of the effects of climate change and regulation in Hudson Bay

By comparing the regulated and re-naturalized models, the impact of climate change can be isolated. This allows for a quantitative differentiation of the spatial and temporal resolution and scale of climate change and regulation's contributions to changing freshwater fluxes to Hudson Bay.

Chapter 3 presents the results of these two parallel HYPE simulation experiments. Seven variables (total precipitation, liquid precipitation, solid precipitation, air temperature, evapotranspiration, snow-water equivalent, and runoff) are analysed for the LGRC and NCRB watersheds at a monthly time step, with discharge examined at a daily resolution from 1981 to 2070. The trends and inter-scenario COV (i.e., relative variation between GCM members), and inter-annual COV (i.e., relative variation between years in the 30-year record) are examined to isolate the differing effects of climate change and regulation on volume, timing and variability of the freshwater flux.

Between 1981 and 2070, total precipitation is increasing in all months. Rainfall increases in all months, but importantly becomes more present in months shouldering the winter season. Snowfall increases in months that are sufficiently cold, but the period where snowfall dominates the precipitation regime is shortened. This is due to increased air temperature, which increases in all months but shows its largest anomaly from December to March.

Increasing precipitation is out-paced by increased evapotranspiration (driven by increased temperature) in summer months (May to August), resulting in decreased runoff. There are also trends of increased late-winter/early-spring runoff, due to the earlier melting of the snowpack. Snowfall is increasing (+0.1 – +0.6 mm/year in the winter, statistically significant in both basins), with mixed effects on snowpack over the winter, not at a significant rate. These results confirm observed trends towards deeper snowpacks over winter (Burn and Whitfield, 2017), but a shorter snow-on-ground period (Kang et al., 2014). Changes over time in evapotranspiration, SWE, and runoff appear in both the regulated and re-naturalized models. But these do not show differences for the same time-periods between the two models. Changes seen between the outlet discharges simulated by the two models can only be accounted for by hydroelectric regulation.

Both the re-naturalized and regulated model (in both basins) simulate statistically significant increasing trends of total discharge. The timing of these increases varies by model configuration (i.e., regulated or re-naturalized) due to the intra-annual re-apportioning of flow in the regulated model. The reservoirs and control structures simulated by this model allow for detention of water (more significant in the LGRC than in the NCRB), with coordinated release at pre-allotted times throughout the year, typically over the winter.

The larger storage capacity of the LGRC system is reflected in the inter-annual and inter-scenario COV values. The NCRB has consistently higher inter-annual and inter-scenario COV than the LGRC. What this describes in the NCRB is a system sufficiently regulated to remove some natural variability, but not enough storage to entirely re-apportion flow throughout the year. Flows generated by wetter GCMs or years cannot be regulated past a certain flow magnitude or timing in the NCRB. The regulated LGRC on the other hand shows seasonality in the COV, with greater inter-annual and inter-scenario COV in spring (when exceptionally large freshet events are passed), and less in winter (when consistent flows are most valuable). This points to the LGRC being more heavily regulated *and* having enough storage to influence its regulation. This is further exemplified by the inter-scenario monthly COV. The NCRB inter-scenario COV changes from year-to-year. The variation in reservoir release is dictated by the flow in any given year. In contrast, the LGRC suggests that the reservoir operations prioritize certain times of the year more than others. In both the LGRC and NCRB, the inter-scenario and inter-annual COV show distinct trends for their respective regulated and re-naturalized results, suggesting that the variability of flow is heavily influenced by the presence, and type, of regulation in each system.

By summarizing all results, we can identify distinct driving factors at different temporal scales. The intra-annual variability is largely due to hydroelectric regulation (flow re-apportionment). The effect of regime shift (nival to pluvial/mixed) affects the timing of runoff to a lesser extent, but not significantly enough to affect results at the outlet. The driver of inter-annual variability (or the lack thereof) is the storage volume of the upstream basin. The degree of change in climatic variability to the basin variables (rain, snow, temperature) does not correlate to the changes in variability in discharge. The inter-scenario and inter-annual changes to discharge are dominated by upstream storage effects. At an inter-decadal scale, the major influencing factor to flux and variability is climate change, seen in both precipitation and air temperature.

4.2 Study limitations and future work

4.2.1 Basin similarities and reservoir discontinuity

The generalization of the regulation routine to ensure applicability to reservoirs with limited or no operational knowledge is an important step to proving this new model routine. If the routine is not generalized, it cannot be applied to other reservoirs, basins, or regulated systems with differing types of regulation (i.e., reservoir regulation sensitivity studies or re-calibration using more up-to-date outflow records).

The routine was proven for nine reservoirs within the NCRB with existing operational data, and further tested in four reservoirs with no operational data. The routine was proven for a variety of reservoir sizes (250 to 24,000 km^2 surface area) and operating styles (flood control, hydroelectric regulation). Due to project scope and time-constraints, however, it was not validated outside of the NCRB. All reservoirs analysed for this work are fed by rivers in largely nival regime that are separated by large physical distances (on the order of hundreds of kilometres). The RAT and the regulation routine in HYPE should be tested in basins of different climatic conditions (i.e., pluvial or mixed regimes), and basins with different inter-reservoir connectivity (i.e., series of cascading reservoirs, parallel reservoirs). Additionally, no large reservoirs (greater than 1 km^3 storage) with multi-year storage were tested.

These reservoirs were tested in isolation, using observed inflow records to ‘nudge’ the hydrologic model. A further study examining basin-wide sensitivity would be of interest. While it is assumed that improving simulation of inflow for each successive reservoir will improve results, a verification of the degree to which reservoirs (or groups of reservoirs) are sensitive to the propagation of improved or degraded simulation performance would be useful for future studies in determining the degree of upstream effect of each reservoir. Knowing the importance of various reservoirs on downstream model confidence would be especially useful if exploring more dynamic regulation methods, such as optimizing groups of reservoirs or choosing to update the operation rules.

4.2.2 Regulation stationarity

This work holds regulation constant, both in infrastructure and operations. Constant infrastructure assumes that no new control structures will be brought online through 2070, which is already questionable given the construction of the Keeyask generating station in the NCRB, with a commissioning date in late 2020. The regulated system model assumes an 'energy future' consistent with today's power demand and energy production; unchanged operations assume the regulation WSL curves and stage-outflow relationships do not change under the impacts of climate change. This excludes operational changes based on extended droughts or floods becoming normalized. It also excludes climate change impacts on power sales and associated market demands. For future site-specific studies or environmental impact assessments, a modelling framework should be created where dams and control structures can be brought online at designated dates. This could also be used to change the rules used to govern regulation by using the RAT to develop different regulation rules from different reference periods.

Additional studies on the inclusion of dynamic optimization could be of interest to hydroelectric operators. Sequential reservoir operations were not used due to computational restraints. Including reservoir optimization would entail re-writing the order of computation of the HYPE model code itself. Rather than each unit (sub-basin) being computed sequentially and fed to the downstream basin, the net basin supply (NBS) for each reservoir of interest would need to be calculated daily. With the daily change in storage known for each reservoir, a composite objective function would need to be optimized (i.e., minimum flood-risk, maximum profit in generation, etc.) simultaneously for all reservoirs of interest without violating any threshold values (i.e., flood risk, minimum ecological outflows, etc.). A study comparing the use of conditional outflows (used in this study) and simultaneous dynamic optimization (integrated reservoir management) may be of interest, but would likely require significant time and effort. It is also recommended that such a study focus on a basin with integrated management. With the NCRB reservoirs operated by so many different operators, such a study would likely not reflect reality.

4.2.3 Upstream studies of regulated basins

The structure of the BaySys group of projects places a focus on the marine system. As a result, the discharge to Hudson Bay was prioritized in all analyses. Published work has attributed the effects of climate change and hydroelectric regulation on freshwater outlets using trends and spectral analysis, but only on the historical period (1960 to 2016; Déry et al., 2018). The sub-watershed behaviour of the terrestrial hydrology is aggregated by watershed outlet. Further studies should look at the spatio-temporal effects of climate change and regulation in the upstream, regulated and unregulated basins. Climate-driven changes in volume, timing, and variability to inflows to regulated reservoirs across the NCRB or LGRC may be changing substantially. Due to time-constraints and project scope, only the effects of the basin as a whole have been analysed.

4.2.4 Uncertainty in hydroclimatic modelling

Numerous ‘layers’ of modelling were undertaken in this project. The climate model outcomes are dependent on RCP scenarios, which make assumptions about future technology and societal decisions. These RCPs are fed into GCMs that model atmospheric chemistry and physics differently. These climate model outputs are then fed into the hydrological model to produce ‘water futures’. The hydrologic modelling is further split into regulated and re-naturalized scenarios, both of which were edited for different model components (regulation for the regulated model, land-cover and reservoir outflows for the re-naturalized model). Every layer, and the interaction between them, introduces additional uncertainty to the results reported here.

A sister project to this (BaySys Project 2.2: Uncertainty Analysis; Barber et al., 2014) is specifically designed to look at the sensitivity and uncertainty in these results (Pokorny et al., in preparation). As part of the BaySys project, the propagation of model, model parameter, model input, and model structural uncertainty is explored with the intent of developing quantitative uncertainty and probability bounds on discharge projections.

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6.1 Appendix A: H-HYPE regulation routine fundamental equations

Table A-1: *Governing equations dictating daily flow stage based on WSL (Eq. 3) and relationship between storage, WSL, inflow, and outflow.*

#	Where	Equation	Undefined Variables
A-3	No Conditions	$WSL_{op-,i} = WSL_{op-,i-1} + \frac{(WSL_{band-,j+1} - WSL_{band-,j})}{(fDOY_{j+1} - fDOY_j)}$ $WSL_{op+,i} = WSL_{op+,i-1} + \frac{(WSL_{band+,j+1} - WSL_{band+,j})}{(fDOY_{j+1} - fDOY_j)}$ $WSL_{tr-,i} = WSL_{op-,i} - \theta_{trans}$ $WSL_{tr+,i} = WSL_{op+,i} + \theta_{trans}$ $WSL_{avg,i} = WSL_{op-,i}(\theta_{weight}) + WSL_{op+,i}(1 - \theta_{weight})$ $WSL_{dr} = \theta_{dr}$ $WSL_{fl} = \theta_{fl}$	$WSL_{band-,j}$: user-specified lower operations band WSL for month *j* $WSL_{band+,j}$: user-specified upper operations band WSL for month *j* $fDOY_j$: day-of-year of the first day of month *j* θ_{trans}: user-specified depth of transition zones θ_{weight}: parameter for weighting ideal operations level θ_{dr}: parameter for specifying WSL below which drought operations are used θ_{fl}: parameter for specifying WSL above which flood operations are used
A-4	No Conditions	$S_i = S_{i-1} + \sum Q_{in,i-1,j} - \sum Q_{out,i-1,j}$ $WSL_i = \left(\frac{(S_i - \theta_{storD})}{\theta_{storA}}\right)^{1/\theta_{storC}} + \theta_{storB}$	S_i: reservoir storage for day *i* $Q_{in,i}$: reservoir inflow for day *i* $Q_{out,i,j}$: reservoir outflow for day *i*, for outlet *j* $\theta_{A, B, C, D}$: fixed storage parameters based on historic stage-storage measurements

Table A-2: *Equations used to derive daily flow by historical percentile.*

#	Where	Equation	Undefined Variables
A-5	No Conditions	$Q_{Stage\ j,perc} = PERCENTILE\left(\begin{bmatrix} Q_{obs\ d,1} \\ \cdots \\ Q_{obs\ d,y} \end{bmatrix}, \theta_{Stage,perc}\right)$	$Q_{obs,\ d,y}$: Observed flow data for day *d*, year *y* $\theta_{stage\ j,\ perc}$: user-specified percentile for stage j

Table A-3: *Equations used to calculate flow using year-round stage-discharge curves.*

#	Where	Equation	Undefined Variables
A-6	$WSL_{dr} \leq WSL_i \leq WSL_{tr-}$	$Q_{low,i} = \theta_{Alow} \times (WSL_i - \theta_{Blow})^{\theta_{Clow}} + \theta_{Dlow}$	$\theta_{Alow, Blow, Clow, Dlow}$: fixed stage-discharge parameters specified for low stage outflows $\theta_{Amid, Bmid, Cmid, Dmid}$: fixed stage-discharge parameters specified for low stage outflows $\theta_{Ahi, Bhi, Chi, Dhi}$: fixed stage-discharge parameters specified for low stage outflows
	$WSL_{op-} \leq WSL_i \leq WSL_{op+}$	$Q_{op,i} = \theta_{Amid} \times (WSL_i - \theta_{Amid})^{\theta_{Amid}} + \theta_{Amid}$	
	$WSL_{tr+} \leq WSL_i \leq WSL_{fl}$	$Q_{hi,i} = \theta_{Ahi} \times (WSL_i - \theta_{Bhi})^{\theta_{Chi}} + \theta_{Dhi}$	

Table A-4: *Equations used to derive and to calculate flow using monthly stage-discharge curves.*

#	Where	Equation	Undefined Variables
A-7	$WSL_{dr} \leq WSL_i \leq WSL_{tr-}$	$Q_{low,j} = \alpha_{low,j} \times \left(WSL_i - \beta_{low,j}\right) \times \omega_{i,j}$	$\omega_{i,j}$: fractional distance between current day (*i*) and middle day of month (*j*)
		$Q_{low,j-1} = \alpha_{low,j-1} \times \left(WSL_i - \beta_{low,j-1}\right) \times \omega_{i,j-1}$	
		$Q_{low,i} = Q_{low,j} + Q_{low,j-1}$	
A-8	$WSL_{op-} \leq WSL_i \leq WSL_{op+}$	$Q_{mid,j} = \alpha_{mid,j} \times \left(WSL_i - \beta_{mid,j}\right) \times \omega_{i,j}$	
		$Q_{mid*,j} = \alpha_{mid,j} \times \left(WSL_i - WSL_{op-}\right) \times \omega_{i,j}$	
		$Q_{mid,j-1} = \alpha_{mid,j-1} \times \left(WSL_i - \beta_{mid,j-1}\right) \times \omega_{i,j-1}$	
		$Q_{mid*,j-1} = \alpha_{mid,j-1} \times \left(WSL_i - WSL_{op-}\right) \times \omega_{i,j-1}$	
		$Q_{op,i} = (Q_{mid,j} + Q_{mid*,j}) + (Q_{mid,j-1} + Q_{mid*,j-1})$	
A-9	No Conditions	$\alpha_{low,j} = \dfrac{\frac{1}{n_{low,j}} \sum_1^{n_{low,j}} Q_{low,regr,j}}{\frac{1}{n_{low,j}} \sum_1^{n_{low,j}} Q_{low,regr,j} - \beta_{dr,j}}$	$n_{low,j}$: number of entries in $Q_{low,regr,j}$ $n_{mid,j}$: number of entries in $Q_{mid,regr,j}$
		$\alpha_{mid,j} = \dfrac{\frac{1}{n_{mid,j}} \sum_1^{n_{mid,j}} Q_{mid,regr,j}}{\frac{1}{n_{mid,j}} \sum_1^{n_{mid,j}} Q_{mid,regr,j} - \beta_{op-,j}}$	
A-10		$\beta_{dr,j} = WSL_{dr}$	All previously defined
		$\beta_{op-,j} = \dfrac{(WSL_{op-,j} + WSL_{op-,j+1})}{2}$	
		$\beta_{op+,j} = \dfrac{(WSL_{op+,j} + WSL_{op+,j+1})}{2}$	

A-11	$\beta_{dr} \leq \begin{bmatrix} WSL_{obs\ 1,j,1} \\ \ldots \\ WSL_{obs\ d,j,1} \\ \ldots \\ WSL_{obs\ 1,j,y} \\ \ldots \\ WSL_{obs\ d,j,y} \end{bmatrix} \leq \beta_{op-}$	$Q_{low,regr,j} = \begin{bmatrix} Q_{obs\ 1,j,1} \\ \ldots \\ Q_{obs\ d,j,1} \\ \ldots \\ Q_{obs\ 1,j,y} \\ \ldots \\ Q_{obs\ d,j,y} \end{bmatrix}$	$WSL_{obs\ d,\ j,\ y}$: observed WSL for month *j*, years *y*, days 1 to *d* $Q_{obs\ d,\ j,\ y}$: observed Q for month *j*, years *y*, days 1 to *d*
	$\beta_{op-} \leq \begin{bmatrix} WSL_{obs\ 1,j,1} \\ \ldots \\ WSL_{obs\ d,j,1} \\ \ldots \\ WSL_{obs\ 1,j,y} \\ \ldots \\ WSL_{obs\ d,j,y} \end{bmatrix} \leq \beta_{op+}$	$Q_{mid,regr,j} = \begin{bmatrix} Q_{obs\ 1,j,1} \\ \ldots \\ Q_{obs\ d,j,1} \\ \ldots \\ Q_{obs\ 1,j,y} \\ \ldots \\ Q_{obs\ d,j,y} \end{bmatrix}$	

Table A-5: *Equations used to calculate outflow for flood and drought conditions.*

#	Where	Equation	Undefined Variables
A-12	$WSL_i \leq WSL_{dr,i}$	$Q_{dr,i} = \theta_{Q-dr}$	$\theta_{Q\text{-}fl}$: user-specified outflow for drought conditions $\theta_{Q\text{-}dr}$: user-specified outflow for flood conditions
	$WSL_i \leq WSL_{fl,i}$	$Q_{fl,i} = \theta_{Q-fl}$	

Table A-6: *Equations used to calculate daily flow based on storage (ideal storage method and storage compensation method).*

#	Where	Equation	Undefined Variables
A-13	No Conditions	$S_{avg,i} = \theta_{storA} \times \left(WSL_{avg,i} - \theta_{storB}\right)^{\theta_{storC}} + \theta_{storD}$	$Q_{out,i}$: Final calculated outflow for day *i*
		$\Delta S_{avg,i} = S_{avg,i+1} - \Delta S_{avg,i}$	
		$Q_{op,i} = \left(\frac{\sum_{i-13}^{i} Q_{out,i}}{14}\right) + \left((1 + \theta_i) \times \frac{\sum_{i-13}^{i} \Delta S_{avg,i}}{14}\right)$	
A-14	$WSL_i \leq WSL_{tr-,i}$	$\theta_{,i} = -\theta_{base}$	θ_{base}: parameter for ideal storage gradient function
	$WSL_{tr-,i} \leq WSL_i \leq WSL_{avg,i}$	$\theta_i = -\theta_{base} \times \frac{(WSL_i - WSL_{avg,i})}{(WSL_{tr+,i} - WSL_{avg,i})}$	
	$WSL_{avg,i} \leq WSL_i \leq WSL_{tr+,i}$	$\theta_i = \theta_{base} \times \frac{(WSL_i - WSL_{avg,i})}{(WSL_{tr+,i} - WSL_{avg,i})}$	
	$WSL_{tr+,i} \leq WSL_i$	$\theta_i = \theta_{base}$	
A-15	No Conditions	$Q_{in-avg,i} = \frac{\sum_{i-1}^{i-7} Q_{in}}{7}$	$Q_{out\text{-}a}$: outflow of primary reservoir outlet

		$Q_{out-avg,i} = \frac{\sum_{i-1}^{i-7} Q_{out}}{7}$	Q_{out-b}: outflow of secondary reservoir outlet
		$Q_{avg\Delta} = Q_{in-avg,i} - Q_{out-a-avg,i}$	
	$Q_{avg\Delta} < Q_{low-b,i-1}$	$Q_{high-b,i} = Q_{low-b,i-1}$	
	$Q_{avg\Delta} \geq Q_{low-b,i-1}$	$Q_{high-b,i} = Q_{avg\Delta}$	

Table A-7: *Equations used to calculate flow related to the condition at another sub-basin in the model.*

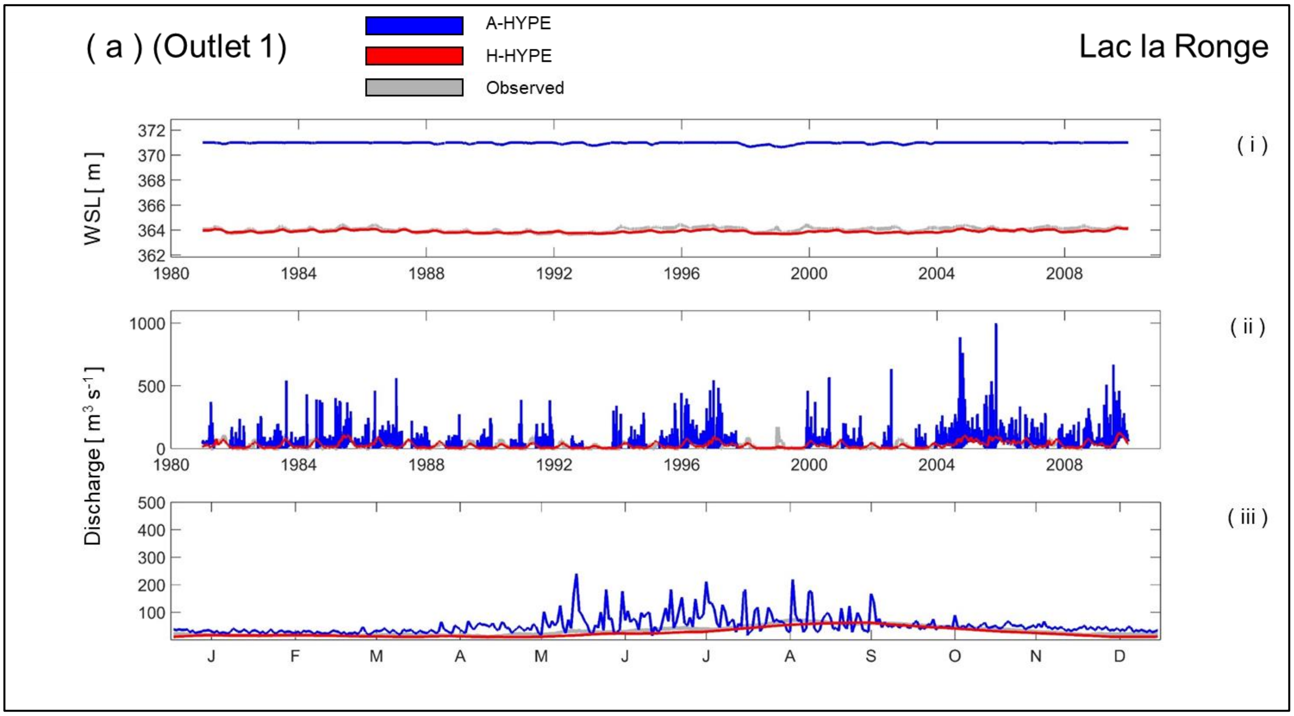
#	Where	Equation	Undefined Variables
A-16	No Conditions	$Q_{cond-avg,i} = \frac{\sum_{i-14}^{i-1} Q_{cond}}{14}$	$Q_{cond,i}$: discharge for day *i* at another location in the model $\theta_{Acon,\ Bcon,\ Ccon,\ Dcon}$: fixed discharge-discharge parameters conditioning the outlet
	$WSL_{dr} \leq WSL_i \leq WSL_{fl}$	$Q_{op,i} = \theta_{Acon} \times (Q_{cond-avg,i} - \theta_{Acon})^{\theta_{Acon}} + \theta_{Acon}$	

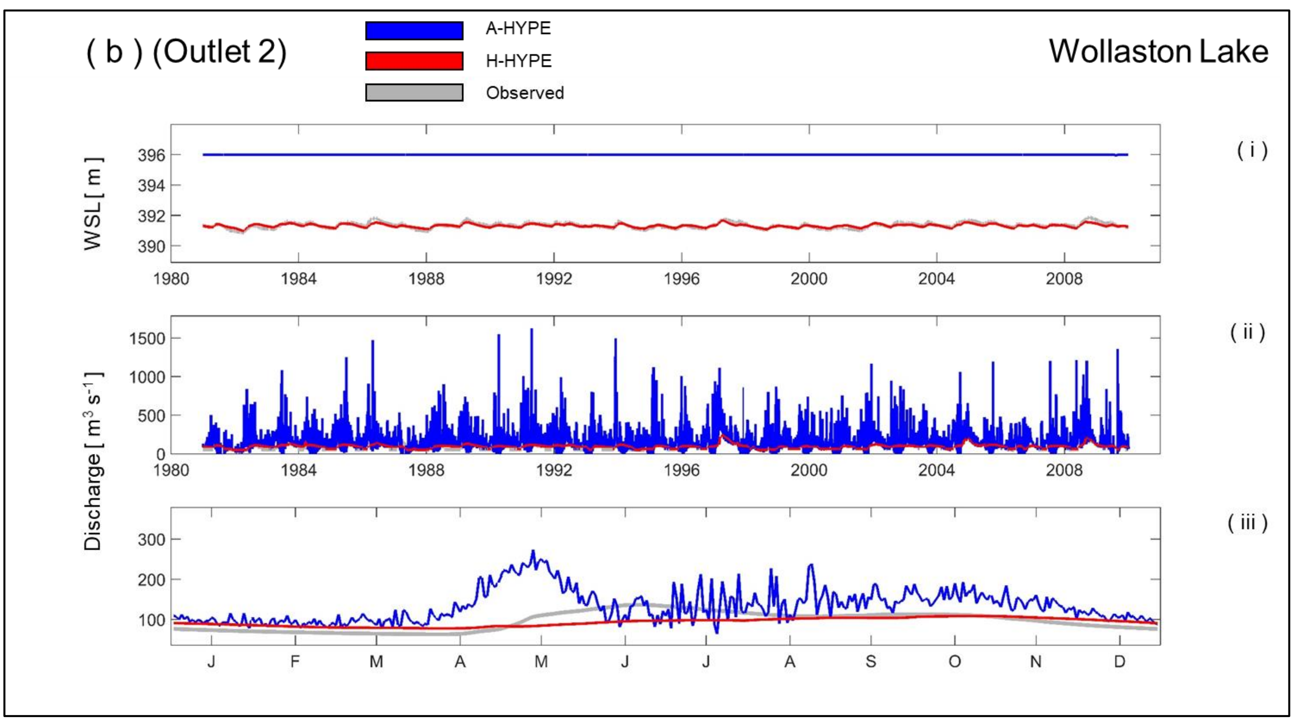
Table A-8: *Outflow type selection after and outflow calculation and flow corrections applied.*

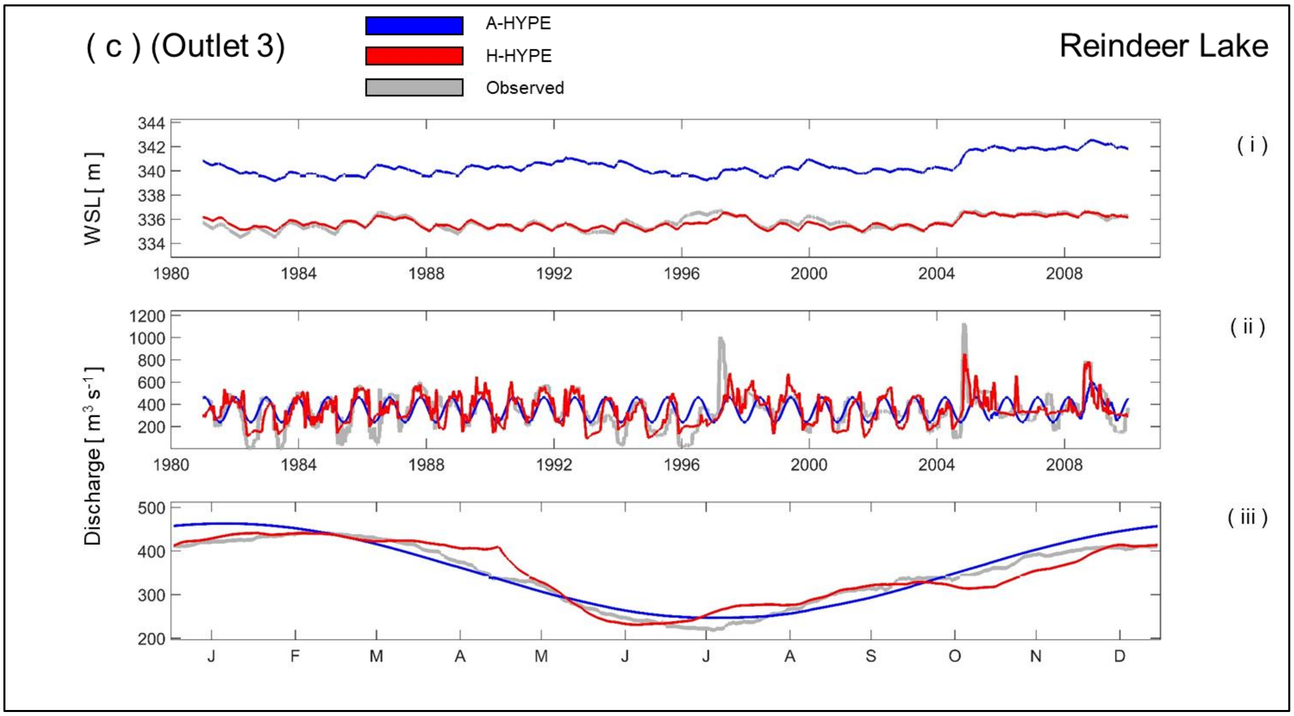
#	Where	Equation	Undefined Variables
A-17	$WSL_i \leq WSL_{dr,i}$	$Q_{dec,i} = Q_{dr,i}$	All previously defined
	$WSL_{dr,i} \leq WSL_i \leq WSL_{tr-,i}$	$Q_{dec,i} = Q_{low,i}$	
	$WSL_{tr-,i} \leq WSL_i \leq WSL_{op-,i}$	$Q_{dec,i} = Q_{tr-,i}$	
	$WSL_{op-,i} \leq WSL_i \leq WSL_{op+,i}$	$Q_{dec,i} = Q_{op,i}$	
	$WSL_{op+,i} \leq WSL_i \leq WSL_{tr+,i}$	$Q_{dec,i} = Q_{tr+,i}$	
	$WSL_{tr+,i} \leq WSL_i \leq WSL_{fl,i}$	$Q_{dec,i} = Q_{hi,i}$	
	$WSL_{fl,i} \leq WSL_i$	$Q_{dec,i} = Q_{fl,i}$	
A-18	$Q_{low,i} \leq Q_{dr,i}$	$Q_{low,i} = Q_{dr,i}$	
	$Q_{low,i} > Q_{dr,i}$	$Q_{low,i} = Q_{low,i}$	
	$Q_{op,i} \leq Q_{low,i}$	$Q_{op,i} = Q_{low,i}$	
	$Q_{op,i} \geq Q_{hi,i}$	$Q_{op,i} = Q_{hi,i}$	
	$Q_{op,i} > Q_{low,i}, Q_{op,i} < Q_{hi,i}$	$Q_{op,i} = Q_{op,i}$	

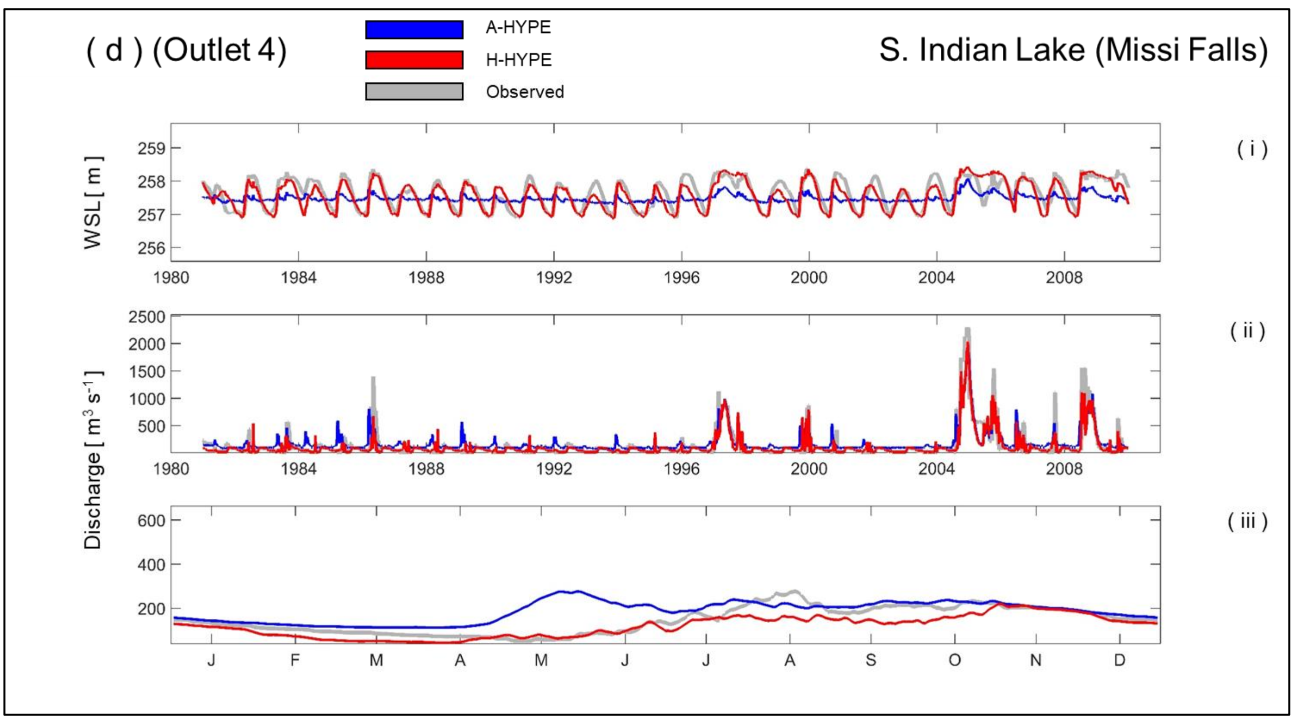
A-19	$Q_{dec,i} \geq \theta_{Q-PH}, WSL_i \leq WSL_{op+,i}$	$Q_{PH,i} = \theta_{Q-PH}$	$\theta_{Q\text{-}PH}$: maximum permissible powerhouse flow $\theta_{Q\Delta wkly\text{-}max}$: maximum permissible flow change within a week $\theta_{Q\Delta dly\text{-}max}$: maximum permissible flow change between days
	$Q_{dec,i} \geq \theta_{Q-PH}, WSL_i \geq WSL_{op+,i}$	$Q_{PH,i} = Q_{dec,i}$	
	$Q_{dec,i} \leq \theta_{Q-PH}$	$Q_{PH,i} = Q_{dec,i}$	
A-20	No Conditions	$Q_{week,i} = [Q_{PH,i-6} \quad \dots \quad Q_{PH,i}]$	
		$Q_{i,wk+} = \text{MAX}(Q_{week,i})$	
		$Q_{i,wk-} = \text{MIN}(Q_{week,i})$	
		$Q_{i,\Delta wk} = Q_{i,wk+} - Q_{i,wk-}$	
A-21	$Q_{i,\Delta wkly} > \theta_{Q-\Delta wkly-max}, \frac{Q_{i,\Delta wk}}{7} < 0$	$Q_{wk,i} = Q_{i,wk-} + \theta_{Q-\Delta wkly-max}$	
	$Q_{i,\Delta wkly} > \theta_{Q-\Delta wkly-max}, \frac{Q_{i,\Delta wk}}{7} > 0$	$Q_{wk,i} = Q_{i,wk+} - \theta_{Q-\Delta wkly-max}$	
	$Q_{i,\Delta wkly} < \theta_{Q-\Delta wkly-max}$	$Q_{wk,i} = Q_{PH,i}$	
A-22	No Conditions	$Q_{i,\Delta dly} = \lvert Q_{wk,i} - Q_{out,i-1} \rvert$	
	$Q_{i,\Delta dly} > \theta_{Q-\Delta dlly-max}, Q_{wk,i} < Q_{out,i-1}$	$Q_{out,i} = Q_{wk,i} + \theta_{Q-\Delta dlly-max},$	
	$Q_{i,\Delta dly} > \theta_{Q-\Delta dlly-max}, Q_{wk,i} > Q_{out,i-1}$	$Q_{out,i} = Q_{wk,i} - \theta_{Q-\Delta dlly-max},$	

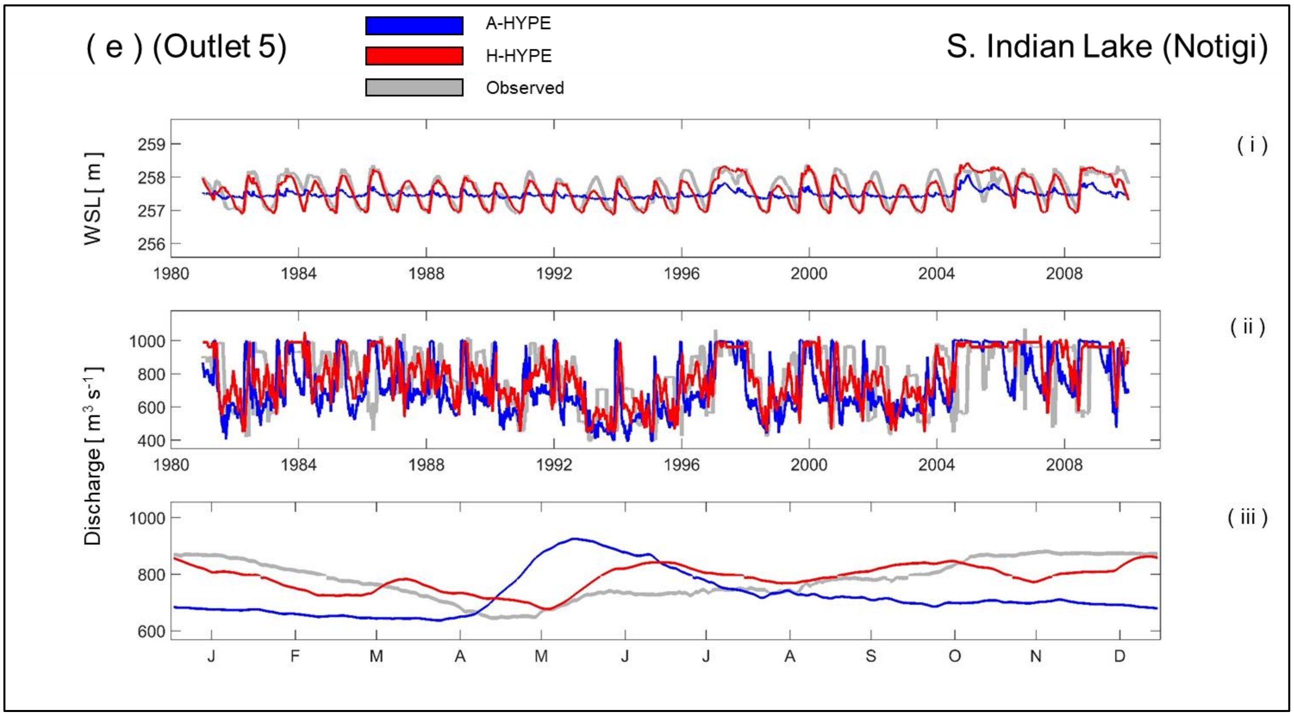
6.2 Appendix B: A-HYPE, H-HYPE and observed regulated reservoir comparison plots



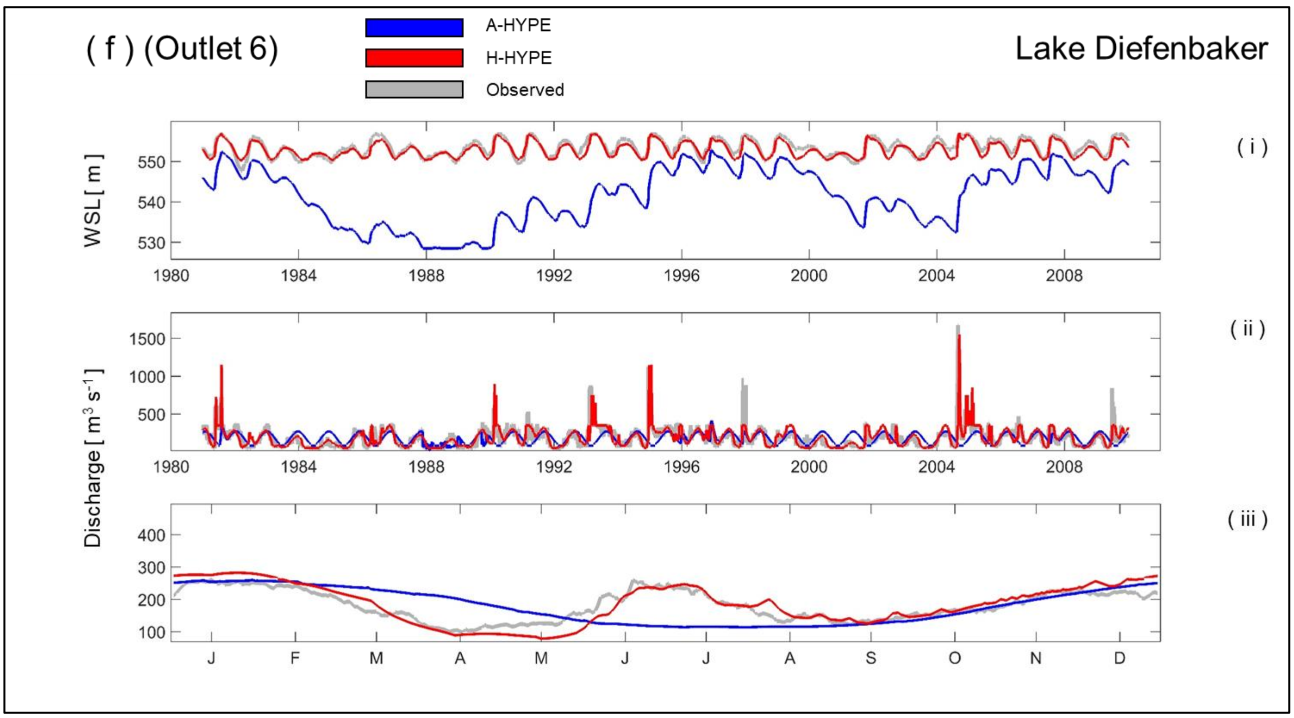



(c) (Outlet 3)
A-HYPE
H-HYPE
Observed
Reindeer Lake
(i)
(ii)
(iii)
WSL [m]
344
342
340
338
336
334
Discharge [m^3 s^{-1}]
1200
1000
800
600
400
200
500
400
300
200
1980
1984
1988
1992
1996
2000
2004
2008
J F M A M J J A S O N D

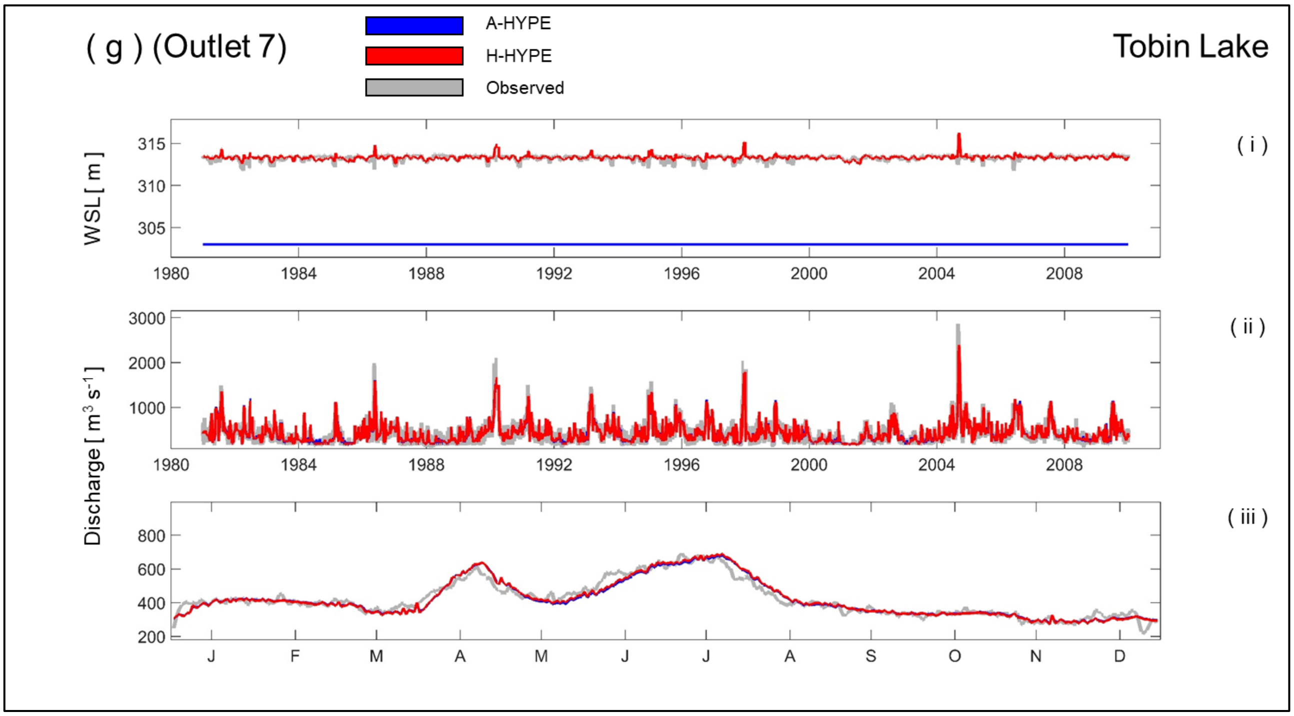

(d) (Outlet 4)
A-HYPE
H-HYPE
Observed
S. Indian Lake (Missi Falls)
(i)
(ii)
(iii)
WSL [m]
259
258
257
256
Discharge [m^3 s^{-1}]
2500
2000
1500
1000
500
600
400
200
1980
1984
1988
1992
1996
2000
2004
2008
J F M A M J J A S O N D

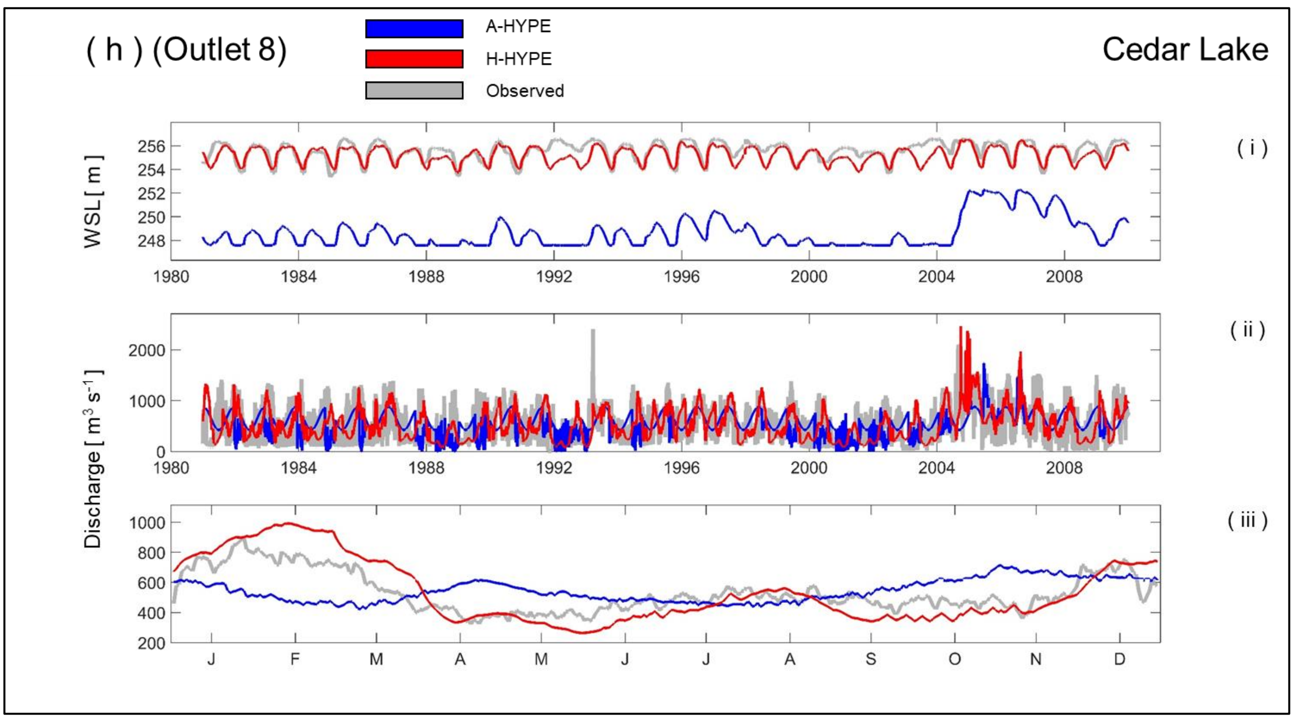


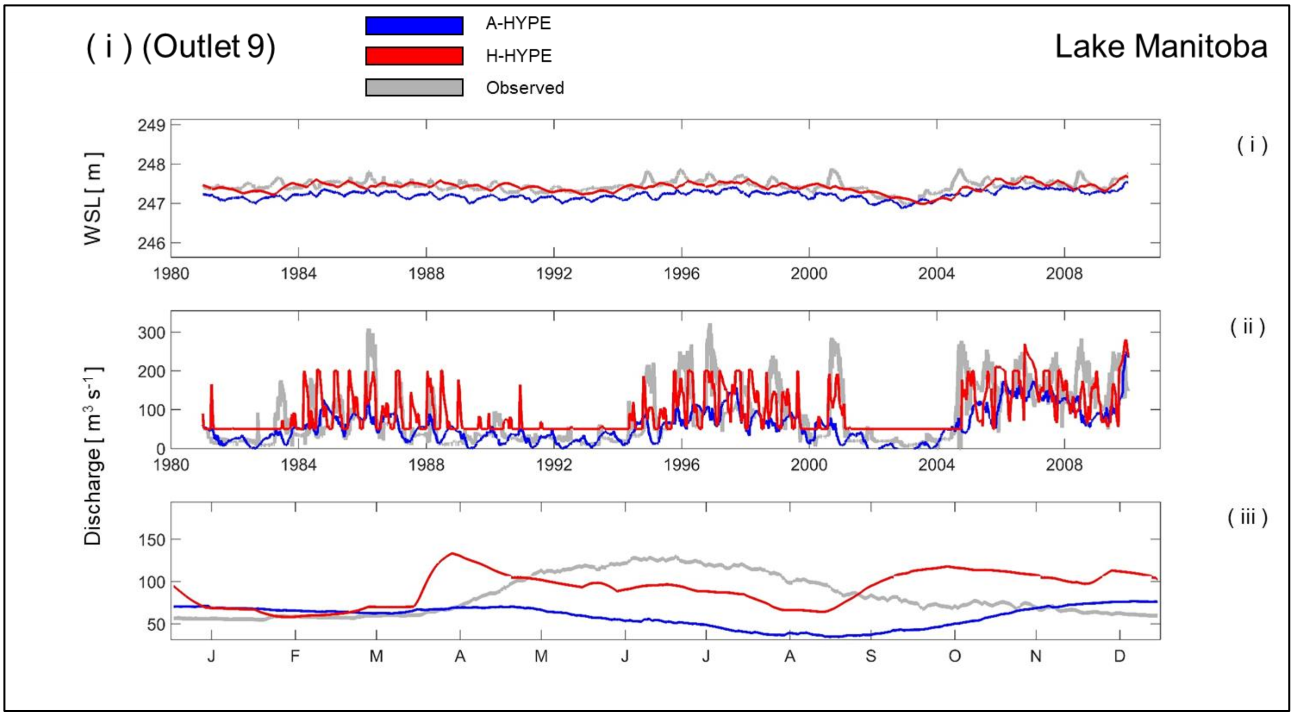
(e) (Outlet 5)
A-HYPE
H-HYPE
Observed
S. Indian Lake (Notigi)
WSL [m]
Discharge [m³ s⁻¹]
(i)
(ii)
(iii)
1980
1984
1988
1992
1996
2000
2004
2008
J
F
M
A
M
J
J
A
S
O
N
D



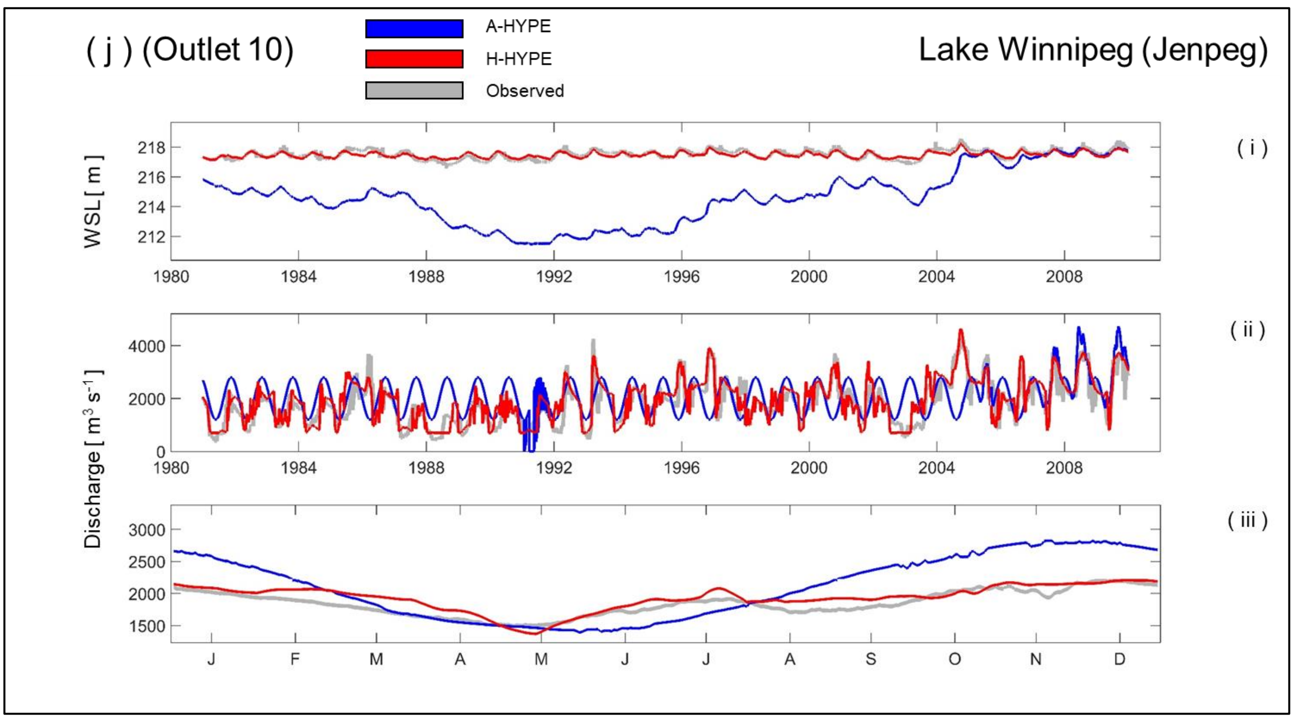
(f) (Outlet 6)
A-HYPE
H-HYPE
Observed
Lake Diefenbaker
WSL [m]
Discharge [m³ s⁻¹]
(i)
(ii)
(iii)
1980
1984
1988
1992
1996
2000
2004
2008
J
F
M
A
M
J
J
A
S
O
N
D


(g) (Outlet 7)
A-HYPE
H-HYPE
Observed
Tobin Lake
WSL [m]
Discharge [m3 s-1]
(i)
(ii)
(iii)
315
310
305
3000
2000
1000
800
600
400
200
1980
1984
1988
1992
1996
2000
2004
2008
J F M A M J J A S O N D

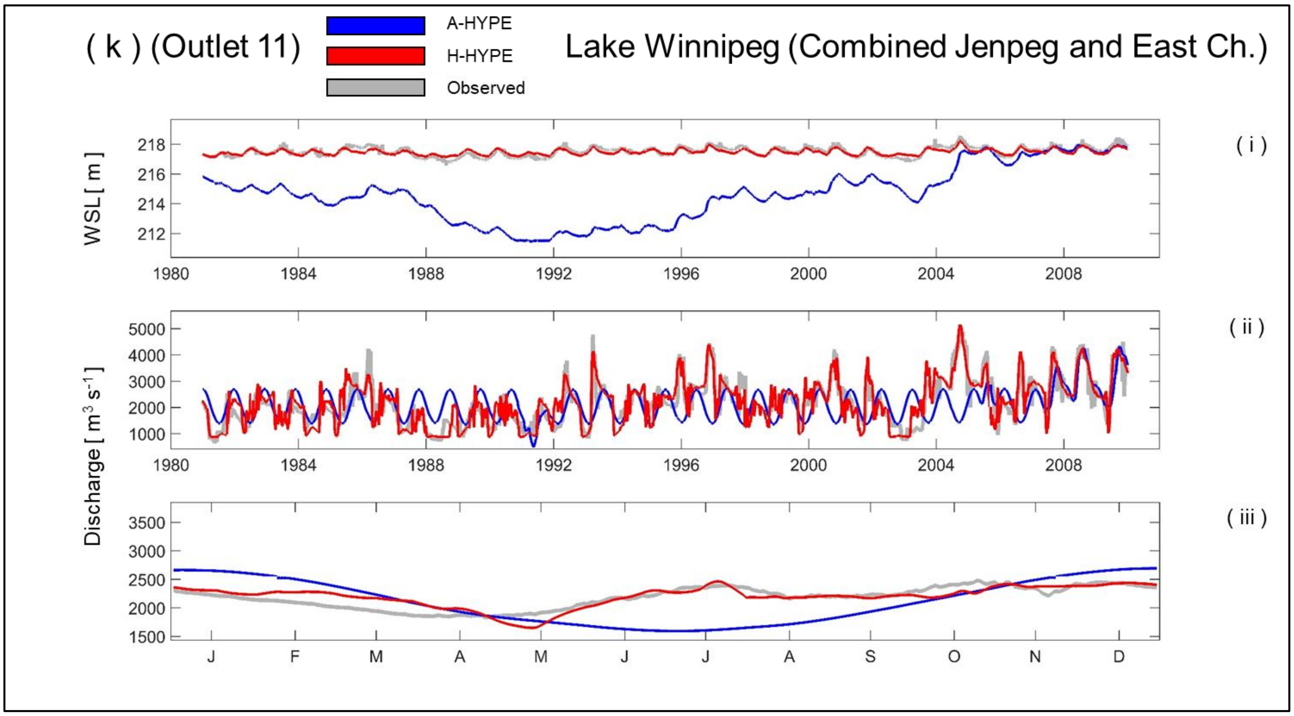

(h) (Outlet 8)
A-HYPE
H-HYPE
Observed
Cedar Lake
WSL [m]
Discharge [m3 s-1]
(i)
(ii)
(iii)
256
254
252
250
248
2000
1000
0
1000
800
600
400
200
1980
1984
1988
1992
1996
2000
2004
2008
J F M A M J J A S O N D

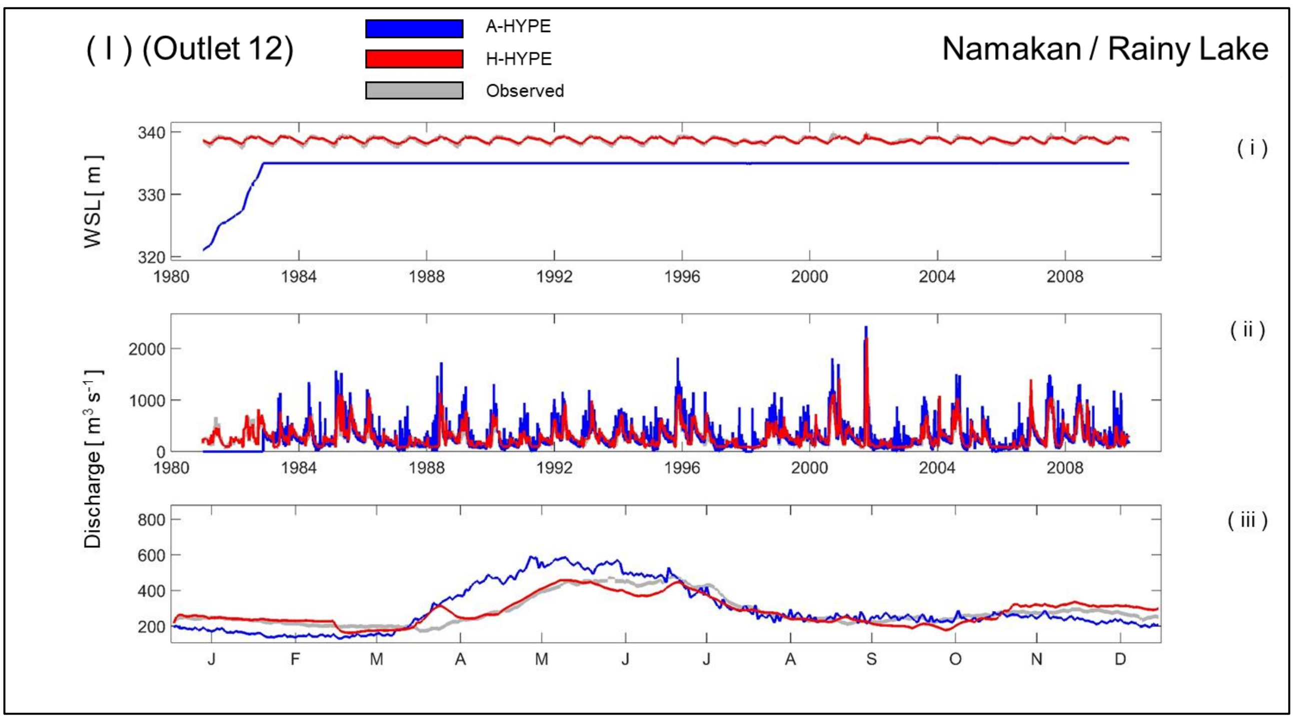


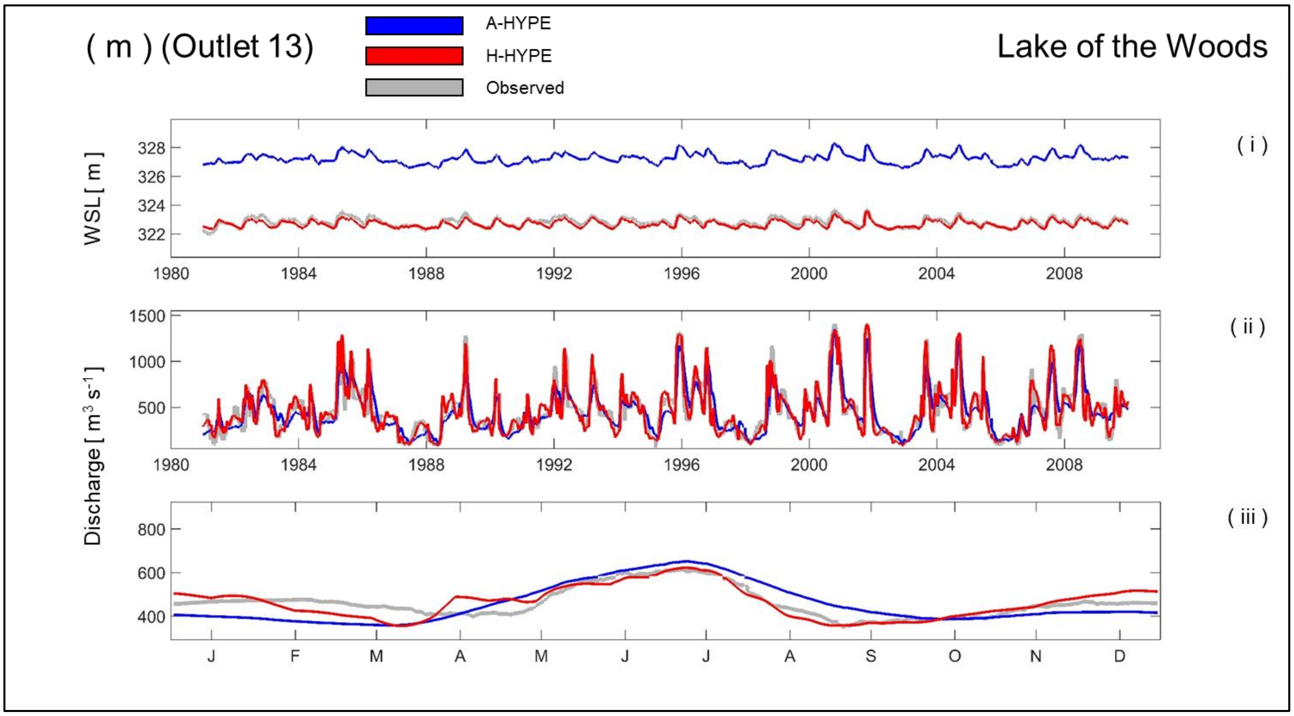
(i) (Outlet 9)
Lake Manitoba
A-HYPE
H-HYPE
Observed
WSL [m]
Discharge [m³ s⁻¹]
(i)
(ii)
(iii)
J F M A M J J A S O N D

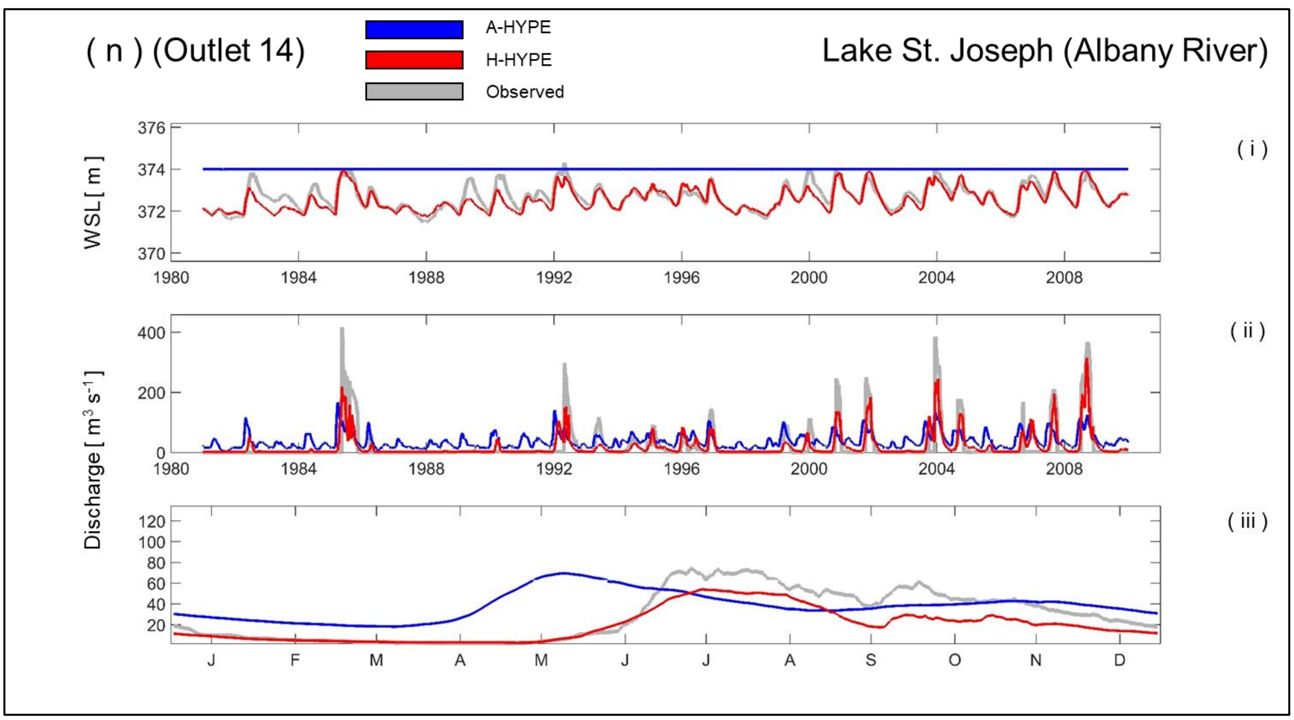


(j) (Outlet 10)
Lake Winnipeg (Jenpeg)
A-HYPE
H-HYPE
Observed
WSL [m]
Discharge [m³ s⁻¹]
(i)
(ii)
(iii)
J F M A M J J A S O N D


(k) (Outlet 11)
A-HYPE
H-HYPE
Observed
Lake Winnipeg (Combined Jenpeg and East Ch.)
WSL [m]
Discharge [m3 s-1]
(i)
(ii)
(iii)
J F M A M J J A S O N D


(l) (Outlet 12)
A-HYPE
H-HYPE
Observed
Namakan / Rainy Lake
WSL [m]
Discharge [m3 s-1]
(i)
(ii)
(iii)
J F M A M J J A S O N D


(m) (Outlet 13)
A-HYPE
H-HYPE
Observed
Lake of the Woods
(i)
(ii)
(iii)
WSL [m]
Discharge [m^3 s^{-1}]
J F M A M J J A S O N D


(n) (Outlet 14)
A-HYPE
H-HYPE
Observed
Lake St. Joseph (Albany River)
(i)
(ii)
(iii)
WSL [m]
Discharge [m^3 s^{-1}]
J F M A M J J A S O N D

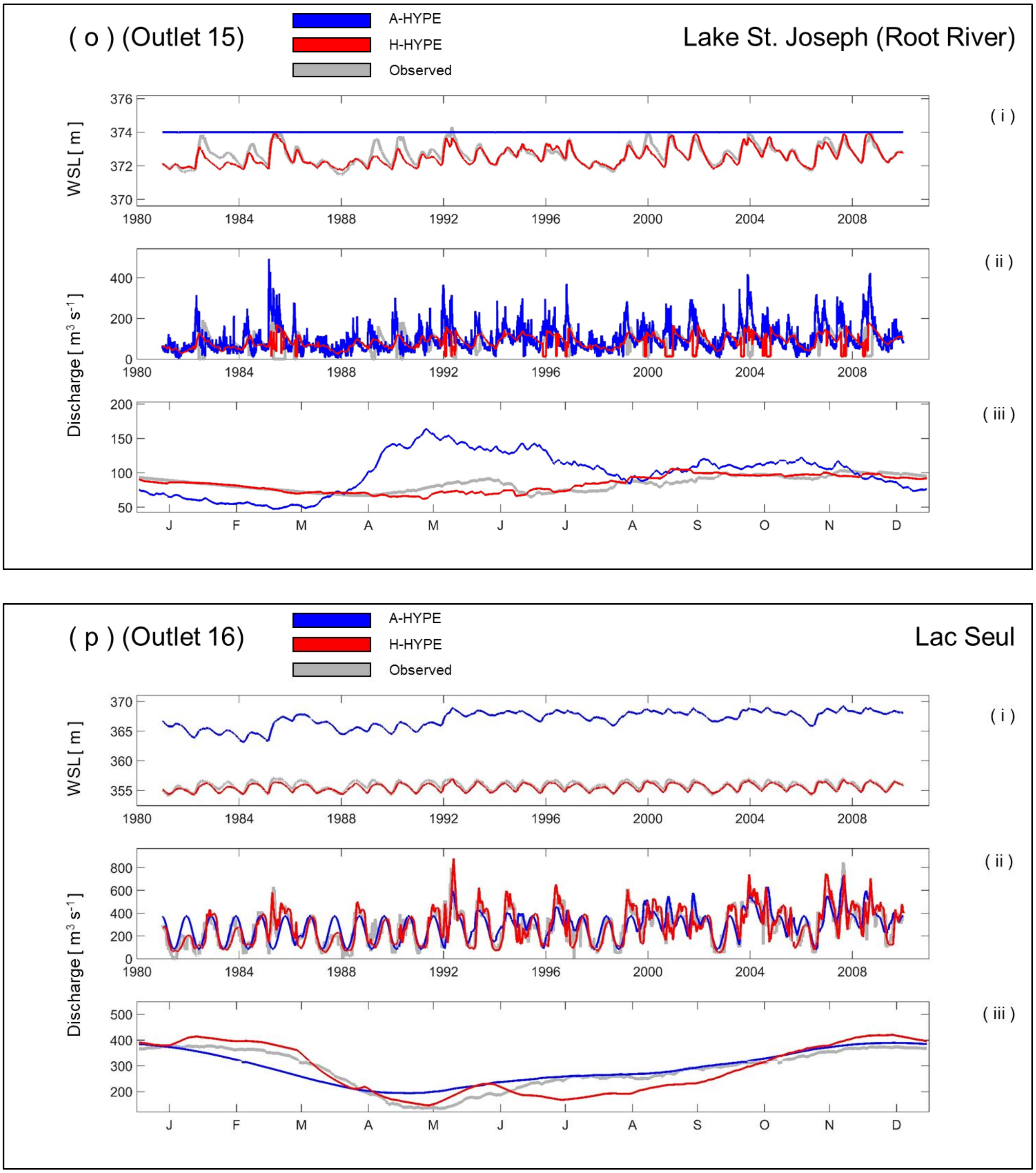
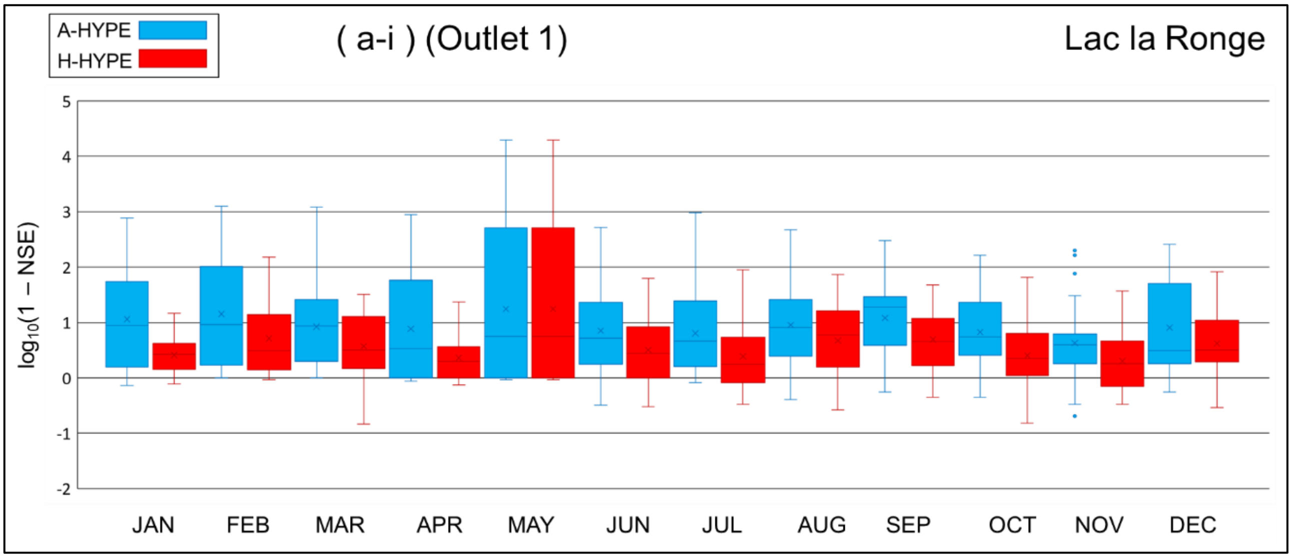
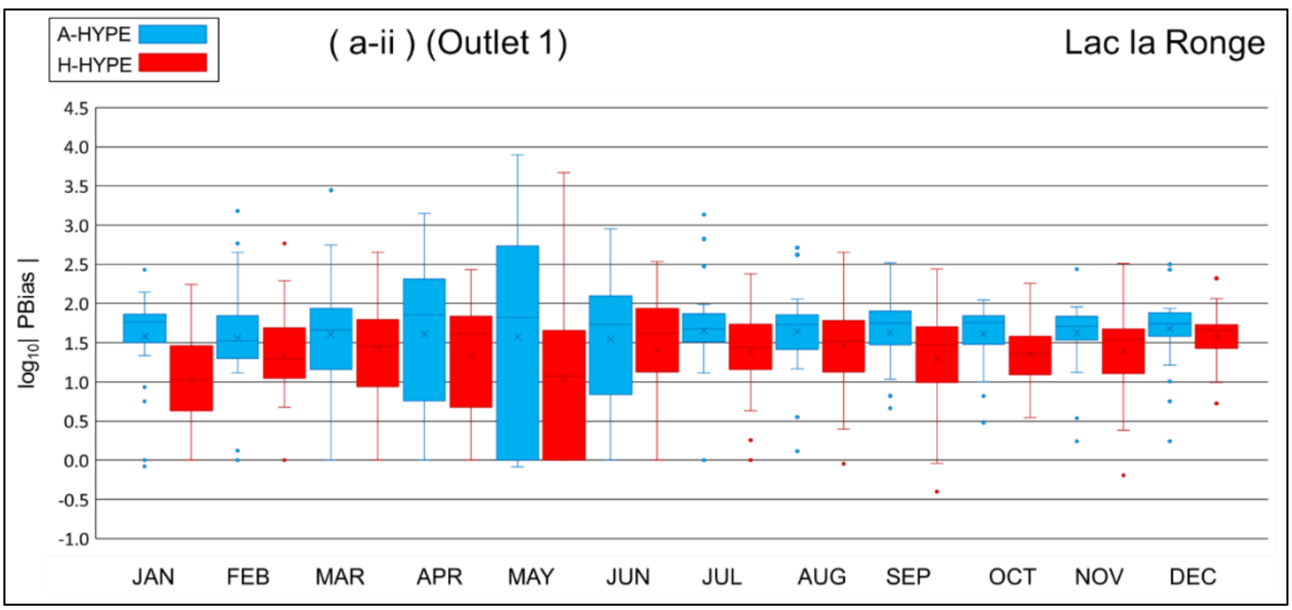
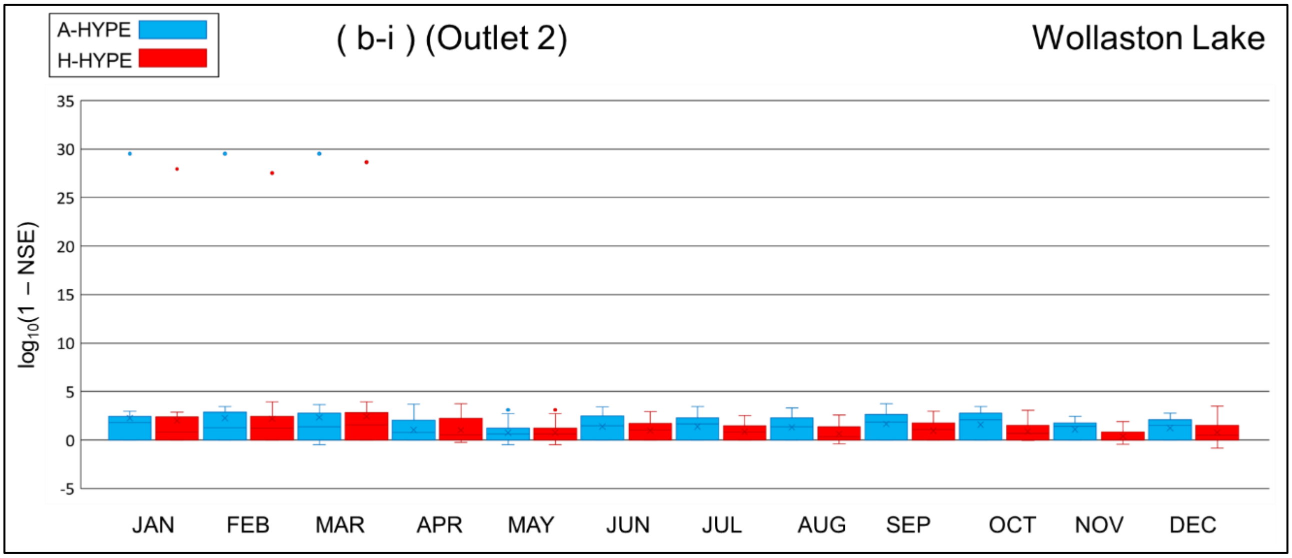


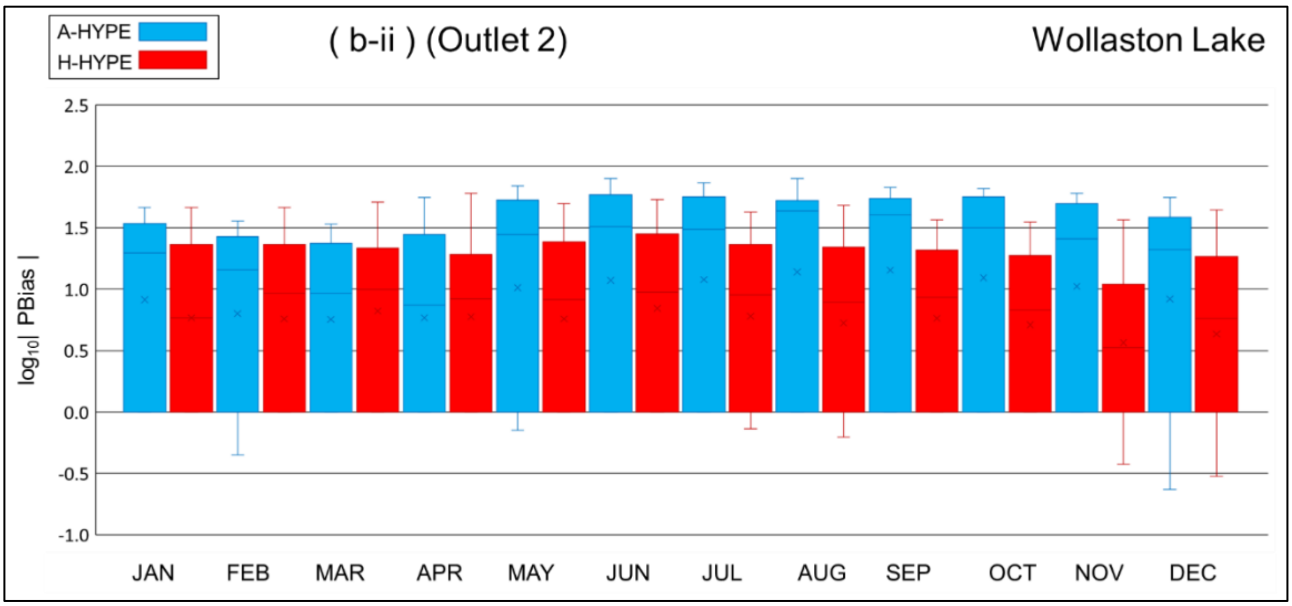
Figure B-1: *Comparison of observed data (grey), existing HYPE regulation routine (A-HYPE; blue), and new HYPE regulation routine for (H-HYPE; red) for the 1981 to 2010 validation period. (i) Daily water surface level, (ii) daily computed outflow, (iii) daily average annual discharge.*

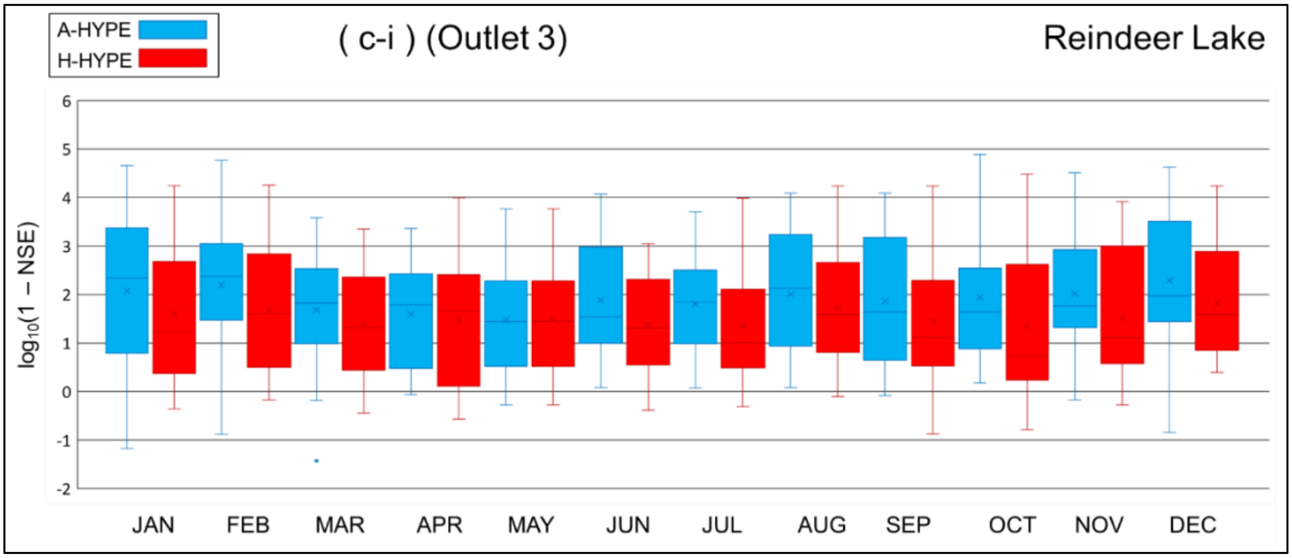
6.3 Appendix C: Monthly NSE-error and absolute mean bias for NCRB regulation

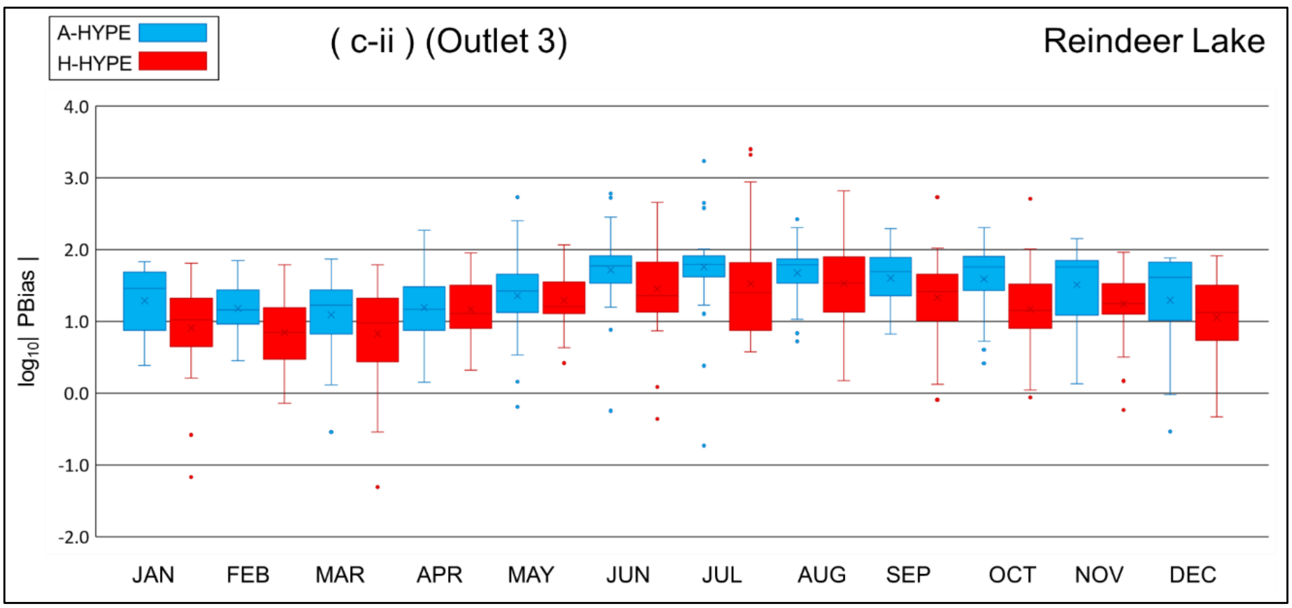


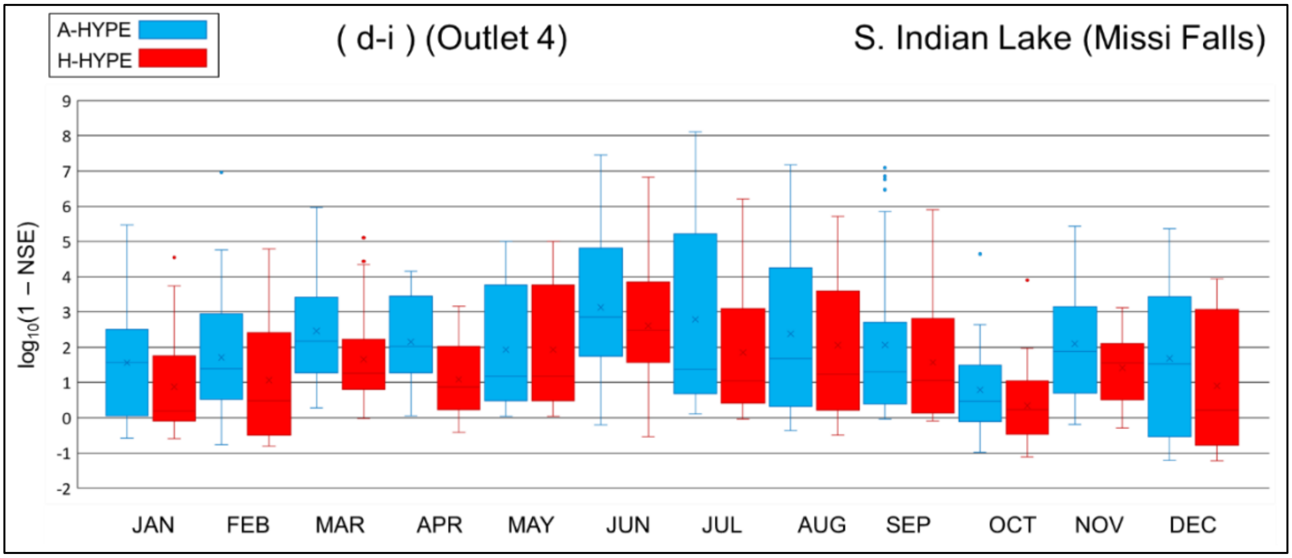


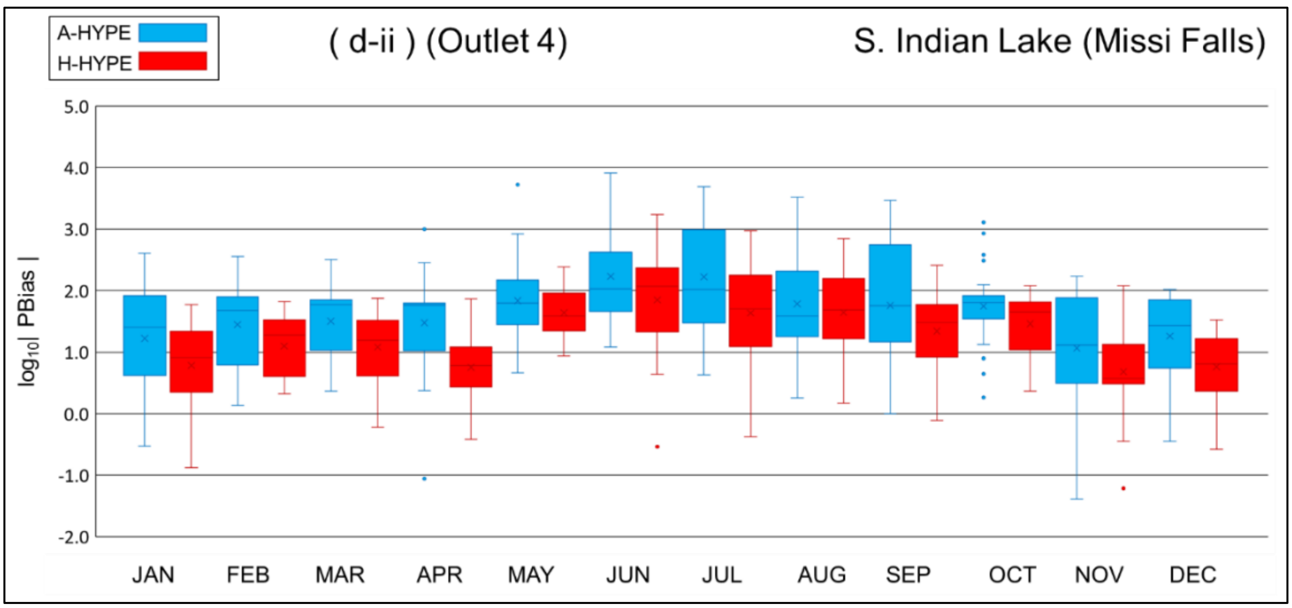

A-HYPE
H-HYPE
(b-i) (Outlet 2)
Wollaston Lake
$\log_{10}(1 - NSE)$
35
30
25
20
15
10
5
0
-5
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

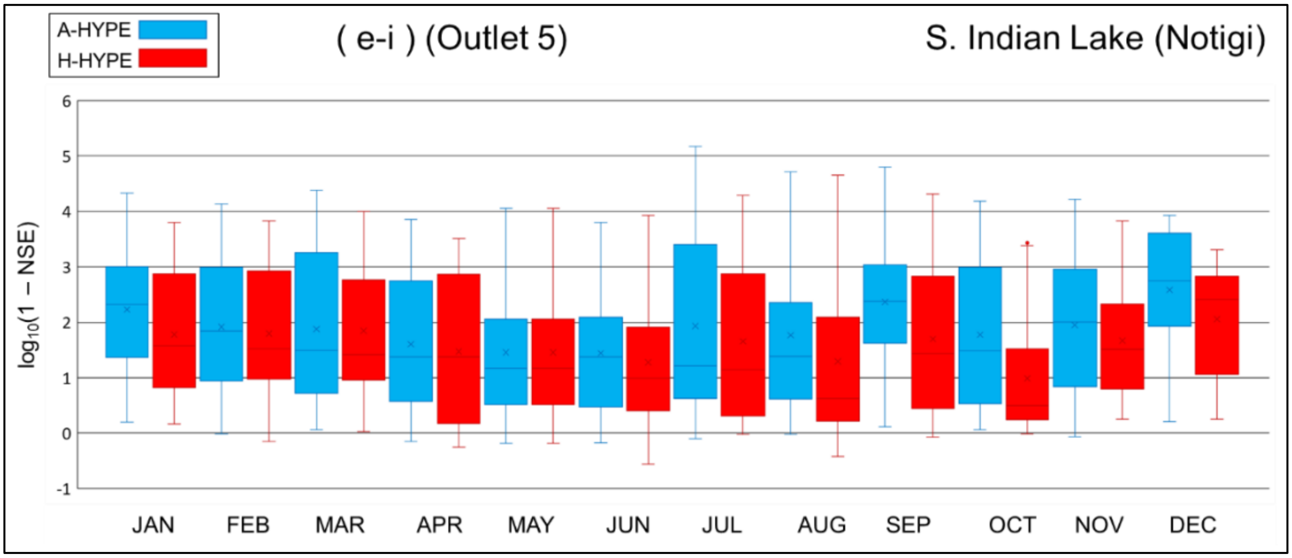

A-HYPE
H-HYPE
(b-ii) (Outlet 2)
Wollaston Lake
$\log_{10}$| PBias |
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

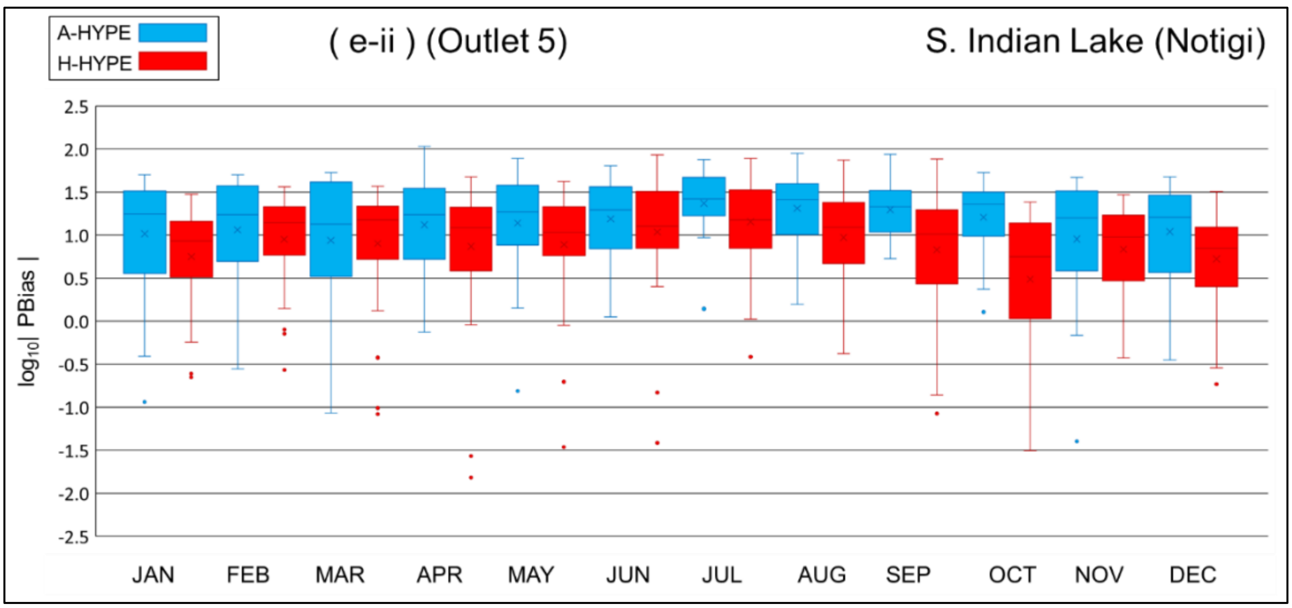

A-HYPE
H-HYPE
(c-i) (Outlet 3)
Reindeer Lake
log10(1 – NSE)
6
5
4
3
2
1
0
-1
-2
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

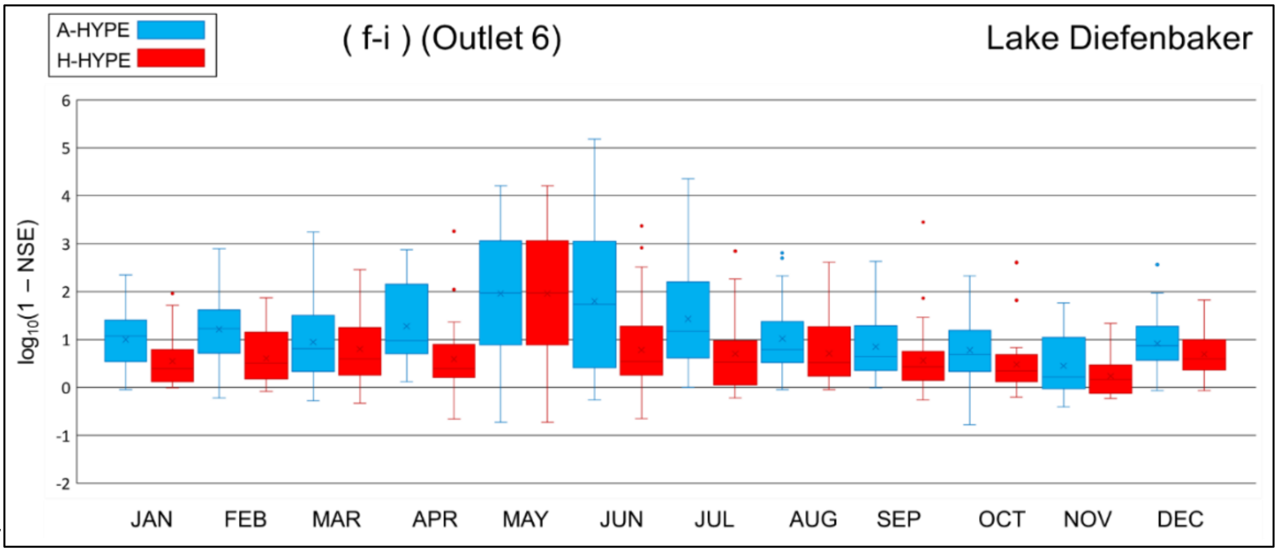

A-HYPE
H-HYPE
(c-ii) (Outlet 3)
Reindeer Lake
log10| PBias |
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC


A-HYPE
H-HYPE
(d-i) (Outlet 4)
S. Indian Lake (Missi Falls)
log10(1 − NSE)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

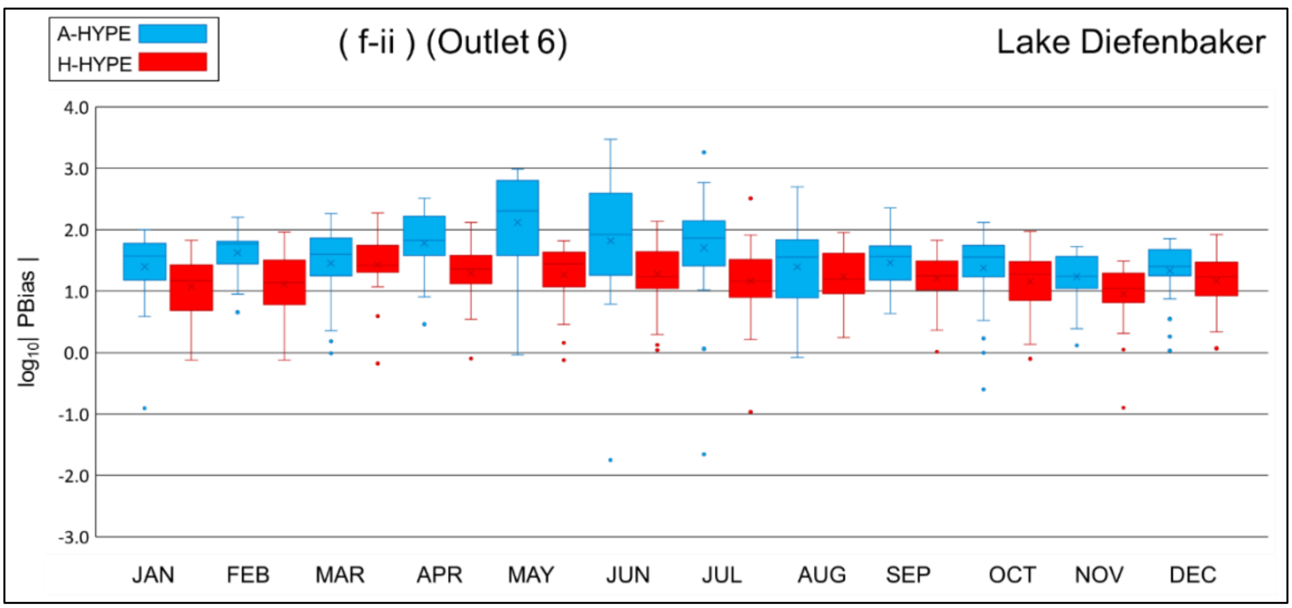

A-HYPE
H-HYPE
(d-ii) (Outlet 4)
S. Indian Lake (Missi Falls)
log10| PBias |
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

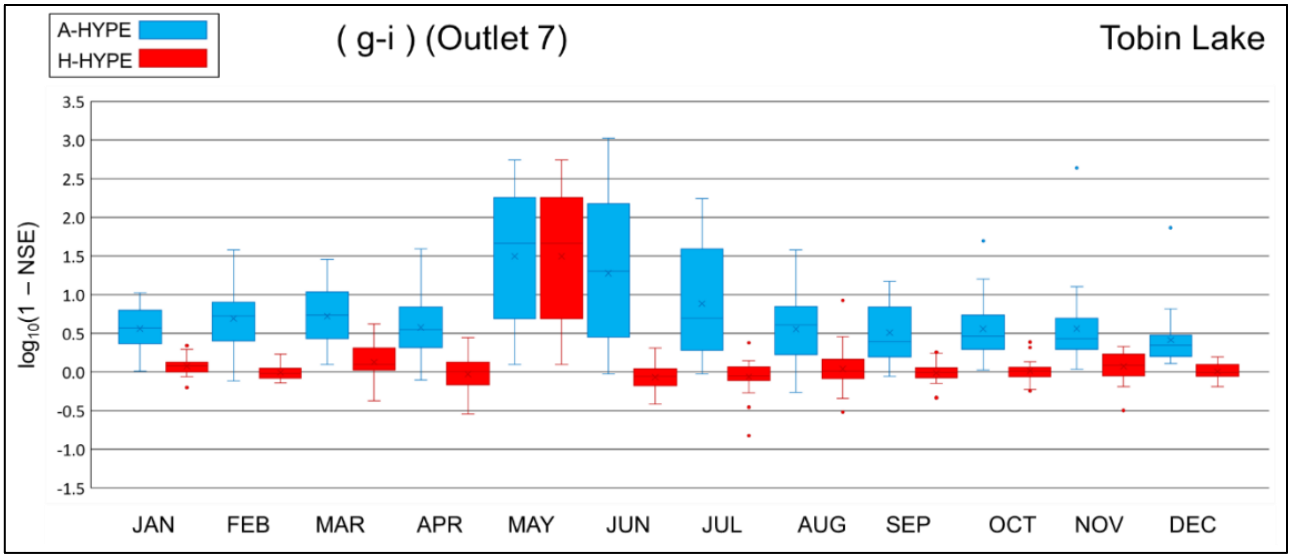

A-HYPE
H-HYPE
(e-i) (Outlet 5)
S. Indian Lake (Notigi)
log10(1 – NSE)
6
5
4
3
2
1
0
-1
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC


A-HYPE
H-HYPE
(e-ii) (Outlet 5)
S. Indian Lake (Notigi)
log10| PBias |
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

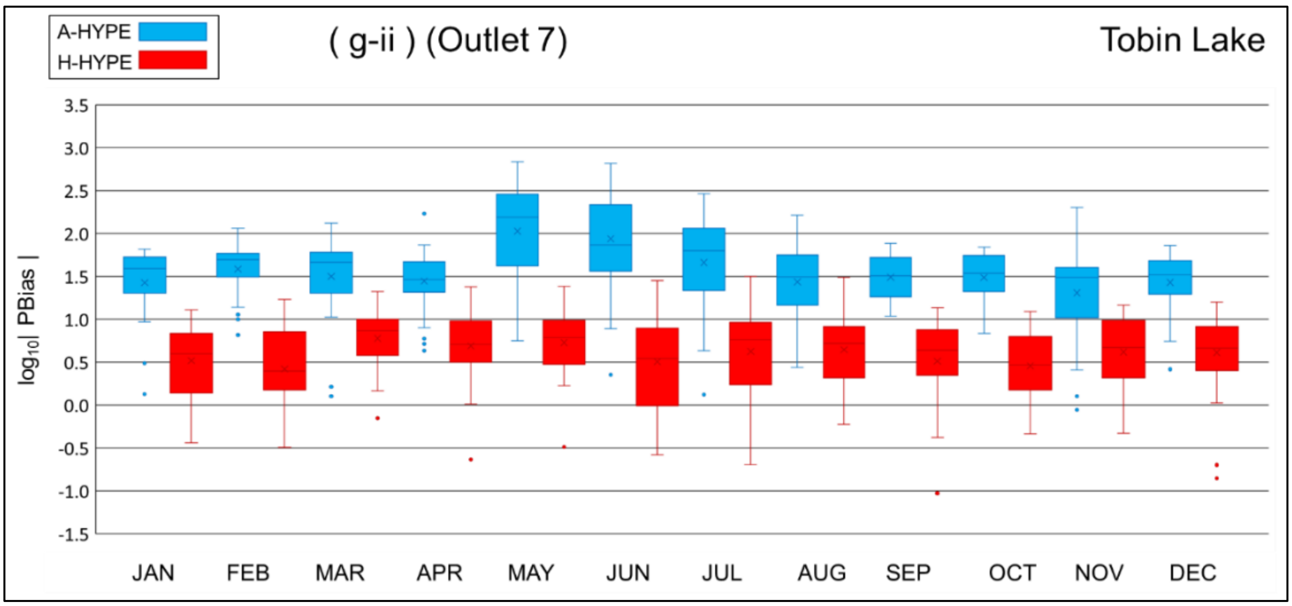

A-HYPE
H-HYPE
(f-i) (Outlet 6)
Lake Diefenbaker
log10(1 – NSE)
6
5
4
3
2
1
0
-1
-2
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

7

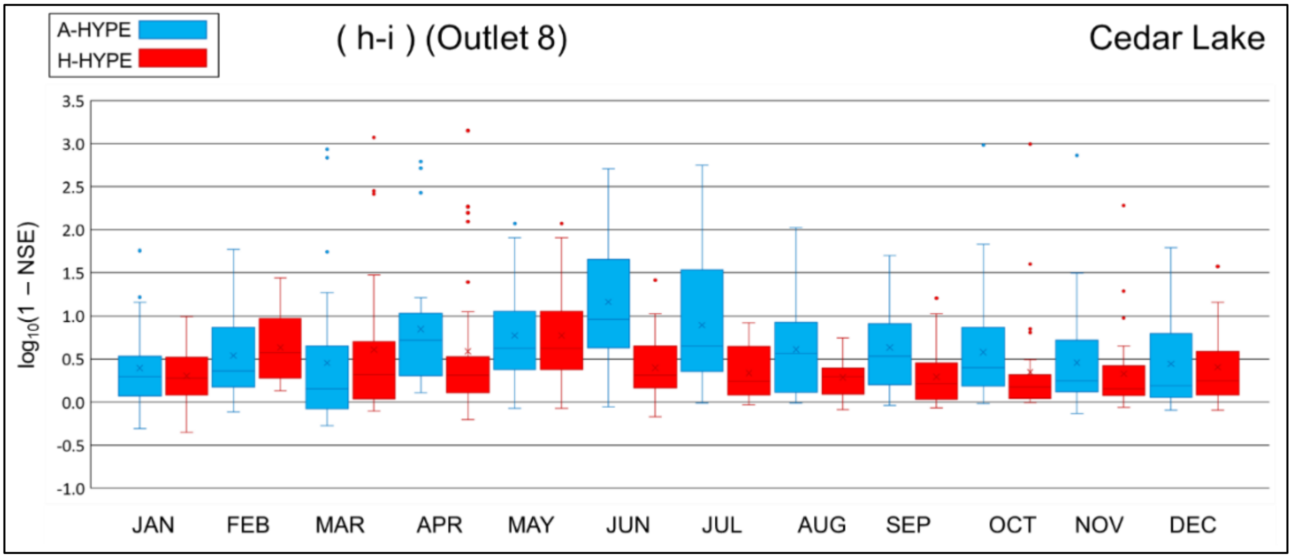

A-HYPE
H-HYPE
(f-ii) (Outlet 6)
Lake Diefenbaker
log10| PBias |
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

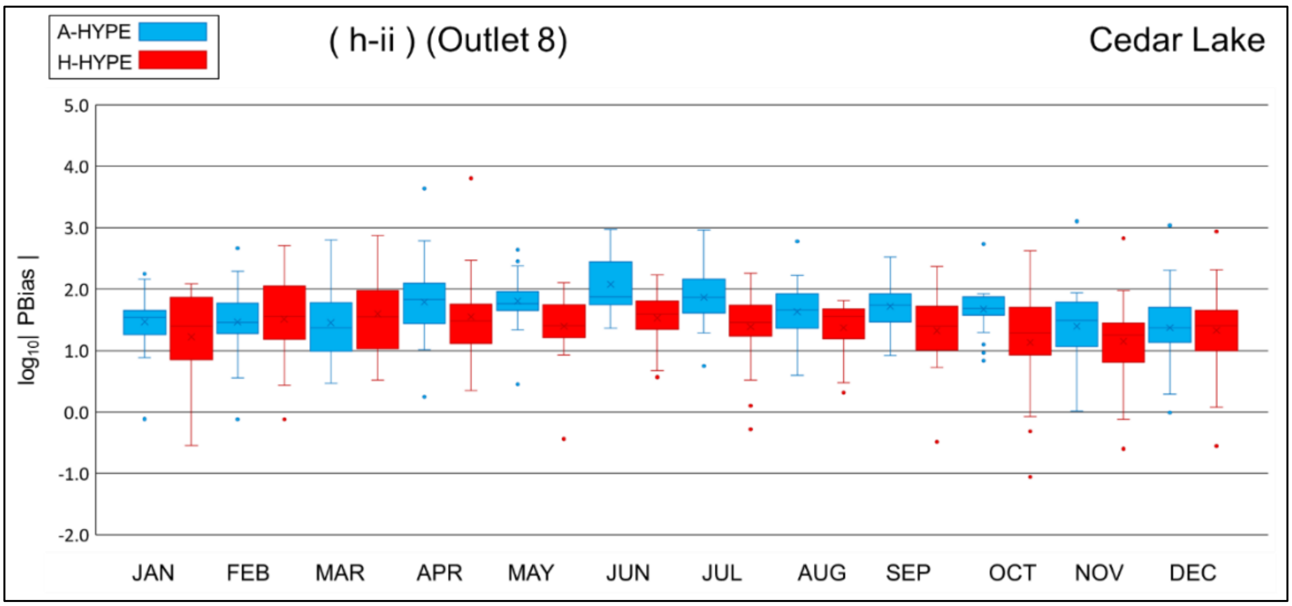


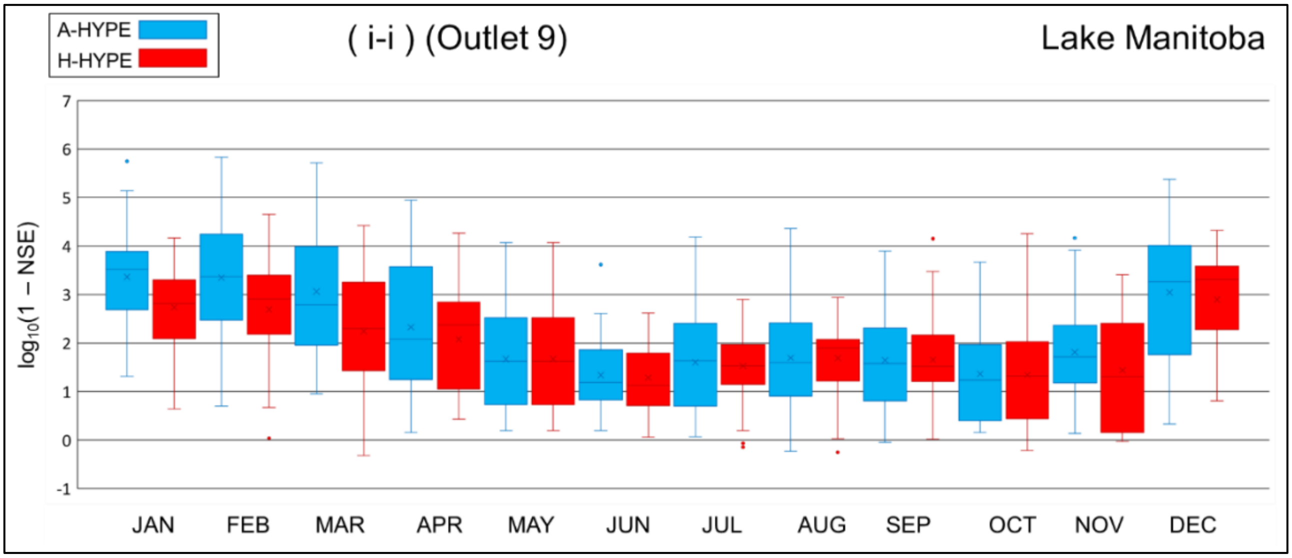
A-HYPE
H-HYPE
(g-i) (Outlet 7)
Tobin Lake
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
$\log_{10}(1 - \mathrm{NSE})$
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

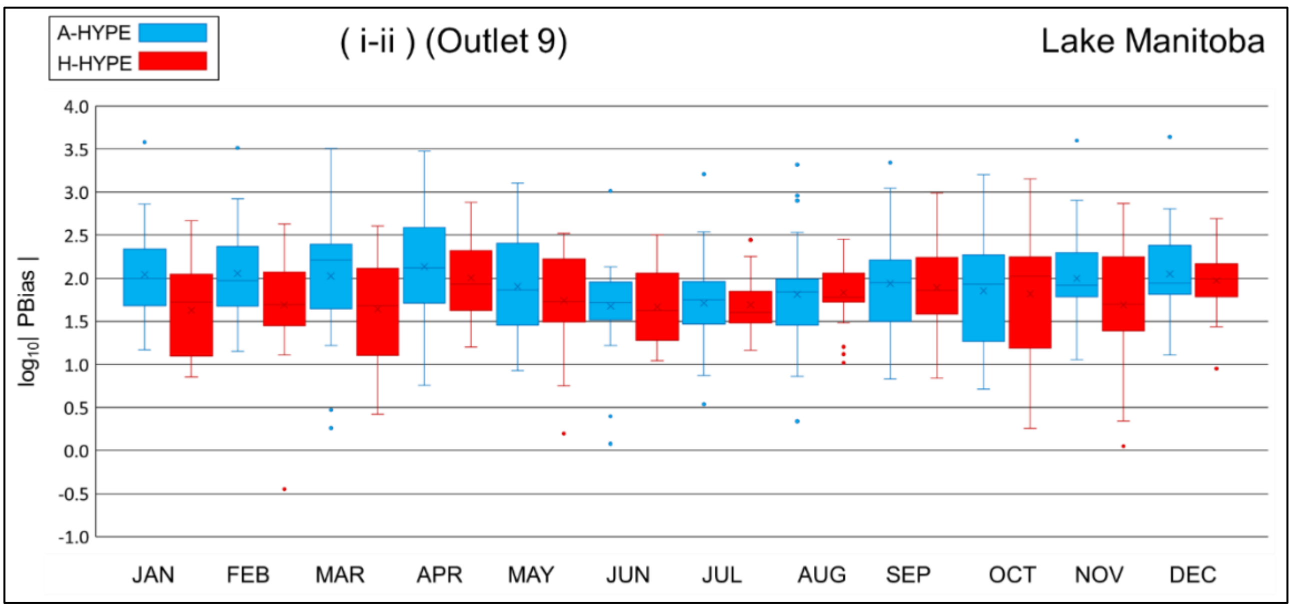


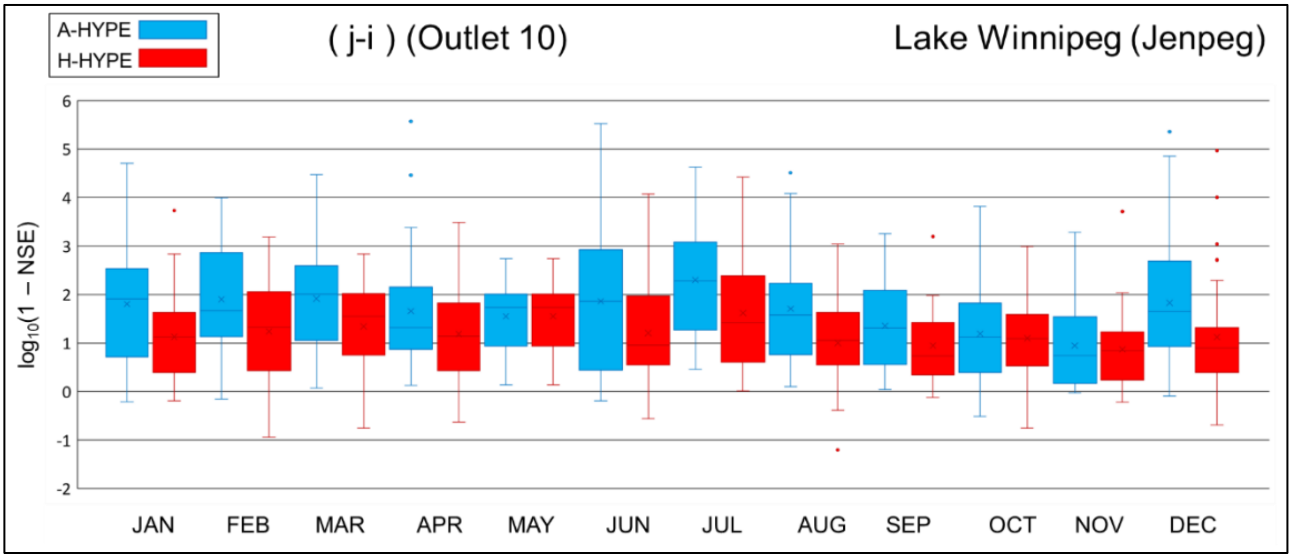
A-HYPE
H-HYPE
(g-ii) (Outlet 7)
Tobin Lake
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
$\log_{10}|\ \mathrm{PBias}\ |$
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

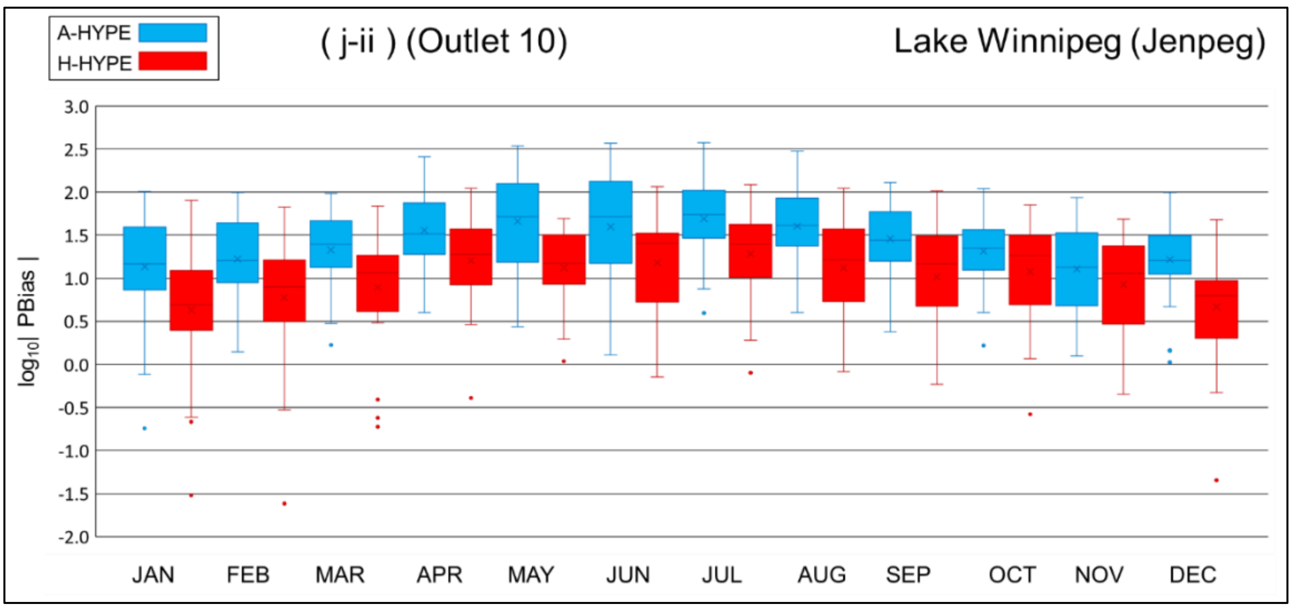

A-HYPE
H-HYPE
(h-i) (Outlet 8)
Cedar Lake
log10(1 – NSE)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

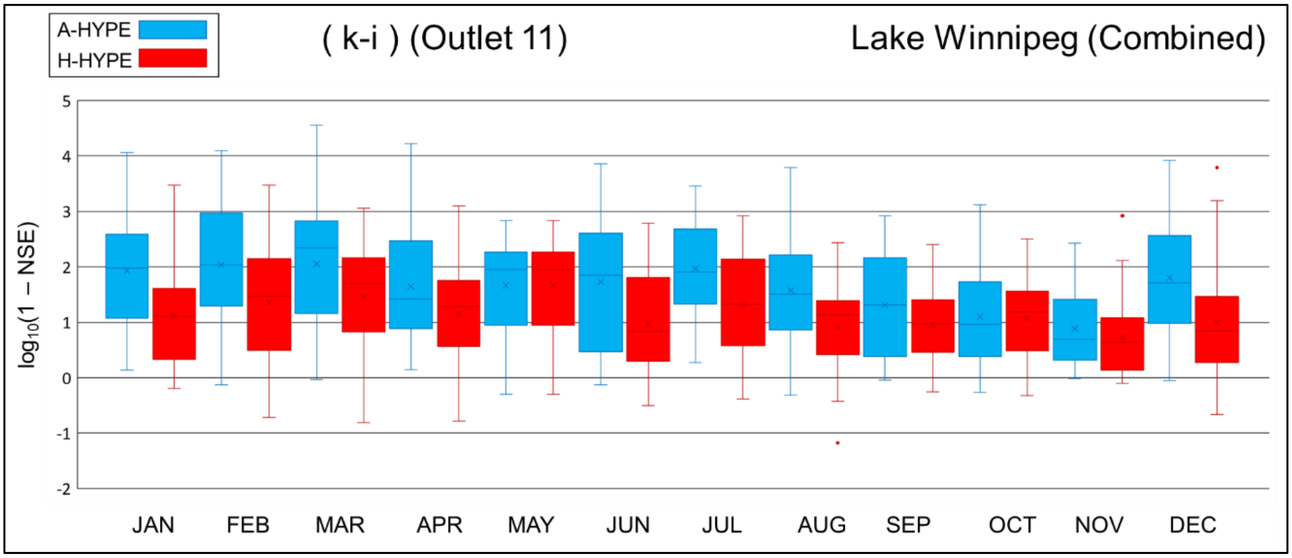

A-HYPE
H-HYPE
(h-ii) (Outlet 8)
Cedar Lake
log10| PBias |
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

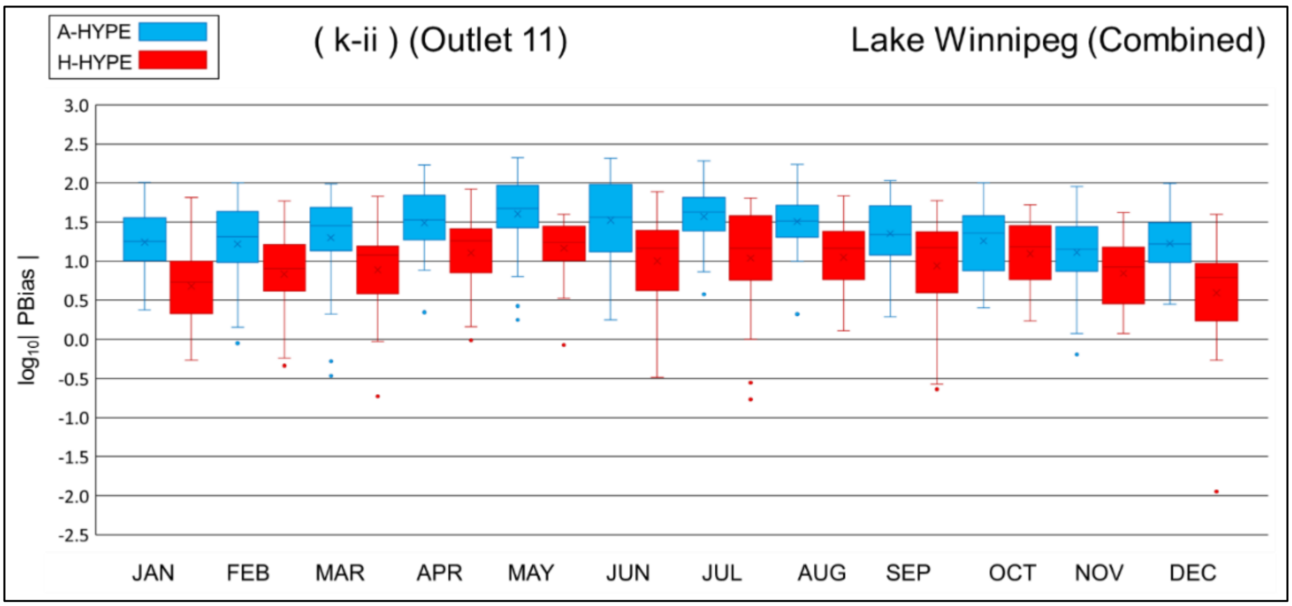

A-HYPE
H-HYPE
(i-i) (Outlet 9)
Lake Manitoba
log10(1 − NSE)
7
6
5
4
3
2
1
0
-1
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

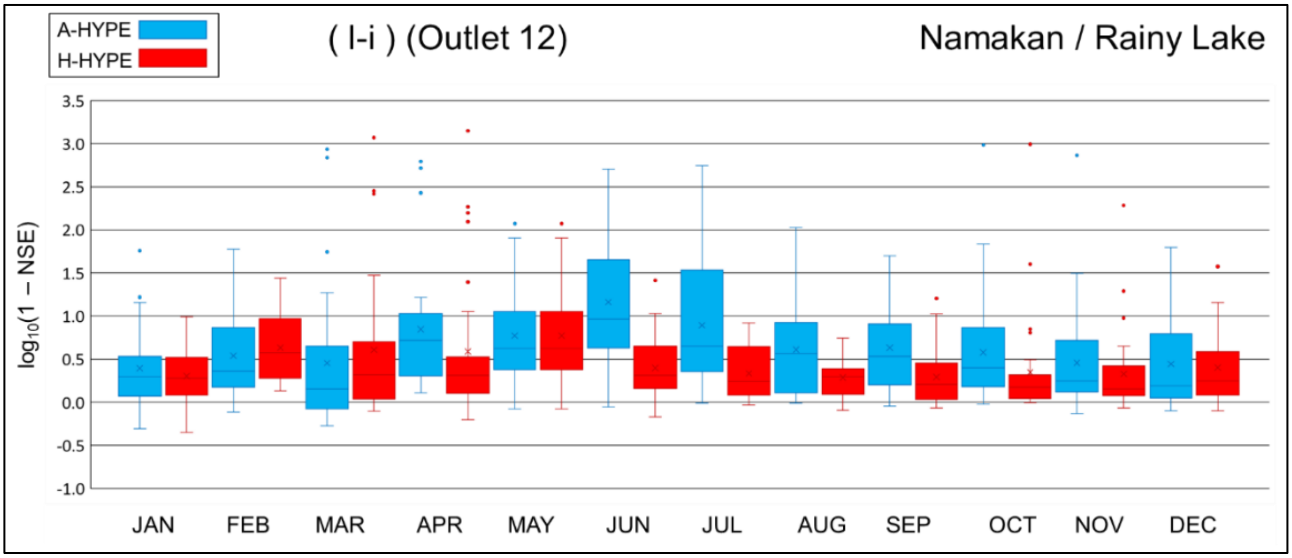

A-HYPE
H-HYPE
(i-ii) (Outlet 9)
Lake Manitoba
log10| PBias |
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

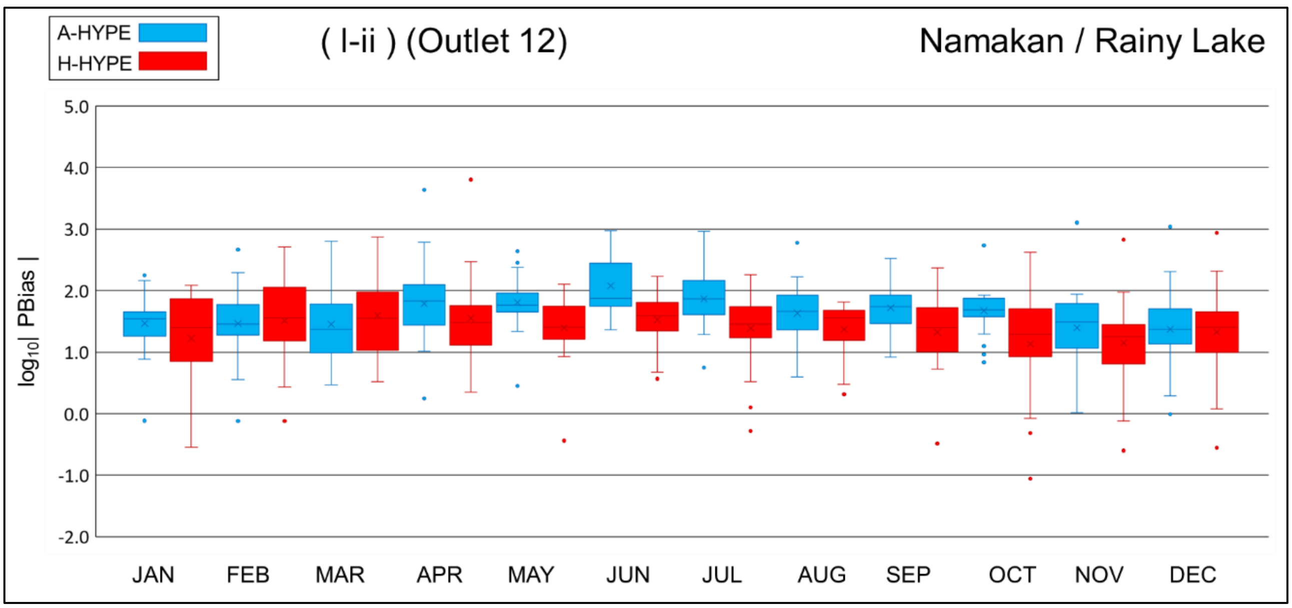

A-HYPE
H-HYPE
(j-i) (Outlet 10)
Lake Winnipeg (Jenpeg)
log10(1 − NSE)
6
5
4
3
2
1
0
-1
-2
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

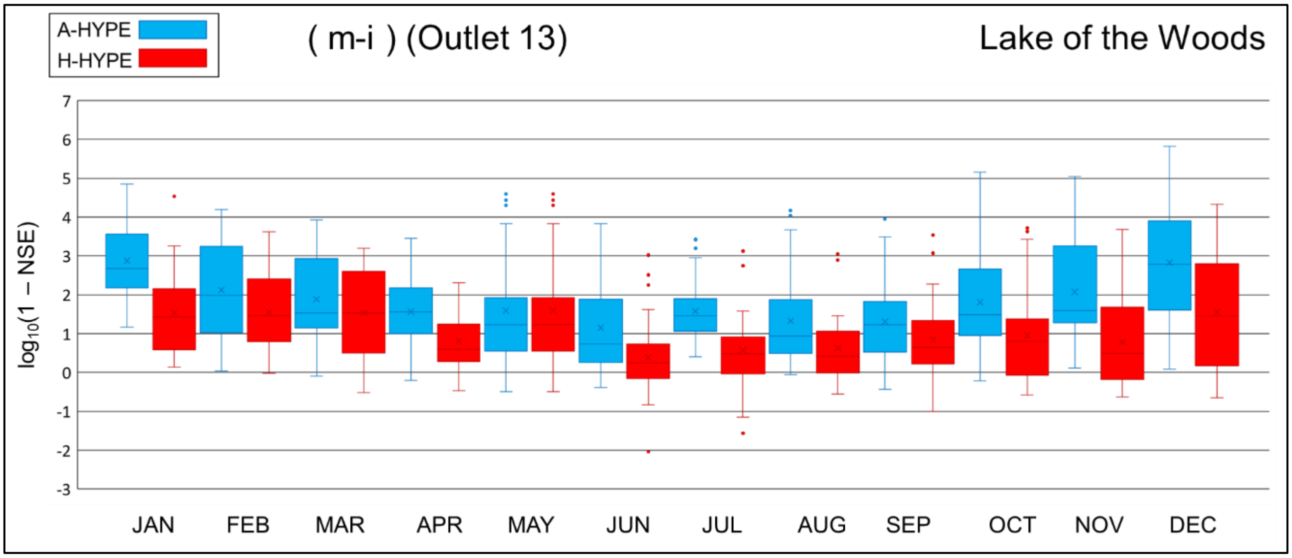

A-HYPE
H-HYPE
(j-ii) (Outlet 10)
Lake Winnipeg (Jenpeg)
log10| PBias |
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

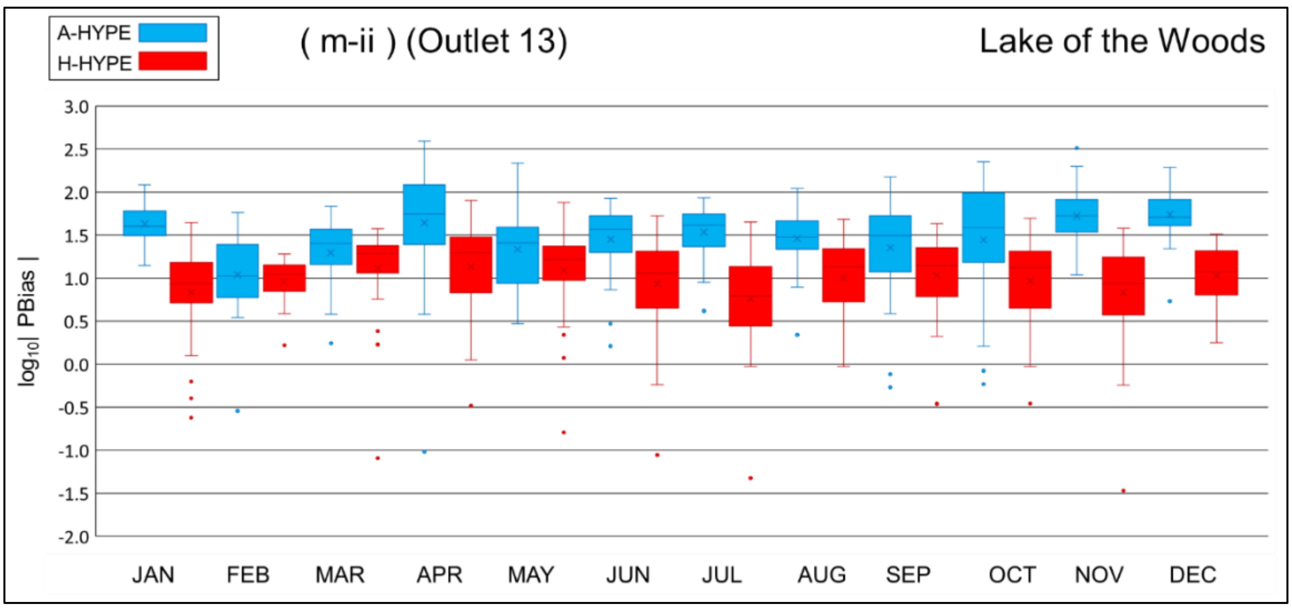

A-HYPE
H-HYPE
(k-i) (Outlet 11)
Lake Winnipeg (Combined)
log10(1 – NSE)
5
4
3
2
1
0
-1
-2
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

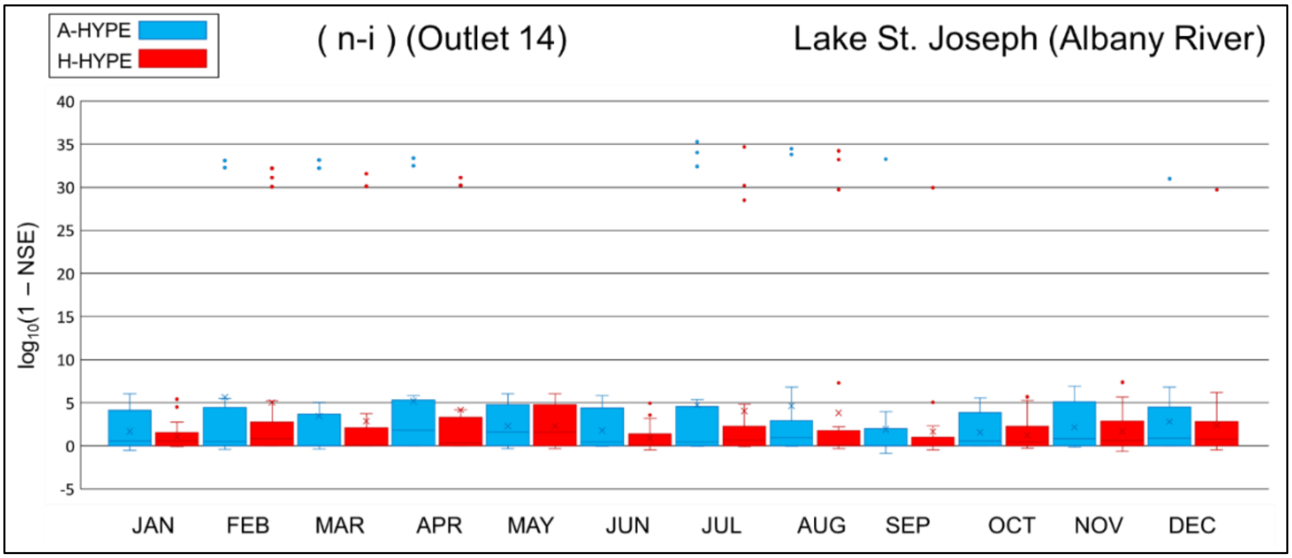

A-HYPE
H-HYPE
(k-ii) (Outlet 11)
Lake Winnipeg (Combined)
log10| PBias |
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

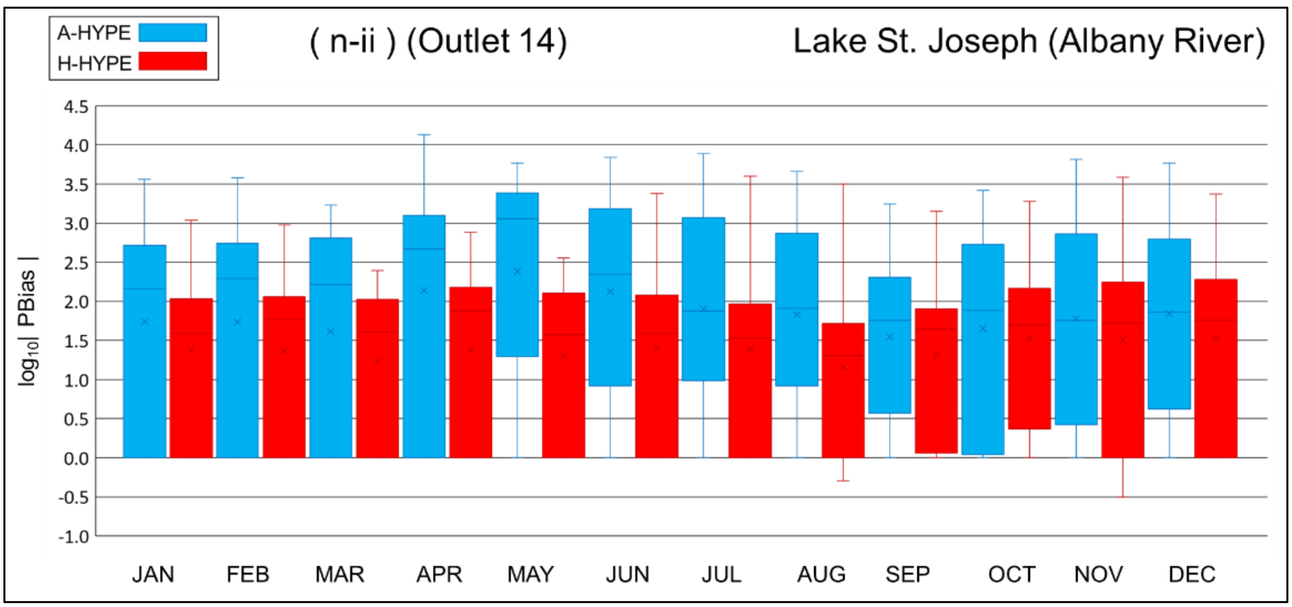

A-HYPE
H-HYPE
(I-i) (Outlet 12)
Namakan / Rainy Lake
log10(1 – NSE)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

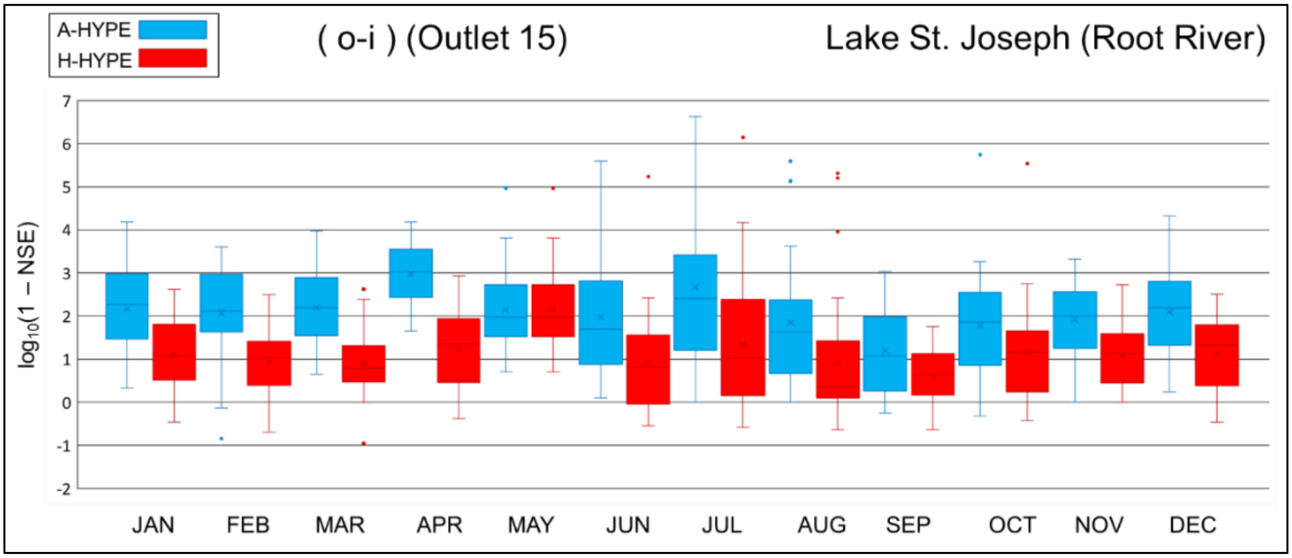

A-HYPE
H-HYPE
(I-ii) (Outlet 12)
Namakan / Rainy Lake
log10| PBias |
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

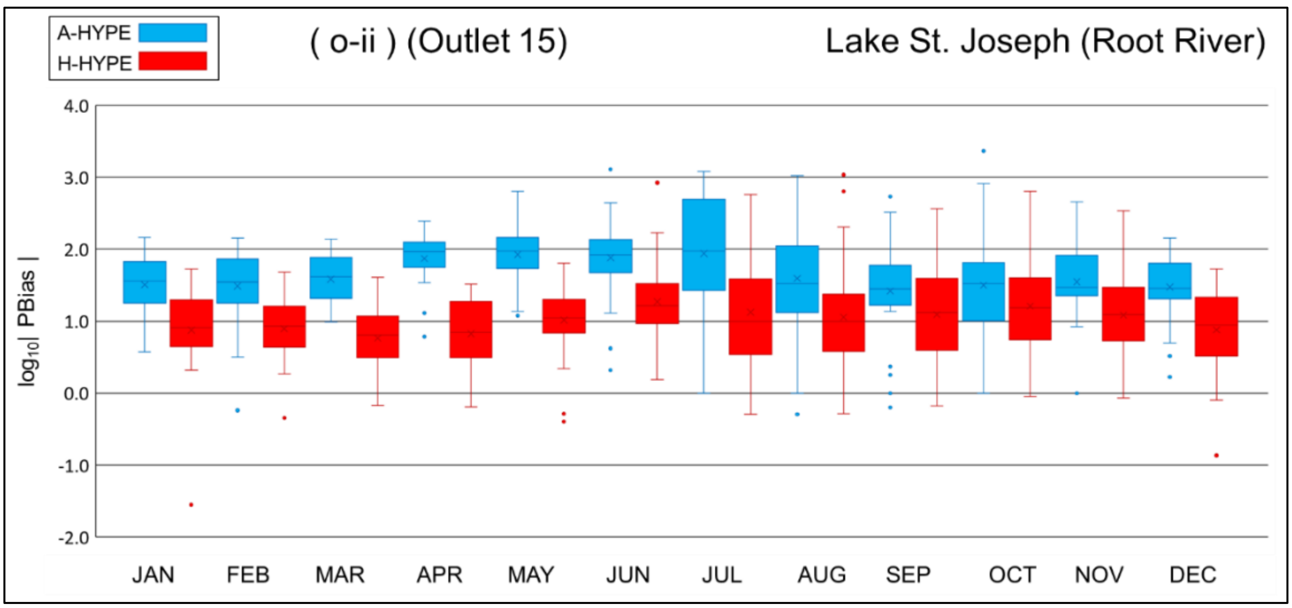

A-HYPE
H-HYPE
(m-i) (Outlet 13)
Lake of the Woods
log10(1 – NSE)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC


A-HYPE
H-HYPE
(m-ii) (Outlet 13)
Lake of the Woods
log10| PBias |
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC


A-HYPE
H-HYPE
(n-i) (Outlet 14)
Lake St. Joseph (Albany River)
log10(1 − NSE)
40
35
30
25
20
15
10
5
0
-5
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC


A-HYPE
H-HYPE
(n-ii) (Outlet 14)
Lake St. Joseph (Albany River)
log10| PBias |
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC


A-HYPE
H-HYPE
(o-i) (Outlet 15)
Lake St. Joseph (Root River)
log10(1 – NSE)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC


A-HYPE
H-HYPE
(o-ii) (Outlet 15)
Lake St. Joseph (Root River)
log10| PBias |
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

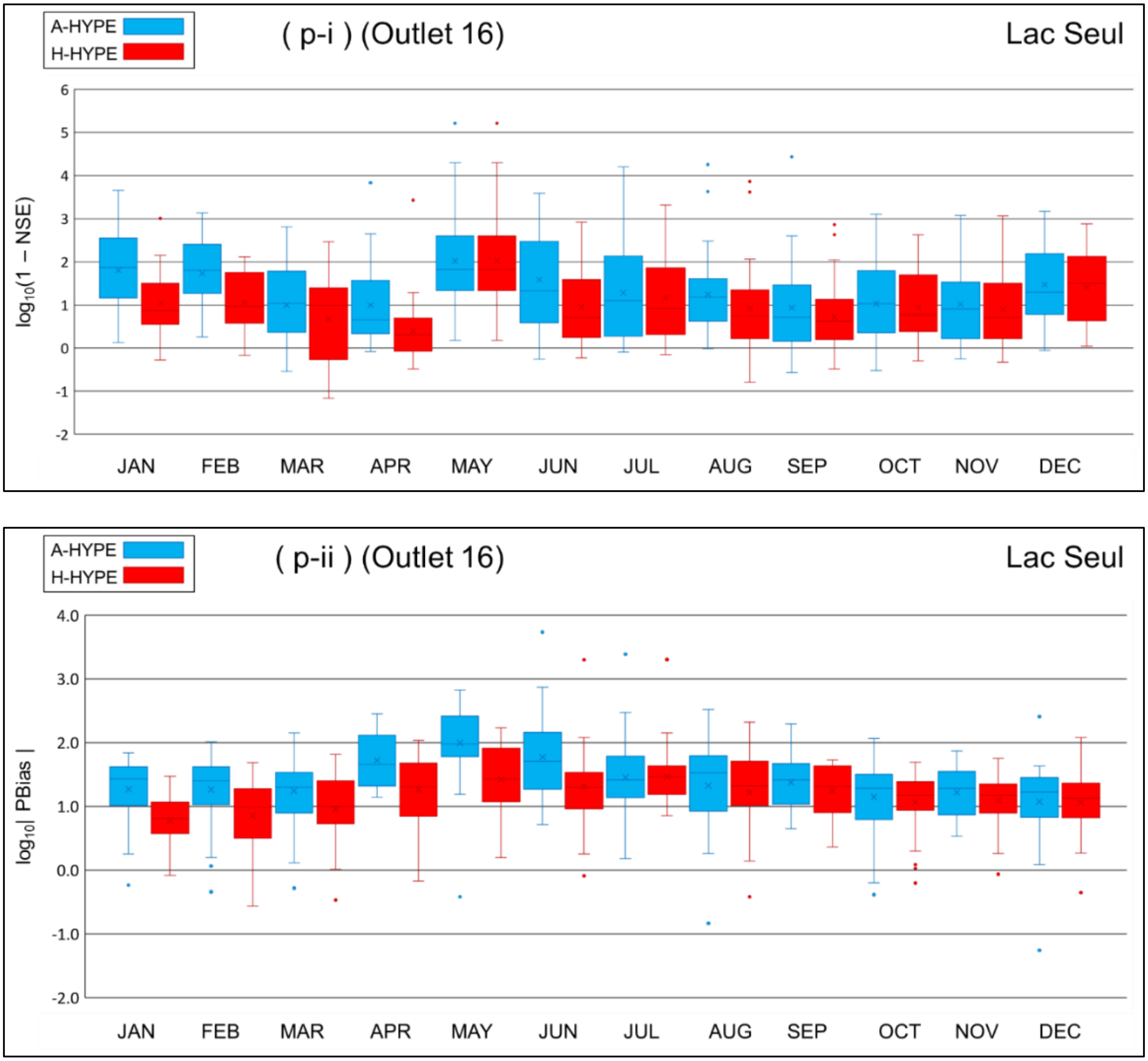


Figure C-1: *Monthly distributions of (i) NSE error (1 – NSE) and (ii) absolute mean bias (|Bias|) for (blue) A-HYPE and (red) H-HYPE at* log_{10} *base.*

6.4 Appendix D: Validation and Reference Period Statistics for H-HYPE Routine

Table D-1: *Summary of calibration metrics (a) NSE and (b) percent bias of mean for 16 outlets from 1981 to 2010 period for A-HYPE dam and new H-HYPE dam routine. Right-hand panel is the difference between the two models; values in bold with orange background are weakened by the introduction of H-HYPE. The number of binned seasonal evaluations for (c) NSE and (d) percent bias.*

#	NSE (a)	A-HYPE					H-HYPE				
		Winter	Spring	Summer	Fall	Yearly	Winter	Spring	Summer	Fall	Yearly
1	Lac la Ronge	-2.416	-1.542	-8.525	-4.114	-4.231	0.870	0.644	0.483	0.510	0.671
2	Wollaston Lake	-12.540	-10.294	-43.396	-20.133	-28.632	-0.267	0.339	-0.137	0.435	0.442
3	Reindeer Lake	-0.064	0.219	0.100	0.120	0.264	0.287	0.080	0.448	0.449	0.491
4	S. Indian Lake (Missi Falls)	0.871	-1.288	0.604	0.870	0.699	0.871	0.266	0.610	0.873	0.752
5	S. Indian Lake (Notigi)	-1.634	-0.254	-0.668	-0.900	-0.538	0.210	0.349	-0.162	0.224	0.240
6	Lake Diefenbaker	-0.207	-0.459	-0.128	0.148	-0.053	0.074	0.407	0.411	0.676	0.464
7	Tobin Lake	0.444	0.634	0.762	0.676	0.735	0.410	0.611	0.766	0.660	0.728
8	Cedar Lake	-0.367	-0.335	0.121	-0.245	-0.101	-0.079	-0.145	0.202	0.215	0.127
9	Lake Manitoba	0.253	0.558	0.708	-0.005	0.058	0.346	0.237	0.447	0.173	0.377
10	Lake Winnipeg (JENPEG)	-1.146	0.156	0.176	-0.623	-0.051	0.665	0.683	0.782	0.379	0.687
11	Lake Winnipeg (Cross Lake)	-0.361	0.101	-0.044	0.160	0.035	0.717	0.686	0.783	0.492	0.709
12	Namakan/Rainy Lake	-0.272	0.065	0.421	0.363	0.325	0.744	0.852	0.800	0.775	0.818
13	Lake of the Woods	0.548	0.789	0.835	0.714	0.789	0.773	0.716	0.928	0.855	0.863
14	Lake St. Joseph (Albany outlet)	-0.271	-47.803	0.209	0.344	0.164	0.361	0.569	0.731	0.647	0.697
15	Lake St. Joseph (Root River)	-0.183	-8.175	-2.846	-2.507	-2.703	0.498	0.375	-0.068	-0.092	0.079
16	Lac Seul	0.198	0.387	0.455	0.575	0.538	0.583	0.740	0.648	0.608	0.714

#	% Bias (b)	A-HYPE					H-HYPE				
		Winter	Spring	Summer	Fall	Yearly	Winter	Spring	Summer	Fall	Yearly
1	Lac la Ronge	-10.8	51.4	155.3	-27.6	-60.3	-4.0	23.9	-5.8	-5.6	-2.7
2	Wollaston Lake	30.1	30.5	60.5	23.0	20.5	15.4	2.4	-17.3	-4.4	-3.5
3	Reindeer Lake	3.1	-1.6	-2.3	5.2	-0.1	0.7	4.4	4.5	-5.1	0.9
4	S. Indian Lake (Missi Falls)	21.9	290.2	-11.3	3.9	6.6	-15.6	-19.9	-21.8	-17.6	-18.6
5	S. Indian Lake (Notigi)	-18.4	27.2	-2.4	-19.3	-3.5	-5.8	3.2	8.2	-1.8	0.6
6	Lake Diefenbaker	8.0	19.6	-19.9	-2.8	0.5	12.3	-10.5	-0.8	4.4	2.7
7	Tobin Lake	0.7	-1.5	5.4	1.6	-0.4	-1.6	-0.5	1.3	0.5	0.0
8	Cedar Lake	-34.1	39.0	-9.3	42.1	1.2	14.6	7.8	-10.7	-15.2	0.7
9	Lake Manitoba	-30.4	9.4	4.9	-51.8	-55.3	37.3	20.7	-26.8	40.3	11.3
10	Lake Winnipeg (JENPEG)	16.9	-5.1	9.0	35.1	3.5	3.7	6.0	5.3	3.7	4.6
11	Lake Winnipeg (Cross Lake)	18.9	-8.7	-23.3	6.0	-9.8	3.6	3.1	-0.9	-1.8	0.9
12	Namakan/Rainy Lake	-35.6	32.2	-14.5	-14.5	1.2	8.7	4.9	-7.8	-2.1	0.0
13	Lake of the Woods	-19.4	10.2	15.8	-6.6	-0.2	2.9	0.4	-2.4	1.1	0.4
14	Lake St. Joseph (Albany outlet)	505.7	1881.2	-21.3	47.1	36.4	-6.3	62.2	1.9	-29.9	-10.1
15	Lake St. Joseph (Root River)	-31.4	91.6	23.1	16.3	26.4	-1.5	-4.2	5.7	8.9	2.4
16	Lac Seul	-11.9	41.0	4.7	4.9	2.0	8.4	6.2	-15.8	-1.8	0.1

Number of Seasonal Evaluations Falling within Ranges								
A-HYPE				**NSE (c)**	**H-HYPE**			
Winter	**Spring**	**Summer**	**Fall**		**Winter**	**Spring**	**Summer**	**Fall**
11	8	6	7	< 0	2	1	3	1
2	4	4	3	0 - 1/3	3	3	1	3
2	3	3	3	1/3 - 2/3	6	7	6	8
1	1	3	3	2/3 - 1	5	5	6	4
Percent of Seasonal Evaluations Falling within Ranges								
50.0				< 0	10.9			
20.3				0 - 1/3	15.6			
17.2				1/3 - 2/3	42.2			
12.5				2/3 - 1	31.3			
Number and Percent of Seasonal Evaluations where Results Improved								
60.0								
94%								

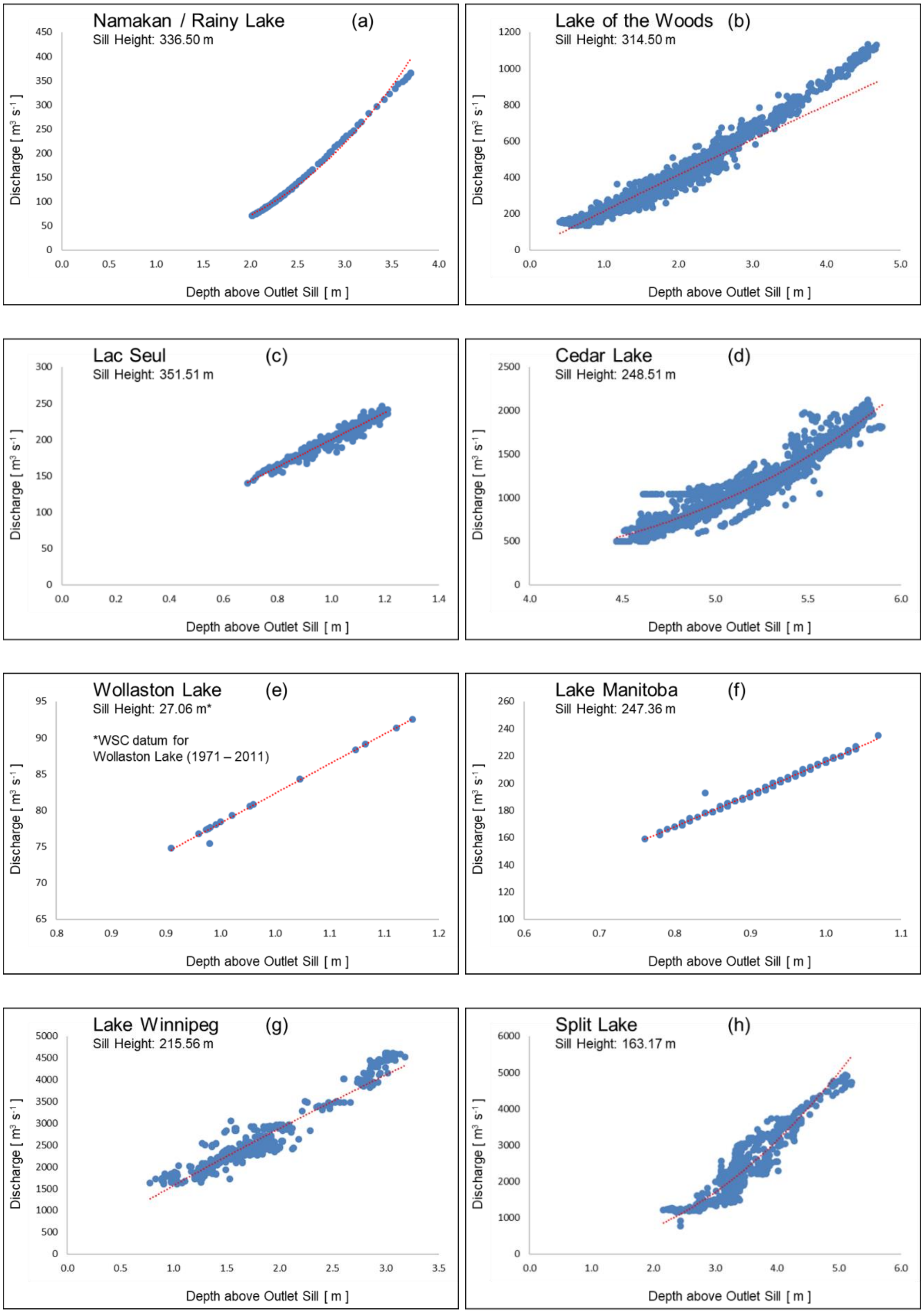
Number of Seasonal Evaluations Falling within Ranges								
A-HYPE				**Bias (d)**	**H-HYPE**			
Winter	**Spring**	**Summer**	**Fall**		**Winter**	**Spring**	**Summer**	**Fall**
1	4	2	1	> |50|	0	1	0	0
5	5	0	4	|50| - |25|	1	0	1	2
7	2	7	4	|25| - |10|	4	4	4	2
3	5	7	7	< |10|	11	11	11	12
Percent of Seasonal Evaluations Falling within Ranges								
12.5				> |50|	1.6			
21.9				|50| - |25|	6.3			
31.3				|25| - |10|	21.9			
34.4				< |10|	70.3			
Number and Percent of Seasonal Evaluations where Results Improved								
50.0								
78%								

6.5 Appendix E: Re-Naturalization of Reservoirs and Land-Cover

Table E-1: *Re-naturalized reservoir outflow coefficients from pre-development stage-discharge data.*

Reservoir Name			Least-Squares Regressed Parameters		
			α [-]	β [-]	Sill [m]
a	1	Namakan / Rainy Lake	10.619	2.7621	336.50
b	2	Lake of the Woods	213.950	0.9495	314.50
c	3	Lac Seul	199.960	0.9407	351.51
d	4	Cedar Lake	0.395	4.8247	248.51
e	5	Wollaston Lake	82.317	0.9930	27.06
f	6	Lake Manitoba	215.720	1.1209	247.36
g	7	Lake Winnipeg	1573.400	0.8746	215.56
h	8	Split Lake	168.080	2.1101	163.17
i	9	S. Indian Lake	12.945	3.3625	251.40
j	10	Lac la Ronge	11.020	3.0138	362.82
k	11	Reindeer Lake	2×10^{-7}	18.6030	333.40
l	12	Umfreville Lake	1.133	5.4403	316.00
m	13	Sipiwesk Lake	1237.500	0.8333	183.79

Computed discharge (red line) calculated using observed WSL, comparing observed and calculated discharge using $Q_i = \alpha (WSL_i - Sill)^{\beta}$*. Wollaston Lake outlet minimum height (sill) is a datum used by WSC from 1971-2011.*


Namakan / Rainy Lake (a)
Sill Height: 336.50 m
Discharge [m³ s⁻¹]
Depth above Outlet Sill [m]
0 50 100 150 200 250 300 350 400 450
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
Lake of the Woods (b)
Sill Height: 314.50 m
Discharge [m³ s⁻¹]
Depth above Outlet Sill [m]
0 200 400 600 800 1000 1200
0.0 1.0 2.0 3.0 4.0 5.0
Lac Seul (c)
Sill Height: 351.51 m
Discharge [m³ s⁻¹]
Depth above Outlet Sill [m]
0 50 100 150 200 250 300
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
Cedar Lake (d)
Sill Height: 248.51 m
Discharge [m³ s⁻¹]
Depth above Outlet Sill [m]
0 500 1000 1500 2000 2500
4.0 4.5 5.0 5.5 6.0
Wollaston Lake (e)
Sill Height: 27.06 m*
*WSC datum for
Wollaston Lake (1971 – 2011)
Discharge [m³ s⁻¹]
Depth above Outlet Sill [m]
65 70 75 80 85 90 95
0.8 0.9 0.9 1.0 1.0 1.1 1.1 1.2
Lake Manitoba (f)
Sill Height: 247.36 m
Discharge [m³ s⁻¹]
Depth above Outlet Sill [m]
100 120 140 160 180 200 220 240 260
0.6 0.7 0.8 0.9 1.0 1.1
Lake Winnipeg (g)
Sill Height: 215.56 m
Discharge [m³ s⁻¹]
Depth above Outlet Sill [m]
0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
Split Lake (h)
Sill Height: 163.17 m
Discharge [m³ s⁻¹]
Depth above Outlet Sill [m]
0 1000 2000 3000 4000 5000 6000
0.0 1.0 2.0 3.0 4.0 5.0 6.0

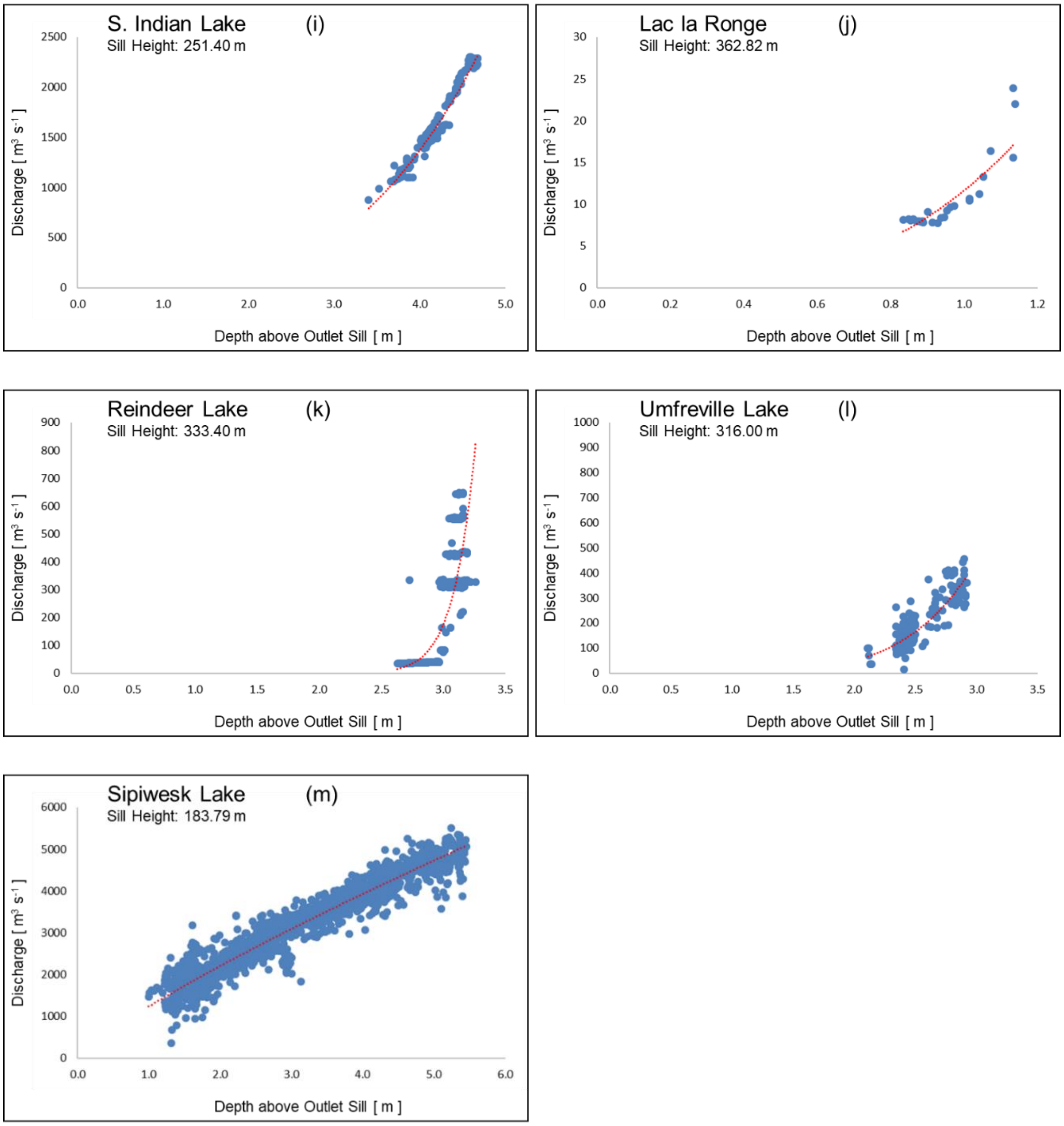


Figure E-1**:** *Observed stage-discharge data from pre-development period for re-naturalized reservoirs. Sill heights retrieved by personal communication with Manitoba Hydro. Stage and discharge data retrieved from WSC records corresponding to years listed in Table 3-2.*

6.6 Appendix F: Seasonal Analysis (Value, Trend, Change) for Regulated Basins

Table F-1: *For all periods/model configurations, seasonal value by variable (units and aggregation vary, Table 3-5), seasonal trend by variable (by year), seasonal inter-annual COV (30-year period), seasonal inter-scenario COV (between GCMs), intercomparison absolute change, intercomparison percent change. Bold trend values indicate significance (Mann-Kendall, α = 5%); green cells indicate increasing (positive) red for decreasing (negative), and blue indicates no (negligible) trend.*

(a) Total Precipitation [mm]	NCRB	LGRC

Value [mm]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	56	99	218	115	488	124	128	269	231	752
CalibNat		Re-Naturalized		56	99	218	115	488	124	128	269	231	752
HistReg	GCM Ensemble	Regulated		61	97	208	129	494	84	95	197	163	538
HistNat		Re-Naturalized		61	97	208	129	494	84	95	197	163	538
Fut1Reg		Regulated	2021-2050	65	109	213	136	524	93	104	207	177	582
Fut1Nat		Re-Naturalized		65	109	213	136	524	93	104	207	177	582
Fut2Reg		Regulated	2041-2070	72	116	212	142	542	105	114	214	187	620
Fut2Nat		Re-Naturalized		72	116	212	142	542	105	114	214	187	620

Trend [mm/yr]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0.3	0.6	0.5	0.0	1.3	-0.2	**-0.9**	1.1	-0.1	0.0
CalibNat		Re-Naturalized		0.3	0.6	0.5	0.0	1.3	-0.2	**-0.9**	1.1	-0.1	0.0
HistReg	GCM Ensemble	Regulated		**0.1**	**0.3**	**0.4**	**0.2**	**1.1**	**0.3**	**0.3**	**0.3**	**0.4**	**1.3**
HistNat		Re-Naturalized		**0.1**	**0.3**	**0.4**	**0.2**	**1.1**	**0.3**	**0.3**	**0.3**	**0.4**	**1.3**
Fut1Reg		Regulated	2021-2050	**0.2**	**0.5**	0.0	**0.2**	**0.9**	**0.5**	**0.4**	**0.4**	**0.5**	**1.7**
Fut1Nat		Re-Naturalized		**0.2**	**0.5**	0.0	**0.2**	**0.9**	**0.5**	**0.4**	**0.4**	**0.5**	**1.7**
Fut2Reg		Regulated	2041-2070	**0.4**	**0.4**	0.1	**0.5**	**1.4**	**0.6**	**0.6**	0.3	**0.8**	**2.2**
Fut2Nat		Re-Naturalized		**0.4**	**0.4**	0.1	**0.5**	**1.4**	**0.6**	**0.6**	0.3	**0.8**	**2.2**

Absolute Change [mm]		NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
Model-State Analysis	HistNat - HistReg	0	0	0	0	0	0	0	0	0	0
	Fut1Nat - Fut1Reg	0	0	0	0	0	0	0	0	0	0
	Fut2Nat - Fut2Reg	0	0	0	0	0	0	0	0	0	0
Climate Change Analysis	Fut1Reg - HistReg	5	12	5	7	29	10	10	10	14	44
	Fut1Nat - HistNat	5	12	5	7	29	10	10	10	14	44
	Fut2Reg - HistReg	11	20	4	13	48	21	20	17	24	81
	Fut2Nat - HistNat	11	20	4	13	48	21	20	17	24	81
GCM Bias Analysis	HistReg - CalibReg	4	-3	-9	14	6	-40	-33	-72	-67	-213
	HistNat - CalibNat	4	-3	-9	14	6	-40	-33	-72	-67	-213

Percent Change [%]		NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
Model-State Analysis	HistNat - HistReg	0	0	0	0	0	0	0	0	0	0
	Fut1Nat - Fut1Reg	0	0	0	0	0	0	0	0	0	0
	Fut2Nat - Fut2Reg	0	0	0	0	0	0	0	0	0	0
Climate Change Analysis	Fut1Reg - HistReg	8	13	2	6	6	12	10	5	9	8
	Fut1Nat - HistNat	8	13	2	6	6	12	10	5	9	8
	Fut2Reg - HistReg	18	21	2	10	10	25	21	9	14	15
	Fut2Nat - HistNat	18	21	2	10	10	25	21	9	14	15
GCM Bias Analysis	HistReg - CalibReg	8	-3	-4	12	1	-33	-26	-27	-29	-28
	HistNat - CalibNat	8	-3	-4	12	1	-33	-26	-27	-29	-28

Inter-Annual COV [%]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	22	19	15	18	10	21	20	15	18	11
CalibNat		Re-Naturalized		22	19	15	18	10	21	20	15	18	11
HistReg	GCM Ensemble	Regulated		5	5	4	4	3	7	5	3	5	3
HistNat		Re-Naturalized		5	5	4	4	3	7	5	3	5	3
Fut1Reg		Regulated	2021-2050	5	6	3	3	2	5	5	3	4	3
Fut1Nat		Re-Naturalized		5	6	3	3	2	5	5	3	4	3
Fut2Reg		Regulated	2041-2070	6	5	3	4	3	6	5	2	4	4
Fut2Nat		Re-Naturalized		6	5	3	4	3	6	5	2	4	4

Inter-Scenario COV [%]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010										
CalibNat		Re-Naturalized											
HistReg	GCM Ensemble	Regulated		4	5	4	5	4	14	11	10	8	10
HistNat		Re-Naturalized		4	5	4	5	4	14	11	10	8	10
Fut1Reg		Regulated	2021-2050	6	10	4	5	4	16	13	11	11	11
Fut1Nat		Re-Naturalized		6	10	4	5	4	16	13	11	11	11
Fut2Reg		Regulated	2041-2070	7	11	7	6	5	17	16	11	11	12
Fut2Nat		Re-Naturalized		7	11	7	6	5	17	16	11	11	12

Trend Significance [binary]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0	0	0	0	0	0	**1**	0	0	0
CalibNat		Re-Naturalized		0	0	0	0	0	0	**1**	0	0	0
HistReg	GCM Ensemble	Regulated		**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
HistNat		Re-Naturalized		**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Fut1Reg		Regulated	2021-2050	**1**	**1**	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Fut1Nat		Re-Naturalized		**1**	**1**	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Fut2Reg		Regulated	2041-2070	**1**	**1**	0	**1**	**1**	**1**	**1**	0	**1**	**1**
Fut2Nat		Re-Naturalized		**1**	**1**	0	**1**	**1**	**1**	**1**	0	**1**	**1**

(b) Rainfall [mm] | **NCRB** | **LGRC**

Value [mm]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	1	70	217	81	370	1	44	267	144	456
CalibNat		Re-Naturalized		1	70	217	81	370	1	44	267	144	456
HistReg	GCM Ensemble	Regulated		0	58	208	83	350	0	23	195	81	299
HistNat		Re-Naturalized		0	58	208	83	350	0	23	195	81	299
Fut1Reg		Regulated	2021-2050	1	75	213	95	384	0	35	206	102	344
Fut1Nat		Re-Naturalized		1	75	213	95	384	0	35	206	102	344
Fut2Reg		Regulated	2041-2070	2	83	212	103	399	1	43	213	115	372
Fut2Nat		Re-Naturalized		2	83	212	103	399	1	43	213	115	372

Trend [mm/yr]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0.0	0.6	0.5	0.1	1.2	0.0	0.0	1.2	0.5	1.7
CalibNat		Re-Naturalized		0.0	0.6	0.5	0.1	1.2	0.0	0.0	1.2	0.5	1.7
HistReg	GCM Ensemble	Regulated		0.0	**0.4**	**0.4**	**0.4**	**1.1**	0.0	**0.3**	**0.3**	**0.5**	**1.1**
HistNat		Re-Naturalized		0.0	**0.4**	**0.4**	**0.4**	**1.1**	0.0	**0.3**	**0.3**	**0.5**	**1.1**
Fut1Reg		Regulated	2021-2050	**0.0**	**0.5**	0.0	**0.3**	**0.7**	0.0	**0.3**	**0.4**	**0.7**	**1.4**
Fut1Nat		Re-Naturalized		**0.0**	**0.5**	0.0	**0.3**	**0.7**	0.0	**0.3**	**0.4**	**0.7**	**1.4**
Fut2Reg		Regulated	2041-2070	**0.1**	**0.4**	0.1	**0.6**	**1.2**	**0.0**	**0.5**	**0.3**	**1.0**	**1.8**
Fut2Nat		Re-Naturalized		**0.1**	**0.4**	0.1	**0.6**	**1.2**	**0.0**	**0.5**	**0.3**	**1.0**	**1.8**

Absolute Change [mm]		NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
Model-State Analysis	HistNat - HistReg	0	0	0	0	0	0	0	0	0	0
	Fut1Nat - Fut1Reg	0	0	0	0	0	0	0	0	0	0
	Fut2Nat - Fut2Reg	0	0	0	0	0	0	0	0	0	0
Climate Change Analysis	Fut1Reg - HistReg	1	17	5	12	34	0	12	12	21	44
	Fut1Nat - HistNat	1	17	5	12	34	0	12	12	21	44
	Fut2Reg - HistReg	1	25	4	20	50	1	20	18	34	73
	Fut2Nat - HistNat	1	25	4	20	50	1	20	18	34	73
GCM Bias Analysis	HistReg - CalibReg	-1	-12	-9	2	-21	-1	-21	-72	-63	-157
	HistNat - CalibNat	-1	-12	-9	2	-21	-1	-21	-72	-63	-157

Percent Change [%]		NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
Model-State Analysis	HistNat - HistReg	0	0	0	0	0	0	0	0	0	0
	Fut1Nat - Fut1Reg	0	0	0	0	0	0	0	0	0	0
	Fut2Nat - Fut2Reg	0	0	0	0	0	0	0	0	0	0
Climate Change Analysis	Fut1Reg - HistReg	185	29	2	14	10	128	49	6	26	15
	Fut1Nat - HistNat	185	29	2	14	10	128	49	6	26	15
	Fut2Reg - HistReg	493	43	2	24	14	310	83	9	43	24
	Fut2Nat - HistNat	493	43	2	24	14	310	83	9	43	24
GCM Bias Analysis	HistReg - CalibReg	-78	-17	-4	2	-6	-84	-47	-27	-44	-34
	HistNat - CalibNat	-78	-17	-4	2	-6	-84	-47	-27	-44	-34

Inter-Annual COV [%]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	105	28	15	20	12	210	32	15	20	12
CalibNat		Re-Naturalized		105	28	15	20	12	210	32	15	20	12
HistReg	GCM Ensemble	Regulated		38	8	4	6	4	50	14	3	8	4
HistNat		Re-Naturalized		38	8	4	6	4	50	14	3	8	4
Fut1Reg		Regulated	2021-2050	36	7	3	5	3	40	10	3	7	4
Fut1Nat		Re-Naturalized		36	7	3	5	3	40	10	3	7	4
Fut2Reg		Regulated	2041-2070	38	7	3	6	4	48	11	2	8	5
Fut2Nat		Re-Naturalized		38	7	3	6	4	48	11	2	8	5

Inter-Scenario COV [%]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010										
CalibNat		Re-Naturalized											
HistReg	GCM Ensemble	Regulated		32	9	4	5	4	40	43	10	21	16
HistNat		Re-Naturalized		32	9	4	5	4	40	43	10	21	16
Fut1Reg		Regulated	2021-2050	54	20	4	8	6	74	46	11	25	18
Fut1Nat		Re-Naturalized		54	20	4	8	6	74	46	11	25	18
Fut2Reg		Regulated	2041-2070	78	23	7	10	7	78	55	11	24	19
Fut2Nat		Re-Naturalized		78	23	7	10	7	78	55	11	24	19

Trend Significance [binary]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0	0	0	0	0	0	0	0	0	0
CalibNat		Re-Naturalized		0	0	0	0	0	0	0	0	0	0
HistReg	GCM Ensemble	Regulated		0	**1**	**1**	**1**	**1**	0	**1**	**1**	**1**	**1**
HistNat		Re-Naturalized		0	**1**	**1**	**1**	**1**	0	**1**	**1**	**1**	**1**
Fut1Reg		Regulated	2021-2050	**1**	**1**	0	**1**	**1**	0	**1**	**1**	**1**	**1**
Fut1Nat		Re-Naturalized		**1**	**1**	0	**1**	**1**	0	**1**	**1**	**1**	**1**
Fut2Reg		Regulated	2041-2070	**1**	**1**	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Fut2Nat		Re-Naturalized		**1**	**1**	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**

(c) Snowfall [mm]				NCRB					LGRC				
Value [mm]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	55	29	0	34	118	123	84	2	87	296
CalibNat	GFD-Hydro	Re-Naturalized	1981-2010	55	29	0	34	118	123	84	2	87	296
HistReg	GCM Ensemble	Regulated	1981-2010	60	38	0	46	145	83	71	2	82	239
HistNat	GCM Ensemble	Re-Naturalized	1981-2010	60	38	0	46	145	83	71	2	82	239
Fut1Reg	GCM Ensemble	Regulated	2021-2050	65	33	0	41	139	93	70	1	75	239
Fut1Nat	GCM Ensemble	Re-Naturalized	2021-2050	65	33	0	41	139	93	70	1	75	239
Fut2Reg	GCM Ensemble	Regulated	2041-2070	70	33	0	39	143	104	71	1	72	248
Fut2Nat	GCM Ensemble	Re-Naturalized	2041-2070	70	33	0	39	143	104	71	1	72	248
Trend [mm/yr]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0.3	0.0	0.0	-0.1	0.2	-0.3	**-0.9**	0.0	-0.6	-1.7
CalibNat	GFD-Hydro	Re-Naturalized	1981-2010	0.3	0.0	0.0	-0.1	0.2	-0.3	**-0.9**	0.0	-0.6	-1.7
HistReg	GCM Ensemble	Regulated	1981-2010	**0.1**	0.0	**0.0**	-0.1	-0.1	**0.3**	0.0	**0.0**	-0.2	0.2
HistNat	GCM Ensemble	Re-Naturalized	1981-2010	**0.1**	0.0	**0.0**	-0.1	-0.1	**0.3**	0.0	**0.0**	-0.2	0.2
Fut1Reg	GCM Ensemble	Regulated	2021-2050	**0.2**	0.0	0.0	-0.1	0.2	**0.5**	0.1	0.0	-0.1	**0.4**
Fut1Nat	GCM Ensemble	Re-Naturalized	2021-2050	**0.2**	0.0	0.0	-0.1	0.2	**0.5**	0.1	0.0	-0.1	**0.4**
Fut2Reg	GCM Ensemble	Regulated	2041-2070	**0.3**	0.0	0.0	**-0.1**	0.2	**0.6**	0.1	**0.0**	**-0.2**	**0.5**
Fut2Nat	GCM Ensemble	Re-Naturalized	2041-2070	**0.3**	0.0	0.0	**-0.1**	0.2	**0.6**	0.1	**0.0**	**-0.2**	**0.5**
Absolute Change [mm]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
Model-State Analysis		HistNat - HistReg		0	0	0	0	0	0	0	0	0	0
Model-State Analysis		Fut1Nat - Fut1Reg		0	0	0	0	0	0	0	0	0	0
Model-State Analysis		Fut2Nat - Fut2Reg		0	0	0	0	0	0	0	0	0	0
Climate Change Analysis		Fut1Reg - HistReg		4	-5	0	-5	-5	10	-2	-1	-7	0
Climate Change Analysis		Fut1Nat - HistNat		4	-5	0	-5	-5	10	-2	-1	-7	0
Climate Change Analysis		Fut2Reg - HistReg		10	-5	0	-6	-2	20	0	-1	-11	8
Climate Change Analysis		Fut2Nat - HistNat		10	-5	0	-6	-2	20	0	-1	-11	8
GCM Bias Analysis		HistReg - CalibReg		5	9	0	12	27	-39	-13	0	-4	-56
GCM Bias Analysis		HistNat - CalibNat		5	9	0	12	27	-39	-13	0	-4	-56
Percent Change [%]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
Model-State Analysis		HistNat - HistReg		0	0	0	0	0	0	0	0	0	0
Model-State Analysis		Fut1Nat - Fut1Reg		0	0	0	0	0	0	0	0	0	0
Model-State Analysis		Fut2Nat - Fut2Reg		0	0	0	0	0	0	0	0	0	0
Climate Change Analysis		Fut1Reg - HistReg		7	-12	-51	-10	-4	12	-3	-49	-9	0
Climate Change Analysis		Fut1Nat - HistNat		7	-12	-51	-10	-4	12	-3	-49	-9	0
Climate Change Analysis		Fut2Reg - HistReg		16	-13	-55	-14	-1	24	0	-57	-13	3
Climate Change Analysis		Fut2Nat - HistNat		16	-13	-55	-14	-1	24	0	-57	-13	3
GCM Bias Analysis		HistReg - CalibReg		10	31	-48	36	23	-32	-15	-3	-5	-19
GCM Bias Analysis		HistNat - CalibNat		10	31	-48	36	23	-32	-15	-3	-5	-19
Inter-Annual COV [%]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	23	33	297	31	18	20	25	146	31	16
CalibNat	GFD-Hydro	Re-Naturalized	1981-2010	23	33	297	31	18	20	25	146	31	16
HistReg	GCM Ensemble	Regulated	1981-2010	5	6	75	7	3	7	5	31	6	3
HistNat	GCM Ensemble	Re-Naturalized	1981-2010	5	6	75	7	3	7	5	31	6	3
Fut1Reg	GCM Ensemble	Regulated	2021-2050	5	8	69	7	3	5	5	18	4	2
Fut1Nat	GCM Ensemble	Re-Naturalized	2021-2050	5	8	69	7	3	5	5	18	4	2
Fut2Reg	GCM Ensemble	Regulated	2041-2070	5	8	77	7	4	6	4	23	5	3
Fut2Nat	GCM Ensemble	Re-Naturalized	2041-2070	5	8	77	7	4	6	4	23	5	3
Inter-Scenario COV [%]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010										
CalibNat	GFD-Hydro	Re-Naturalized	1981-2010										
HistReg	GCM Ensemble	Regulated	1981-2010	4	7	84	9	6	14	6	51	7	5
HistNat	GCM Ensemble	Re-Naturalized	1981-2010	4	7	84	9	6	14	6	51	7	5
Fut1Reg	GCM Ensemble	Regulated	2021-2050	6	17	119	13	8	16	13	92	13	7
Fut1Nat	GCM Ensemble	Re-Naturalized	2021-2050	6	17	119	13	8	16	13	92	13	7
Fut2Reg	GCM Ensemble	Regulated	2041-2070	7	26	139	16	10	17	16	102	14	7
Fut2Nat	GCM Ensemble	Re-Naturalized	2041-2070	7	26	139	16	10	17	16	102	14	7
Trend Significance [binary]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0	0	0	0	0	0	**1**	0	0	0
CalibNat	GFD-Hydro	Re-Naturalized	1981-2010	0	0	0	0	0	0	**1**	0	0	0
HistReg	GCM Ensemble	Regulated	1981-2010	**1**	0	**1**	0	0	**1**	0	**1**	0	0
HistNat	GCM Ensemble	Re-Naturalized	1981-2010	**1**	0	**1**	0	0	**1**	0	**1**	0	0
Fut1Reg	GCM Ensemble	Regulated	2021-2050	**1**	0	0	0	0	**1**	0	0	0	**1**
Fut1Nat	GCM Ensemble	Re-Naturalized	2021-2050	**1**	0	0	0	0	**1**	0	0	0	**1**
Fut2Reg	GCM Ensemble	Regulated	2041-2070	**1**	0	0	**1**	0	**1**	0	**1**	**1**	**1**
Fut2Nat	GCM Ensemble	Re-Naturalized	2041-2070	**1**	0	0	**1**	0	**1**	0	**1**	**1**	**1**

(d) Air Temperature [°C]				NCRB					LGRC				
Value [°C]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	-15	2	16	3	1	-21	-6	12	1	-3
CalibNat	GFD-Hydro	Re-Naturalized	1981-2010	-15	2	16	3	1	-21	-6	12	1	-3
HistReg	GCM Ensemble	Regulated	1981-2010	-17	-1	15	1	-1	-22	-9	10	-2	-6
HistNat	GCM Ensemble	Re-Naturalized	1981-2010	-17	-1	15	1	-1	-22	-9	10	-2	-6
Fut1Reg	GCM Ensemble	Regulated	2021-2050	-15	1	17	3	1	-19	-6	11	-1	-4
Fut1Nat	GCM Ensemble	Re-Naturalized	2021-2050	-15	1	17	3	1	-19	-6	11	-1	-4
Fut2Reg	GCM Ensemble	Regulated	2041-2070	-13	2	18	4	3	-17	-5	12	1	-2
Fut2Nat	GCM Ensemble	Re-Naturalized	2041-2070	-13	2	18	4	3	-17	-5	12	1	-2

Trend [°C/yr]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0.0	0.0	0.0	0.1	0.0	**0.1**	0.1	**0.0**	**0.1**	**0.1**
CalibNat	GFD-Hydro	Re-Naturalized	1981-2010	0.0	0.0	0.0	0.1	0.0	**0.1**	0.1	**0.0**	**0.1**	**0.1**
HistReg	GCM Ensemble	Regulated	1981-2010	**0.1**	**0.0**	**0.0**	**0.0**	**0.0**	**0.1**	**0.1**	**0.0**	**0.0**	**0.1**
HistNat	GCM Ensemble	Re-Naturalized	1981-2010	**0.1**	**0.0**	**0.0**	**0.0**	**0.0**	**0.1**	**0.1**	**0.0**	**0.0**	**0.1**
Fut1Reg	GCM Ensemble	Regulated	2021-2050	**0.1**	**0.1**	**0.0**	**0.0**	**0.1**	**0.1**	**0.1**	**0.0**	**0.0**	**0.1**
Fut1Nat	GCM Ensemble	Re-Naturalized	2021-2050	**0.1**	**0.1**	**0.0**	**0.0**	**0.1**	**0.1**	**0.1**	**0.0**	**0.0**	**0.1**
Fut2Reg	GCM Ensemble	Regulated	2041-2070	**0.1**	**0.0**	**0.1**	**0.0**	**0.1**	**0.1**	**0.1**	**0.0**	**0.1**	**0.1**
Fut2Nat	GCM Ensemble	Re-Naturalized	2041-2070	**0.1**	**0.0**	**0.1**	**0.0**	**0.1**	**0.1**	**0.1**	**0.0**	**0.1**	**0.1**

Absolute Change [°C]		Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
Model-State Analysis	HistNat - HistReg	0	0	0	0	0	0	0	0	0	0
Model-State Analysis	Fut1Nat - Fut1Reg	0	0	0	0	0	0	0	0	0	0
Model-State Analysis	Fut2Nat - Fut2Reg	0	0	0	0	0	0	0	0	0	0
Climate Change Analysis	Fut1Reg - HistReg	2	2	2	2	2	3	2	2	2	2
Climate Change Analysis	Fut1Nat - HistNat	2	2	2	2	2	3	2	2	2	2
Climate Change Analysis	Fut2Reg - HistReg	4	3	3	3	3	5	4	2	3	4
Climate Change Analysis	Fut2Nat - HistNat	4	3	3	3	3	5	4	2	3	4
GCM Bias Analysis	HistReg - CalibReg	-3	-3	-1	-2	-2	-2	-3	-2	-3	-2
GCM Bias Analysis	HistNat - CalibNat	-3	-3	-1	-2	-2	-2	-3	-2	-3	-2

Percent Change [%]		Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
Model-State Analysis	HistNat - HistReg	0	0	0	0	0	0	0	0	0	0
Model-State Analysis	Fut1Nat - Fut1Reg	0	0	0	0	0	0	0	0	0	0
Model-State Analysis	Fut2Nat - Fut2Reg	0	0	0	0	0	0	0	0	0	0
Climate Change Analysis	Fut1Reg - HistReg	14	161	11	155	299	14	26	16	78	37
Climate Change Analysis	Fut1Nat - HistNat	14	161	11	155	299	14	26	16	78	37
Climate Change Analysis	Fut2Reg - HistReg	24	234	18	247	476	23	41	25	121	59
Climate Change Analysis	Fut2Nat - HistNat	24	234	18	247	476	23	41	25	121	59
GCM Bias Analysis	HistReg - CalibReg	-17	-193	-8	-61	-147	-8	-52	-19	-546	-71
GCM Bias Analysis	HistNat - CalibNat	-17	-193	-8	-61	-147	-8	-52	-19	-546	-71

Inter-Annual COV [%]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	-16	116	6	58	71	-12	-34	7	249	-38
CalibNat	GFD-Hydro	Re-Naturalized	1981-2010	-16	116	6	58	71	-12	-34	7	249	-38
HistReg	GCM Ensemble	Regulated	1981-2010	-4	-33	3	48	-70	-4	-6	4	-21	-9
HistNat	GCM Ensemble	Re-Naturalized	1981-2010	-4	-33	3	48	-70	-4	-6	4	-21	-9
Fut1Reg	GCM Ensemble	Regulated	2021-2050	-6	70	2	18	40	-5	-11	3	-94	-16
Fut1Nat	GCM Ensemble	Re-Naturalized	2021-2050	-6	70	2	18	40	-5	-11	3	-94	-16
Fut2Reg	GCM Ensemble	Regulated	2041-2070	-7	29	3	14	21	-6	-12	4	108	-25
Fut2Nat	GCM Ensemble	Re-Naturalized	2041-2070	-7	29	3	14	21	-6	-12	4	108	-25

Inter-Scenario COV [%]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010										
CalibNat	GFD-Hydro	Re-Naturalized	1981-2010										
HistReg	GCM Ensemble	Regulated	1981-2010	-6	-80	4	71	-122	-6	-25	16	-58	-27
HistNat	GCM Ensemble	Re-Naturalized	1981-2010	-6	-80	4	71	-122	-6	-25	16	-58	-27
Fut1Reg	GCM Ensemble	Regulated	2021-2050	-12	248	7	57	105	-11	-47	20	-375	-58
Fut1Nat	GCM Ensemble	Re-Naturalized	2021-2050	-12	248	7	57	105	-11	-47	20	-375	-58
Fut2Reg	GCM Ensemble	Regulated	2041-2070	-17	143	8	45	67	-14	-69	21	396	-101
Fut2Nat	GCM Ensemble	Re-Naturalized	2041-2070	-17	143	8	45	67	-14	-69	21	396	-101

Trend Significance [binary]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0	0	0	0	0	**1**	0	**1**	**1**	**1**
CalibNat	GFD-Hydro	Re-Naturalized	1981-2010	0	0	0	0	0	**1**	0	**1**	**1**	**1**
HistReg	GCM Ensemble	Regulated	1981-2010	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
HistNat	GCM Ensemble	Re-Naturalized	1981-2010	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Fut1Reg	GCM Ensemble	Regulated	2021-2050	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Fut1Nat	GCM Ensemble	Re-Naturalized	2021-2050	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Fut2Reg	GCM Ensemble	Regulated	2041-2070	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Fut2Nat	GCM Ensemble	Re-Naturalized	2041-2070	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**

(e) Actual Evapotranspiration [mm]				NCRB					LGRC				
Value [mm]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	4	98	251	52	405	2	48	240	54	343
CalibNat		Re-Naturalized		4	98	251	52	405	2	48	240	54	343
HistReg	GCM Ensemble	Regulated		4	89	261	56	410	2	41	189	44	276
HistNat		Re-Naturalized		4	89	261	56	410	2	41	189	44	275
Fut1Reg		Regulated	2021-2050	5	109	270	59	443	2	52	208	49	311
Fut1Nat		Re-Naturalized		5	109	270	59	443	2	52	208	49	311
Fut2Reg		Regulated	2041-2070	5	119	273	61	458	2	60	218	52	332
Fut2Nat		Re-Naturalized		5	119	273	61	458	2	60	218	52	332

Trend [mm/yr]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0.0	0.0	0.2	0.2	0.3	0.0	0.4	**0.8**	**0.3**	**1.5**
CalibNat		Re-Naturalized		0.0	0.0	0.2	0.2	0.3	0.0	0.4	**0.8**	**0.3**	**1.5**
HistReg	GCM Ensemble	Regulated		**0.0**	**0.4**	**0.4**	**0.1**	**0.9**	**0.0**	**0.2**	**0.5**	**0.1**	**0.9**
HistNat		Re-Naturalized		**0.0**	**0.4**	**0.4**	**0.1**	**0.9**	**0.0**	**0.2**	**0.5**	**0.1**	**0.9**
Fut1Reg		Regulated	2021-2050	**0.0**	**0.5**	0.1	0.1	**0.7**	**0.0**	**0.4**	**0.4**	**0.1**	**1.0**
Fut1Nat		Re-Naturalized		**0.0**	**0.5**	0.1	0.1	**0.7**	**0.0**	**0.4**	**0.4**	**0.1**	**1.0**
Fut2Reg		Regulated	2041-2070	**0.0**	**0.5**	**0.3**	**0.1**	**0.9**	**0.0**	**0.4**	**0.5**	**0.2**	**1.1**
Fut2Nat		Re-Naturalized		**0.0**	**0.5**	**0.3**	**0.1**	**0.9**	**0.0**	**0.4**	**0.5**	**0.2**	**1.1**

Absolute Change [mm]		Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
Model-State Analysis	HistNat - HistReg	0	0	0	0	0	0	0	0	0	0
	Fut1Nat - Fut1Reg	0	0	0	0	0	0	0	0	0	0
	Fut2Nat - Fut2Reg	0	0	0	0	0	0	0	0	0	0
Climate Change Analysis	Fut1Reg - HistReg	0	20	9	4	33	0	11	19	5	35
	Fut1Nat - HistNat	0	20	10	4	34	0	11	19	5	36
	Fut2Reg - HistReg	1	30	12	5	48	1	18	28	9	56
	Fut2Nat - HistNat	1	30	12	5	48	1	19	29	9	56
GCM Bias Analysis	HistReg - CalibReg	0	-9	10	3	5	0	-7	-50	-10	-67
	HistNat - CalibNat	0	-9	10	3	4	0	-7	-50	-10	-68

Percent Change [%]		Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
Model-State Analysis	HistNat - HistReg	0	0	0	0	0	0	-1	0	0	0
	Fut1Nat - Fut1Reg	0	0	0	0	0	0	0	0	0	0
	Fut2Nat - Fut2Reg	0	0	0	0	0	0	0	0	0	0
Climate Change Analysis	Fut1Reg - HistReg	12	22	4	6	8	20	26	10	12	13
	Fut1Nat - HistNat	12	22	4	6	8	20	26	10	12	13
	Fut2Reg - HistReg	20	33	5	9	12	38	45	15	20	20
	Fut2Nat - HistNat	20	33	5	9	12	38	45	15	20	21
GCM Bias Analysis	HistReg - CalibReg	6	-9	4	7	1	-9	-14	-21	-19	-20
	HistNat - CalibNat	6	-9	4	7	1	-9	-14	-21	-19	-20

Inter-Annual COV [%]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	10	14	5	9	5	25	20	7	9	8
CalibNat		Re-Naturalized		10	14	5	9	5	25	20	7	9	8
HistReg	GCM Ensemble	Regulated		5	4	2	3	2	5	5	3	4	3
HistNat		Re-Naturalized		5	4	2	3	2	5	5	3	4	3
Fut1Reg		Regulated	2021-2050	5	5	1	2	2	7	7	2	3	3
Fut1Nat		Re-Naturalized		5	5	1	2	2	7	7	2	3	3
Fut2Reg		Regulated	2041-2070	4	4	1	3	2	7	7	2	4	3
Fut2Nat		Re-Naturalized		4	4	1	3	2	7	7	2	4	3

Inter-Scenario COV [%]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010										
CalibNat		Re-Naturalized											
HistReg	GCM Ensemble	Regulated		4	7	3	3	4	8	16	16	12	15
HistNat		Re-Naturalized		4	7	3	3	4	8	16	16	12	15
Fut1Reg		Regulated	2021-2050	7	15	3	6	5	12	33	15	15	17
Fut1Nat		Re-Naturalized		7	15	3	6	5	12	33	15	15	17
Fut2Reg		Regulated	2041-2070	7	18	4	7	6	16	41	14	14	18
Fut2Nat		Re-Naturalized		7	19	4	7	6	16	41	14	14	18

Trend Significance [binary]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0	0	0	0	0	0	0	**1**	**1**	**1**
CalibNat		Re-Naturalized		0	0	0	0	0	0	0	**1**	**1**	**1**
HistReg	GCM Ensemble	Regulated		**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
HistNat		Re-Naturalized		**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Fut1Reg		Regulated	2021-2050	**1**	**1**	0	0	**1**	**1**	**1**	**1**	**1**	**1**
Fut1Nat		Re-Naturalized		**1**	**1**	0	0	**1**	**1**	**1**	**1**	**1**	**1**
Fut2Reg		Regulated	2041-2070	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Fut2Nat		Re-Naturalized		**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**

(f) Snow-Water Equivalent [mm]	NCRB	LGRC

Value [mm]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	47	32	0	6	21	129	168	5	15	79
CalibNat		Re-Naturalized		47	32	0	6	21	129	168	5	15	79
HistReg	GCM Ensemble	Regulated		65	53	0	9	32	113	148	10	21	73
HistNat		Re-Naturalized		65	53	0	9	32	113	148	10	21	73
Fut1Reg		Regulated	2021-2050	63	45	0	7	29	111	141	7	17	69
Fut1Nat		Re-Naturalized		63	45	0	7	29	111	141	7	17	69
Fut2Reg		Regulated	2041-2070	63	45	0	7	29	112	143	6	15	69
Fut2Nat		Re-Naturalized		63	45	0	7	29	112	143	6	15	69

Trend [mm/yr]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0.0	0.1	**0.0**	0.0	0.0	-0.7	**-1.7**	-0.1	-0.2	**-0.7**
CalibNat		Re-Naturalized		0.0	0.1	**0.0**	0.0	0.0	-0.7	**-1.7**	-0.1	-0.2	**-0.7**
HistReg	GCM Ensemble	Regulated		-0.1	-0.1	0.0	**-0.1**	-0.1	0.1	0.1	-0.1	**-0.1**	0.0
HistNat		Re-Naturalized		-0.1	-0.1	0.0	**-0.1**	-0.1	0.1	0.1	-0.1	**-0.1**	0.0
Fut1Reg		Regulated	2021-2050	0.0	0.0	0.0	0.0	0.0	**0.1**	0.1	0.0	**-0.1**	0.0
Fut1Nat		Re-Naturalized		0.0	0.0	0.0	0.0	0.0	**0.1**	0.1	0.0	**-0.1**	0.0
Fut2Reg		Regulated	2041-2070	-0.1	0.0	0.0	**0.0**	0.0	0.0	0.0	0.0	**-0.1**	0.0
Fut2Nat		Re-Naturalized		-0.1	0.0	0.0	**0.0**	0.0	0.0	0.0	0.0	**-0.1**	0.0

Absolute Change [mm]		NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
Model-State Analysis	HistNat - HistReg	0	0	0	0	0	0	0	0	0	0
	Fut1Nat - Fut1Reg	0	0	0	0	0	0	0	0	0	0
	Fut2Nat - Fut2Reg	0	0	0	0	0	0	0	0	0	0
Climate Change Analysis	Fut1Reg - HistReg	-2	-8	0	-2	-3	-2	-7	-3	-4	-4
	Fut1Nat - HistNat	-2	-8	0	-2	-3	-2	-7	-3	-4	-4
	Fut2Reg - HistReg	-2	-9	0	-2	-3	-1	-5	-4	-6	-4
	Fut2Nat - HistNat	-2	-9	0	-2	-3	-1	-5	-4	-6	-4
GCM Bias Analysis	HistReg - CalibReg	18	22	0	3	11	-17	-20	5	6	-6
	HistNat - CalibNat	18	22	0	3	11	-17	-20	5	6	-6

Percent Change [%]		NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
Model-State Analysis	HistNat - HistReg	0	0	0	0	0	0	0	0	0	0
	Fut1Nat - Fut1Reg	0	0	0	0	0	0	0	0	0	0
	Fut2Nat - Fut2Reg	0	0	0	0	0	0	0	0	0	0
Climate Change Analysis	Fut1Reg - HistReg	-3	-15	-56	-18	-9	-2	-4	-34	-19	-6
	Fut1Nat - HistNat	-3	-15	-56	-18	-9	-2	-4	-34	-19	-6
	Fut2Reg - HistReg	-3	-17	-59	-27	-11	-1	-3	-39	-29	-5
	Fut2Nat - HistNat	-3	-17	-59	-27	-11	-1	-3	-39	-29	-5
GCM Bias Analysis	HistReg - CalibReg	38	69	170	60	51	-13	-12	106	38	-8
	HistNat - CalibNat	38	69	170	60	51	-13	-12	106	38	-8

Inter-Annual COV [%]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	18	35	130	48	21	18	23	97	49	20
CalibNat		Re-Naturalized		18	35	130	48	21	18	23	97	49	20
HistReg	GCM Ensemble	Regulated		4	7	38	11	5	3	5	18	8	4
HistNat		Re-Naturalized		4	7	38	11	5	3	5	18	8	4
Fut1Reg		Regulated	2021-2050	4	7	35	11	4	3	3	15	8	3
Fut1Nat		Re-Naturalized		4	7	35	11	4	3	3	15	8	3
Fut2Reg		Regulated	2041-2070	4	8	42	11	5	2	4	16	9	3
Fut2Nat		Re-Naturalized		4	8	42	11	5	2	4	16	9	3

Inter-Scenario COV [%]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010										
CalibNat		Re-Naturalized											
HistReg	GCM Ensemble	Regulated		8	12	62	15	10	4	6	47	18	6
HistNat		Re-Naturalized		8	12	62	15	10	4	6	47	18	6
Fut1Reg		Regulated	2021-2050	11	22	115	27	15	6	11	80	30	10
Fut1Nat		Re-Naturalized		11	22	115	27	15	6	11	80	30	10
Fut2Reg		Regulated	2041-2070	14	29	122	32	18	6	14	94	34	11
Fut2Nat		Re-Naturalized		14	29	122	32	18	6	14	94	34	11

Trend Significance [binary]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0	0	**1**	0	0	0	**1**	0	0	**1**
CalibNat		Re-Naturalized		0	0	**1**	0	0	0	**1**	0	0	**1**
HistReg	GCM Ensemble	Regulated		0	0	0	**1**	0	0	0	0	**1**	0
HistNat		Re-Naturalized		0	0	0	**1**	0	0	0	0	**1**	0
Fut1Reg		Regulated	2021-2050	0	0	0	0	0	**1**	0	0	**1**	0
Fut1Nat		Re-Naturalized		0	0	0	0	0	**1**	0	0	**1**	0
Fut2Reg		Regulated	2041-2070	0	0	0	**1**	0	0	0	0	**1**	0
Fut2Nat		Re-Naturalized		0	0	0	**1**	0	0	0	0	**1**	0

(g) Runoff [mm]

Value [mm]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	4	49	31	17	100	11	173	136	95	415
CalibNat		Re-Naturalized		4	49	31	17	100	11	173	136	95	415
HistReg	GCM Ensemble	Regulated		2	49	35	11	97	3	86	140	37	267
HistNat		Re-Naturalized		2	49	35	11	97	3	86	140	37	267
Fut1Reg		Regulated	2021-2050	3	52	27	12	95	5	112	113	47	277
Fut1Nat		Re-Naturalized		3	52	27	12	95	5	112	113	47	277
Fut2Reg		Regulated	2041-2070	4	55	27	13	99	7	128	106	53	294
Fut2Nat		Re-Naturalized		4	55	27	13	99	7	128	106	53	294

Trend [mm/yr]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0.0	0.2	0.3	0.2	0.7	0.1	-0.3	**-1.8**	0.2	-1.7
CalibNat		Re-Naturalized		0.0	0.2	0.3	0.2	0.7	0.1	-0.3	**-1.8**	0.2	-1.7
HistReg	GCM Ensemble	Regulated		**0.0**	**0.2**	0.0	**0.1**	0.3	**0.0**	**0.6**	**-0.4**	**0.2**	**0.5**
HistNat		Re-Naturalized		**0.0**	**0.2**	0.0	**0.1**	0.3	**0.0**	**0.6**	**-0.4**	**0.2**	**0.5**
Fut1Reg		Regulated	2021-2050	**0.0**	**0.2**	-0.1	0.0	0.1	**0.1**	**0.8**	**-0.4**	**0.3**	**0.8**
Fut1Nat		Re-Naturalized		**0.0**	**0.2**	-0.1	0.0	0.1	**0.1**	**0.8**	**-0.4**	**0.3**	**0.8**
Fut2Reg		Regulated	2041-2070	**0.1**	**0.2**	0.0	**0.1**	**0.5**	**0.1**	**0.8**	**-0.4**	**0.5**	**1.1**
Fut2Nat		Re-Naturalized		**0.1**	**0.2**	0.0	**0.1**	**0.5**	**0.1**	**0.8**	**-0.4**	**0.5**	**1.1**

Absolute Change [mm]		NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
Model-State Analysis	HistNat - HistReg	0	0	0	0	0	0	0	0	0	0
	Fut1Nat - Fut1Reg	0	0	0	0	0	0	0	0	0	0
	Fut2Nat - Fut2Reg	0	0	0	0	0	0	0	0	0	0
Climate Change Analysis	Fut1Reg - HistReg	1	3	-7	1	-3	2	26	-27	9	10
	Fut1Nat - HistNat	1	3	-7	1	-3	2	26	-27	9	10
	Fut2Reg - HistReg	2	6	-8	2	2	4	41	-34	16	27
	Fut2Nat - HistNat	2	6	-8	2	2	4	41	-34	16	27
GCM Bias Analysis	HistReg - CalibReg	-2	0	4	-6	-3	-8	-87	4	-57	-148
	HistNat - CalibNat	-2	0	4	-6	-3	-8	-87	4	-57	-148

Percent Change [%]		NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
Model-State Analysis	HistNat - HistReg	0	0	0	0	0	0	0	0	0	0
	Fut1Nat - Fut1Reg	0	0	0	0	0	0	0	0	0	0
	Fut2Nat - Fut2Reg	0	0	0	0	0	0	0	0	0	0
Climate Change Analysis	Fut1Reg - HistReg	53	6	-21	8	-3	79	30	-19	25	4
	Fut1Nat - HistNat	53	6	-21	8	-3	79	30	-19	25	4
	Fut2Reg - HistReg	114	12	-23	16	2	138	48	-24	43	10
	Fut2Nat - HistNat	114	12	-23	16	2	138	48	-24	43	10
GCM Bias Analysis	HistReg - CalibReg	-44	1	14	-35	-3	-73	-50	3	-61	-36
	HistNat - CalibNat	-44	1	14	-35	-3	-73	-50	3	-61	-36

Inter-Annual COV [%]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	43	26	29	39	23	48	21	38	27	16
CalibNat		Re-Naturalized		43	26	29	39	23	48	21	38	27	16
HistReg	GCM Ensemble	Regulated		14	7	9	12	6	16	9	6	11	3
HistNat		Re-Naturalized		14	7	9	12	6	16	9	6	11	3
Fut1Reg		Regulated	2021-2050	13	7	7	12	5	15	8	7	9	3
Fut1Nat		Re-Naturalized		13	7	7	12	5	15	8	7	9	3
Fut2Reg		Regulated	2041-2070	21	7	7	11	6	18	6	7	12	4
Fut2Nat		Re-Naturalized		21	7	7	11	6	18	6	7	12	4

Inter-Scenario COV [%]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010										
CalibNat		Re-Naturalized											
HistReg	GCM Ensemble	Regulated		10	9	17	9	11	34	34	20	25	9
HistNat		Re-Naturalized		10	9	17	9	11	34	34	20	25	9
Fut1Reg		Regulated	2021-2050	19	13	28	16	15	58	32	38	33	12
Fut1Nat		Re-Naturalized		19	13	28	16	15	58	32	38	33	12
Fut2Reg		Regulated	2041-2070	28	15	35	22	18	58	34	46	33	14
Fut2Nat		Re-Naturalized		28	15	35	22	18	58	34	46	33	14

Trend Significance [binary]				NCRB Winter	NCRB Spring	NCRB Summer	NCRB Autumn	NCRB Yearly	LGRC Winter	LGRC Spring	LGRC Summer	LGRC Autumn	LGRC Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0	0	0	0	0	0	0	**1**	0	0
CalibNat		Re-Naturalized		0	0	0	0	0	0	0	**1**	0	0
HistReg	GCM Ensemble	Regulated		**1**	**1**	0	**1**	0	**1**	**1**	**1**	**1**	**1**
HistNat		Re-Naturalized		**1**	**1**	0	**1**	0	**1**	**1**	**1**	**1**	**1**
Fut1Reg		Regulated	2021-2050	**1**	**1**	0	0	0	**1**	**1**	**1**	**1**	**1**
Fut1Nat		Re-Naturalized		**1**	**1**	0	0	0	**1**	**1**	**1**	**1**	**1**
Fut2Reg		Regulated	2041-2070	**1**	**1**	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Fut2Nat		Re-Naturalized		**1**	**1**	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**

(h) Groundwater Level [m]				NCRB					LGRC				
Value [m]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	-2.3	-2.1	-2.2	-2.2	-2.2	-1.5	-1.2	-1.2	-1.3	-1.3
CalibNat		Re-Naturalized		-2.3	-2.1	-2.2	-2.2	-2.2	-1.5	-1.2	-1.2	-1.3	-1.3
HistReg	GCM Ensemble	Regulated		-2.3	-2.1	-2.2	-2.3	-2.2	-1.5	-1.3	-1.2	-1.4	-1.4
HistNat		Re-Naturalized		-2.3	-2.1	-2.2	-2.3	-2.2	-1.5	-1.3	-1.2	-1.4	-1.4
Fut1Reg		Regulated	2021-2050	-2.3	-2.1	-2.2	-2.2	-2.2	-1.5	-1.3	-1.3	-1.4	-1.4
Fut1Nat		Re-Naturalized		-2.3	-2.1	-2.2	-2.2	-2.2	-1.5	-1.3	-1.3	-1.4	-1.4
Fut2Reg		Regulated	2041-2070	-2.2	-2.0	-2.1	-2.2	-2.1	-1.5	-1.3	-1.3	-1.4	-1.4
Fut2Nat		Re-Naturalized		-2.2	-2.0	-2.1	-2.2	-2.1	-1.5	-1.3	-1.3	-1.4	-1.4

Trend [m/yr]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	**0.007**	**0.008**	**0.008**	**0.008**	**0.008**	0.000	0.000	**-0.003**	0.000	-0.001
CalibNat		Re-Naturalized		**0.007**	**0.008**	**0.008**	**0.008**	**0.008**	0.000	0.000	**-0.003**	0.000	-0.001
HistReg	GCM Ensemble	Regulated		**0.004**	**0.005**	**0.004**	**0.004**	**0.004**	**0.000**	**0.001**	**-0.001**	**0.001**	**0.000**
HistNat		Re-Naturalized		**0.004**	**0.005**	**0.004**	**0.004**	**0.004**	**0.000**	**0.001**	**-0.001**	**0.001**	**0.000**
Fut1Reg		Regulated	2021-2050	**0.005**	**0.006**	**0.005**	**0.005**	**0.005**	**0.000**	**0.001**	**-0.001**	**0.001**	**0.000**
Fut1Nat		Re-Naturalized		**0.005**	**0.006**	**0.005**	**0.005**	**0.005**	**0.000**	**0.001**	**-0.001**	**0.001**	**0.000**
Fut2Reg		Regulated	2041-2070	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.000**	**0.001**	**-0.001**	**0.001**	**0.001**
Fut2Nat		Re-Naturalized		**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.000**	**0.001**	**-0.001**	**0.001**	**0.001**

Absolute Change [m]		Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
Model-State Analysis	HistNat - HistReg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Fut1Nat - Fut1Reg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Fut2Nat - Fut2Reg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Climate Change Analysis	Fut1Reg - HistReg	0.02	0.02	-0.01	0.02	0.01	0.01	0.05	-0.06	0.02	0.00
	Fut1Nat - HistNat	0.02	0.02	-0.01	0.02	0.01	0.01	0.05	-0.06	0.02	0.00
	Fut2Reg - HistReg	0.10	0.11	0.06	0.09	0.09	0.01	0.07	-0.07	0.04	0.01
	Fut2Nat - HistNat	0.10	0.11	0.06	0.09	0.09	0.01	0.07	-0.07	0.04	0.01
GCM Bias Analysis	HistReg - CalibReg	-0.04	-0.02	-0.02	-0.06	-0.04	-0.02	-0.15	0.00	-0.14	-0.08
	HistNat - CalibNat	-0.04	-0.02	-0.02	-0.06	-0.04	-0.02	-0.15	0.00	-0.14	-0.08

Percent Change [%]		Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
Model-State Analysis	HistNat - HistReg	0	0	0	0	0	0	0	0	0	0
	Fut1Nat - Fut1Reg	0	0	0	0	0	0	0	0	0	0
	Fut2Nat - Fut2Reg	0	0	0	0	0	0	0	0	0	0
Climate Change Analysis	Fut1Reg - HistReg	1	1	-1	1	0	0	3	-5	2	0
	Fut1Nat - HistNat	1	1	-1	1	0	0	3	-5	2	0
	Fut2Reg - HistReg	4	5	3	4	4	1	6	-6	3	1
	Fut2Nat - HistNat	4	5	3	4	4	1	6	-6	3	1
GCM Bias Analysis	HistReg - CalibReg	-2	-1	-1	-3	-2	-2	-12	0	-10	-6
	HistNat - CalibNat	-2	-1	-1	-3	-2	-2	-12	0	-10	-6

Inter-Annual COV [%]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	-3	-4	-4	-3	-3	-1	-5	-8	-5	-2
CalibNat		Re-Naturalized		-3	-4	-4	-3	-3	-1	-5	-8	-5	-2
HistReg	GCM Ensemble	Regulated		-2	-2	-2	-2	-2	0	-1	-1	-1	0
HistNat		Re-Naturalized		-2	-2	-2	-2	-2	0	-1	-1	-1	0
Fut1Reg		Regulated	2021-2050	-2	-2	-2	-2	-2	0	-1	-1	-1	0
Fut1Nat		Re-Naturalized		-2	-2	-2	-2	-2	0	-1	-1	-1	0
Fut2Reg		Regulated	2041-2070	-1	-2	-1	-1	-1	0	-1	-1	-1	0
Fut2Nat		Re-Naturalized		-1	-2	-1	-1	-1	0	-1	-1	-1	0

Inter-Scenario COV [%]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010										
CalibNat		Re-Naturalized											
HistReg	GCM Ensemble	Regulated		-1	-2	-2	-2	-2	0	-4	-5	-2	-1
HistNat		Re-Naturalized		-1	-2	-2	-2	-2	0	-4	-5	-2	-1
Fut1Reg		Regulated	2021-2050	-1	-3	-3	-2	-2	-1	-5	-7	-3	-1
Fut1Nat		Re-Naturalized		-1	-3	-3	-2	-2	-1	-5	-7	-3	-1
Fut2Reg		Regulated	2041-2070	-1	-2	-2	-1	-2	-1	-6	-8	-3	-2
Fut2Nat		Re-Naturalized		-1	-2	-2	-1	-2	-1	-6	-8	-3	-2

Trend Significance [binary]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	**1**	**1**	**1**	**1**	**1**	0	0	**1**	0	0
CalibNat		Re-Naturalized		**1**	**1**	**1**	**1**	**1**	0	0	**1**	0	0
HistReg	GCM Ensemble	Regulated		**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
HistNat		Re-Naturalized		**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Fut1Reg		Regulated	2021-2050	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Fut1Nat		Re-Naturalized		**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Fut2Reg		Regulated	2041-2070	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Fut2Nat		Re-Naturalized		**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**

(i) Discharge [m³/s]				NCRB					LGRC				
Value [m³/s]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	3350	3597	3604	3297	3462	4386	4654	4488	4020	4387
CalibNat		Re-Naturalized		3191	3199	3620	3472	3371	3299	4225	5430	4205	4290
HistReg	GCM Ensemble	Regulated		3352	3488	3757	3361	3490	3142	2624	3193	2254	2803
HistNat		Re-Naturalized		3314	3187	3652	3508	3415	2074	2316	3988	2590	2742
Fut1Reg		Regulated	2021-2050	3192	3433	3582	3192	3350	3166	2986	3030	2384	2891
Fut1Nat		Re-Naturalized		3164	3116	3454	3339	3268	2173	2651	3827	2661	2828
Fut2Reg		Regulated	2041-2070	3320	3591	3765	3357	3508	3282	3308	3072	2527	3047
Fut2Nat		Re-Naturalized		3290	3257	3588	3483	3404	2312	2956	3904	2813	2996

Trend [m³/s/yr]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	18	16	15	25	19	-15	-2	-35	-11	-16
CalibNat		Re-Naturalized		24	22	22	34	25	-9	-1	-38	-11	-15
HistReg	GCM Ensemble	Regulated		19	19	18	18	18	1	5	0	4	3
HistNat		Re-Naturalized		15	16	14	14	15	4	9	3	4	5
Fut1Reg		Regulated	2021-2050	8	9	9	8	9	3	11	0	6	5
Fut1Nat		Re-Naturalized		5	6	5	5	5	6	14	3	7	8
Fut2Reg		Regulated	2041-2070	12	13	16	16	14	10	21	2	10	11
Fut2Nat		Re-Naturalized		14	14	15	16	15	9	17	4	11	10

Absolute Change [m³/s]		Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
Model-State Analysis	HistNat - HistReg	-39	-301	-105	147	-75	-1068	-308	794	336	-61
	Fut1Nat - Fut1Reg	-28	-316	-128	147	-81	-992	-335	797	276	-64
	Fut2Nat - Fut2Reg	-30	-335	-177	126	-104	-970	-352	832	286	-51
Climate Change Analysis	Fut1Reg - HistReg	-160	-56	-176	-169	-140	24	362	-163	130	88
	Fut1Nat - HistNat	-149	-71	-198	-169	-147	99	334	-160	71	86
	Fut2Reg - HistReg	-32	103	8	-4	19	140	684	-121	273	244
	Fut2Nat - HistNat	-24	69	-64	-25	-11	238	640	-83	223	254
GCM Bias Analysis	HistReg - CalibReg	3	-109	153	65	28	-1244	-2030	-1295	-1766	-1584
	HistNat - CalibNat	123	-11	32	36	45	-1225	-1909	-1442	-1615	-1548

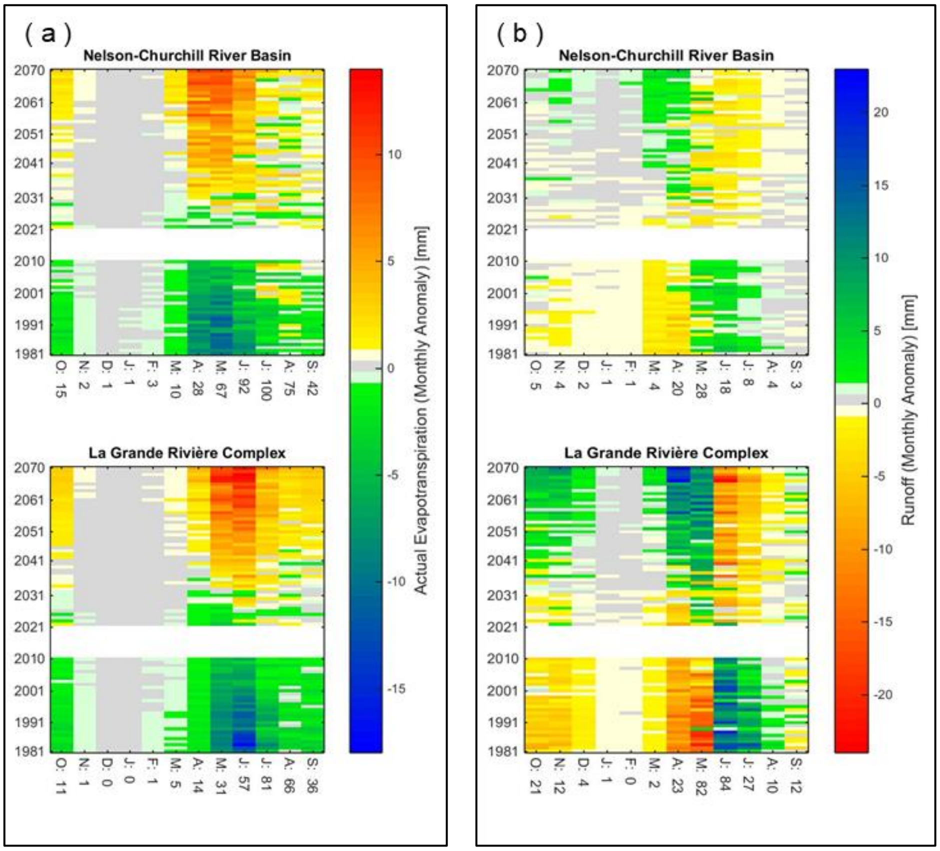
Percent Change [%]		Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
Model-State Analysis	HistNat - HistReg	-1	-9	-3	4	-2	-34	-12	25	15	-2
	Fut1Nat - Fut1Reg	-1	-9	-4	5	-2	-31	-11	26	12	-2
	Fut2Nat - Fut2Reg	-1	-9	-5	4	-3	-30	-11	27	11	-2
Climate Change Analysis	Fut1Reg - HistReg	-5	-2	-5	-5	-4	1	14	-5	6	3
	Fut1Nat - HistNat	-5	-2	-5	-5	-4	5	14	-4	3	3
	Fut2Reg - HistReg	-1	3	0	0	1	4	26	-4	12	9
	Fut2Nat - HistNat	-1	2	-2	-1	0	11	28	-2	9	9
GCM Bias Analysis	HistReg - CalibReg	0	-3	4	2	1	-28	-44	-29	-44	-36
	HistNat - CalibNat	4	0	1	1	1	-37	-45	-27	-38	-36

Inter-Annual COV [%]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	19	19	22	25	20	11	13	22	16	12
CalibNat		Re-Naturalized		22	24	22	25	22	10	14	20	15	12
HistReg	GCM Ensemble	Regulated		7	6	7	7	7	2	7	3	3	2
HistNat		Re-Naturalized		7	7	7	7	7	2	5	3	3	3
Fut1Reg		Regulated	2021-2050	4	4	4	4	4	2	6	2	3	2
Fut1Nat		Re-Naturalized		3	4	3	3	3	3	5	2	3	3
Fut2Reg		Regulated	2041-2070	4	4	5	6	5	3	6	3	5	3
Fut2Nat		Re-Naturalized		5	5	5	5	5	4	5	3	4	3

Inter-Scenario COV [%]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010										
CalibNat		Re-Naturalized											
HistReg	GCM Ensemble	Regulated		12	11	13	14	12	5	26	12	8	8
HistNat		Re-Naturalized		13	12	13	13	13	10	19	9	9	9
Fut1Reg		Regulated	2021-2050	18	15	18	19	17	9	25	17	15	12
Fut1Nat		Re-Naturalized		20	17	18	19	18	14	21	15	14	13
Fut2Reg		Regulated	2041-2070	23	19	24	24	22	11	24	18	19	14
Fut2Nat		Re-Naturalized		25	22	23	24	23	16	24	18	17	14

Trend Significance [binary]				Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
CalibReg	GFD-Hydro	Regulated	1981-2010	0	0	0	0	0	0	0	0	0	0
CalibNat		Re-Naturalized		0	0	0	0	0	0	0	1	0	0
HistReg	GCM Ensemble	Regulated		1	1	1	1	1	0	0	0	1	0
HistNat		Re-Naturalized		1	1	1	1	1	1	1	0	1	1
Fut1Reg		Regulated	2021-2050	1	1	1	1	1	0	1	0	1	1
Fut1Nat		Re-Naturalized		1	1	0	1	1	1	1	0	1	1
Fut2Reg		Regulated	2041-2070	1	1	1	1	1	1	1	0	1	1
Fut2Nat		Re-Naturalized		1	1	1	1	1	1	1	1	1	1

6.7 Appendix G: Heatmaps of Monthly Anomaly for Regulated Basins



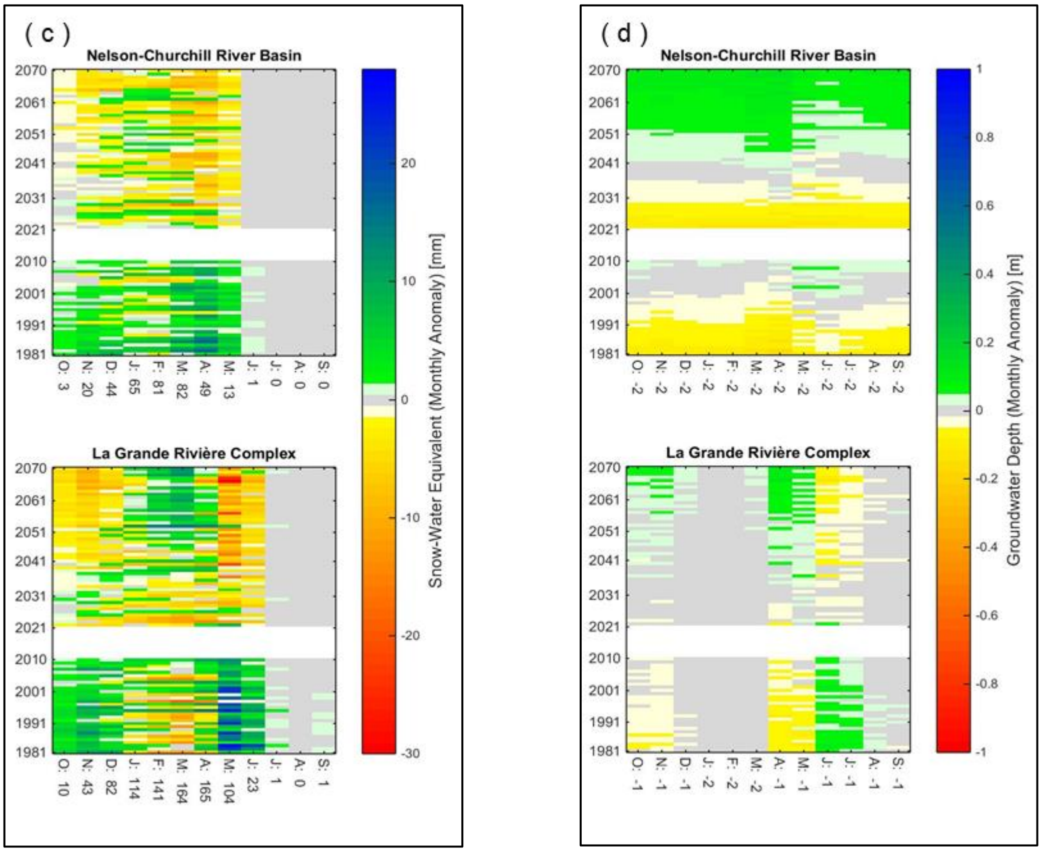
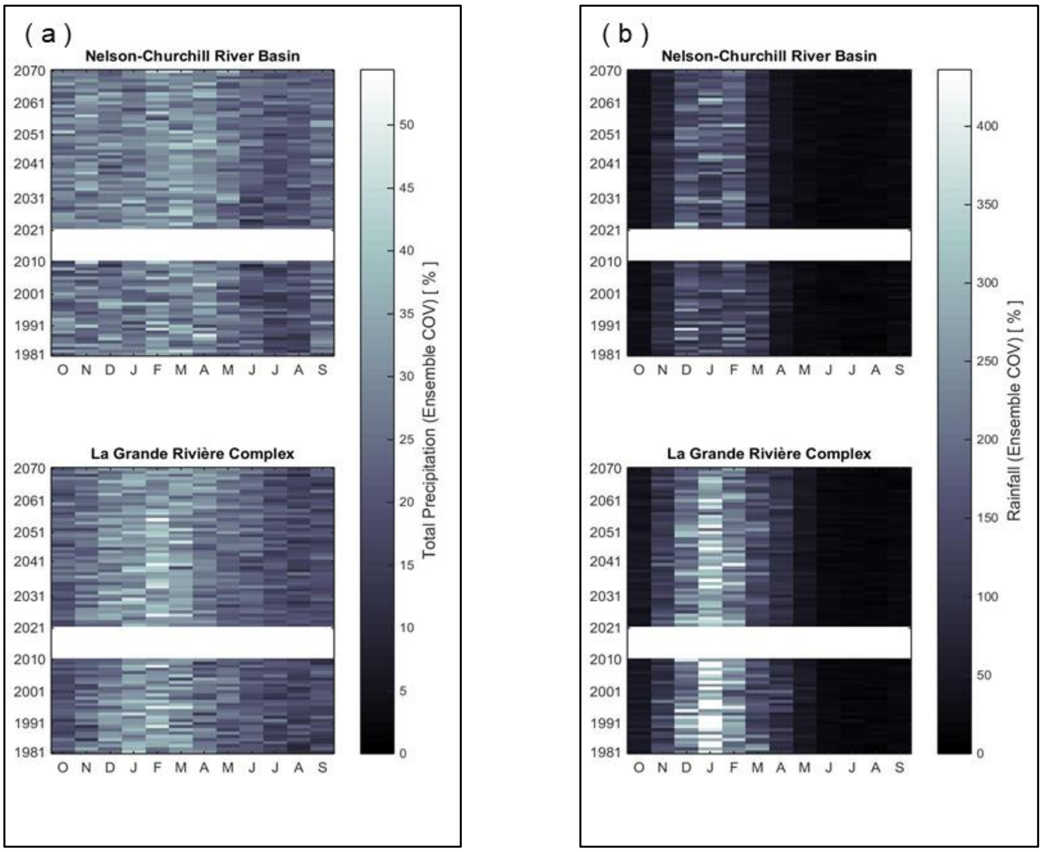
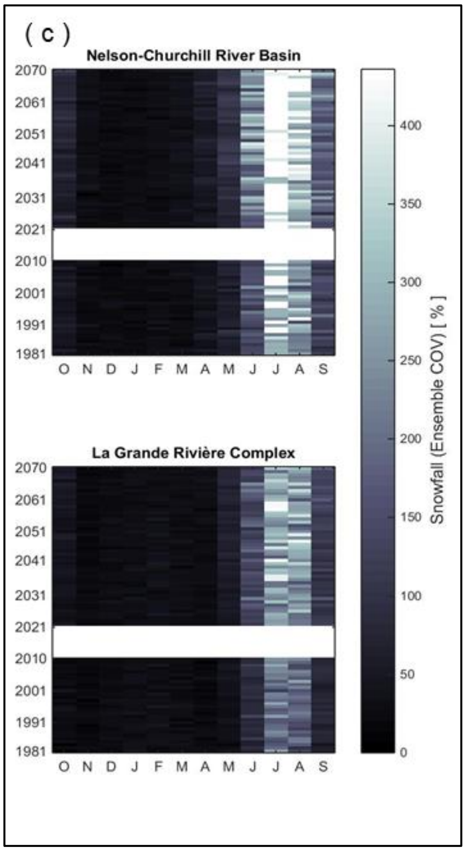
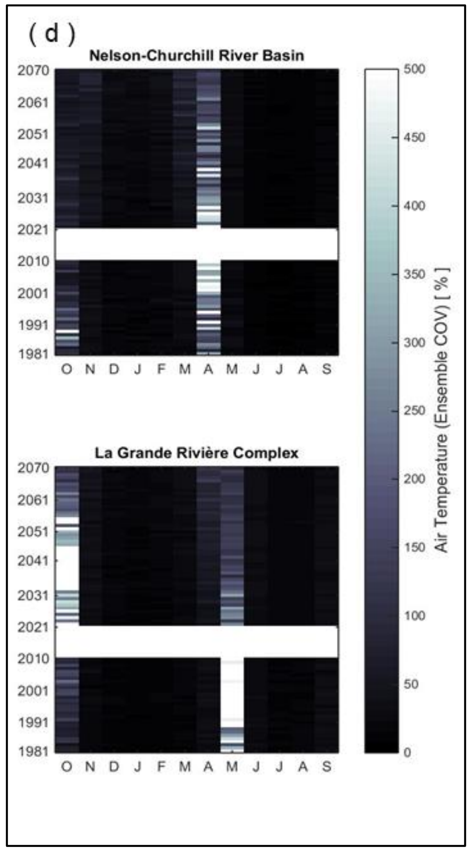


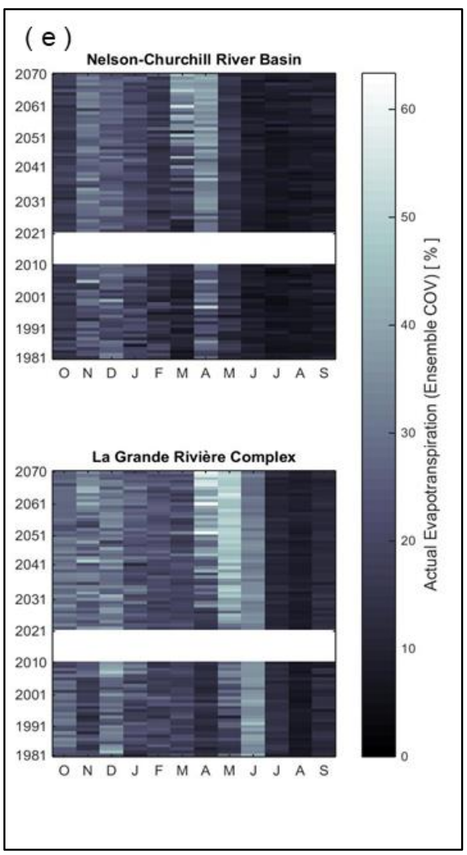
Figure G-1: *Anomaly maps by year and month for NCRB (top) and LGRC (bottom) for different variables; anomaly relative to monthly average (1981-2010, 2021-2070), shown below each month.*

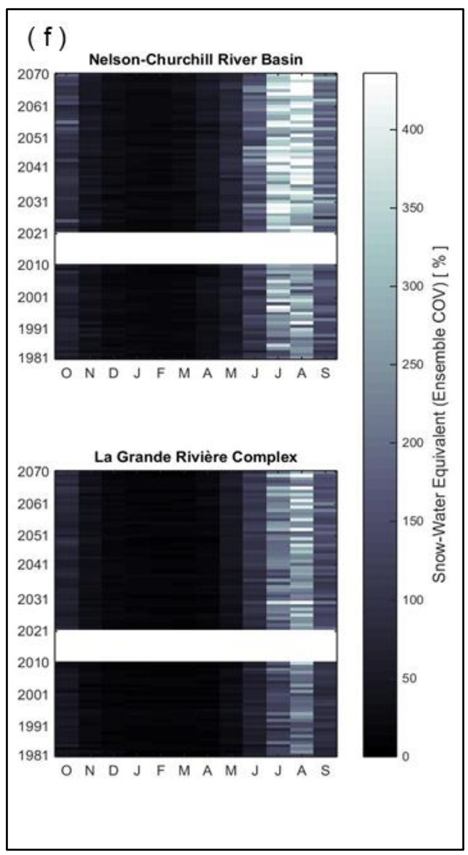
6.8 Appendix H: Heatmaps of Monthly Inter-Scenario COV for Regulated Basins




(c)
Nelson-Churchill River Basin
La Grande Rivière Complex
2070 2061 2051 2041 2031 2021 2010 2001 1991 1981
O N D J F M A M J J A S
Snowfall (Ensemble COV) [%]
0 50 100 150 200 250 300 350 400


(d)
Nelson-Churchill River Basin
La Grande Rivière Complex
2070 2061 2051 2041 2031 2021 2010 2001 1991 1981
O N D J F M A M J J A S
Air Temperature (Ensemble COV) [%]
0 50 100 150 200 250 300 350 400 450 500


(e)
Nelson-Churchill River Basin
La Grande Rivière Complex
2070 2061 2051 2041 2031 2021 2010 2001 1991 1981
O N D J F M A M J J A S
Actual Evapotranspiration (Ensemble COV) [%]
0 10 20 30 40 50 60


(f)
Nelson-Churchill River Basin
La Grande Rivière Complex
2070 2061 2051 2041 2031 2021 2010 2001 1991 1981
O N D J F M A M J J A S
Snow-Water Equivalent (Ensemble COV) [%]
0 50 100 150 200 250 300 350 400

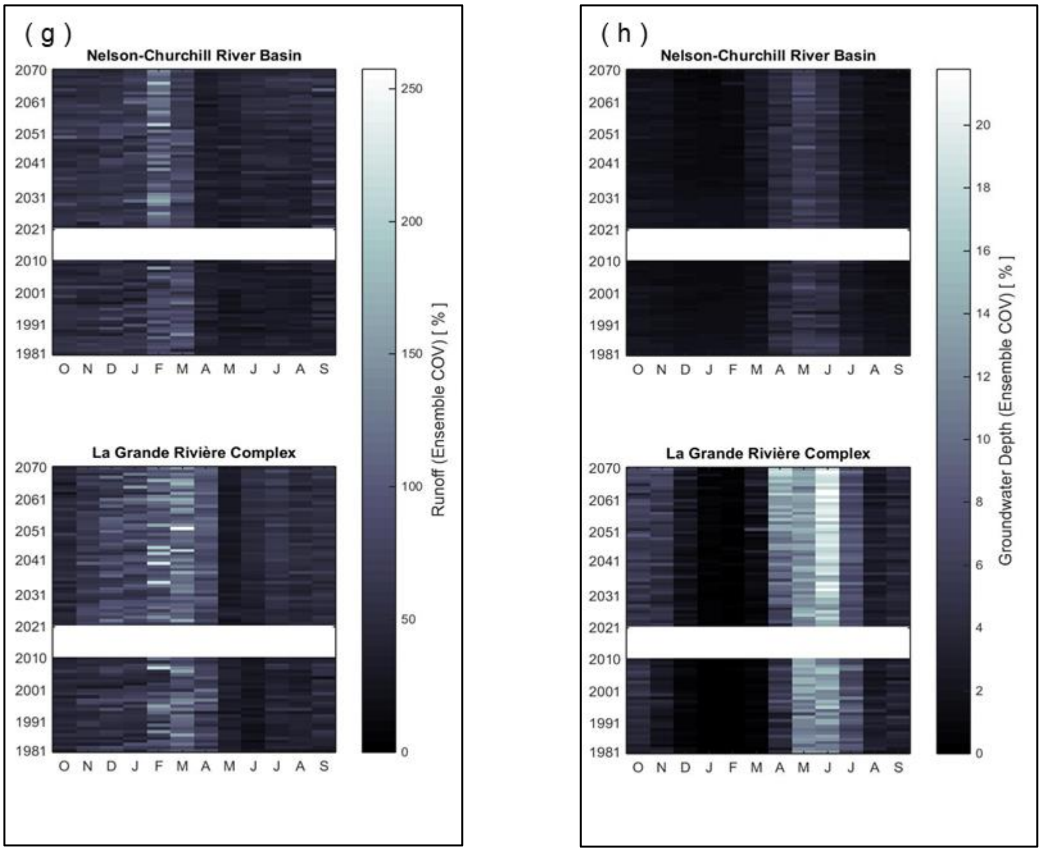
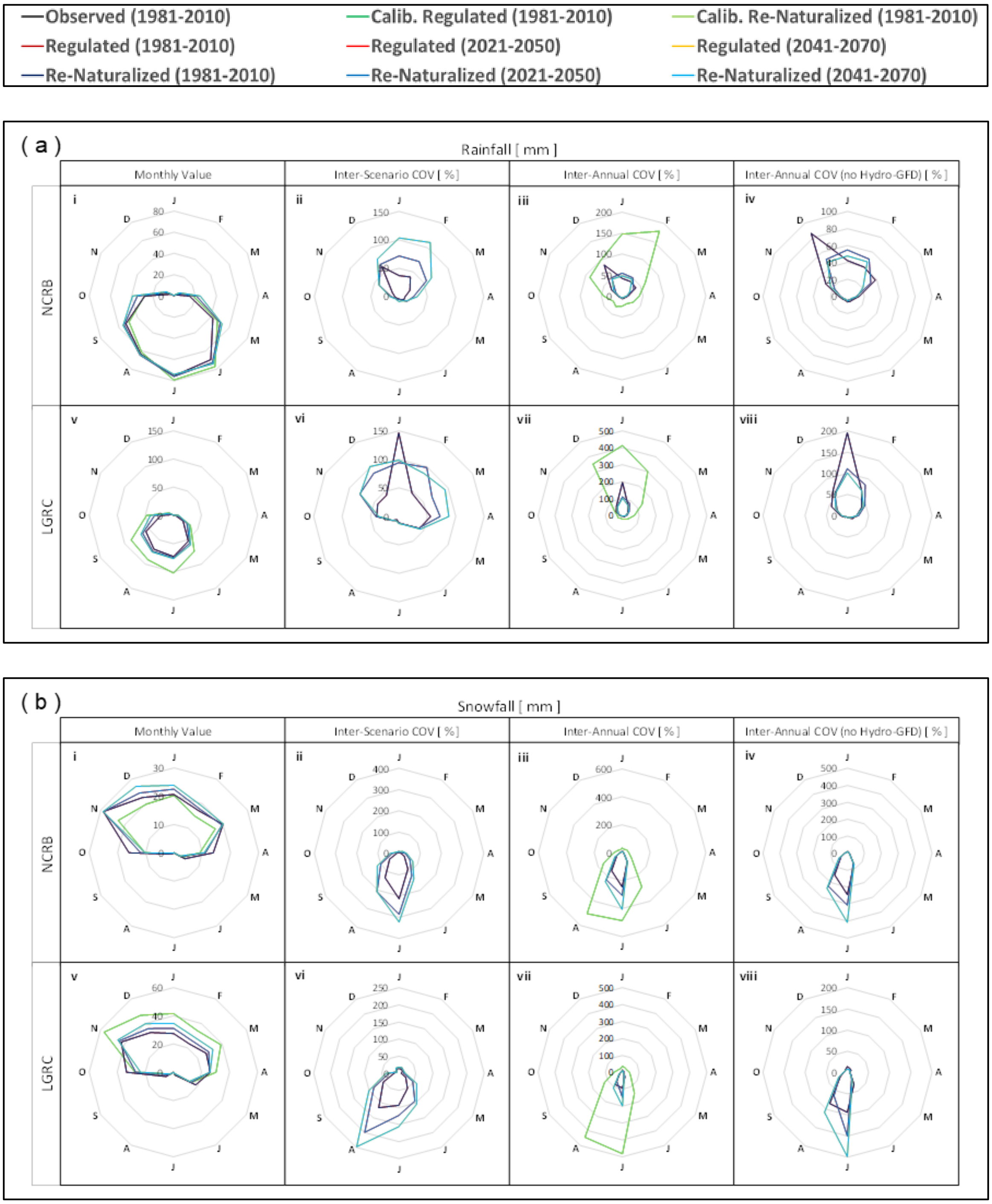
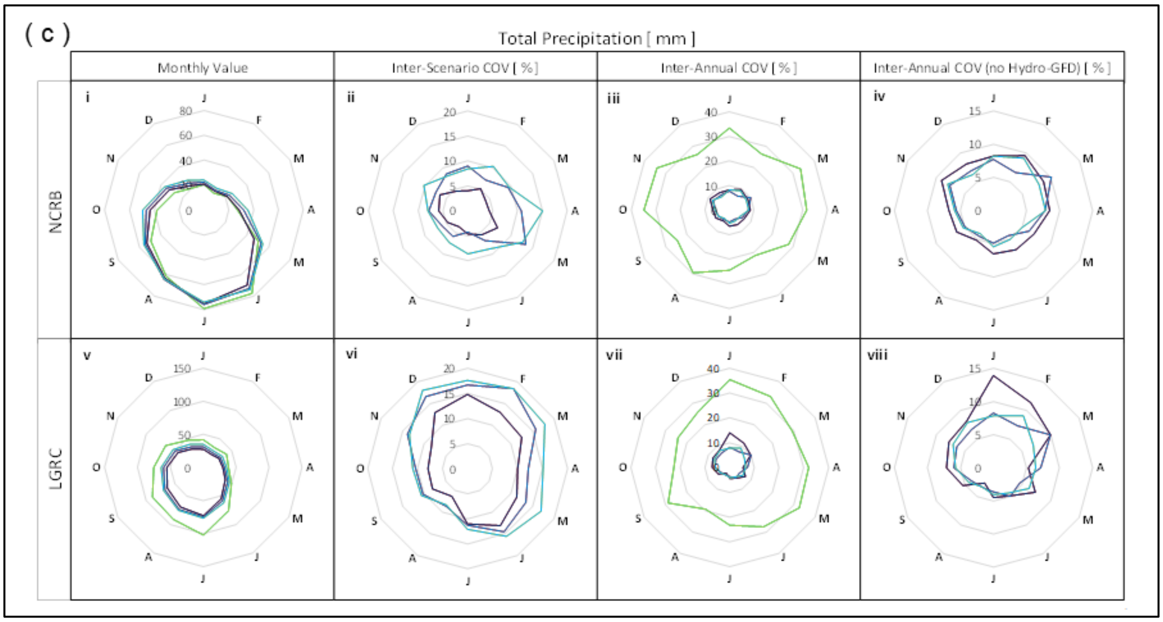
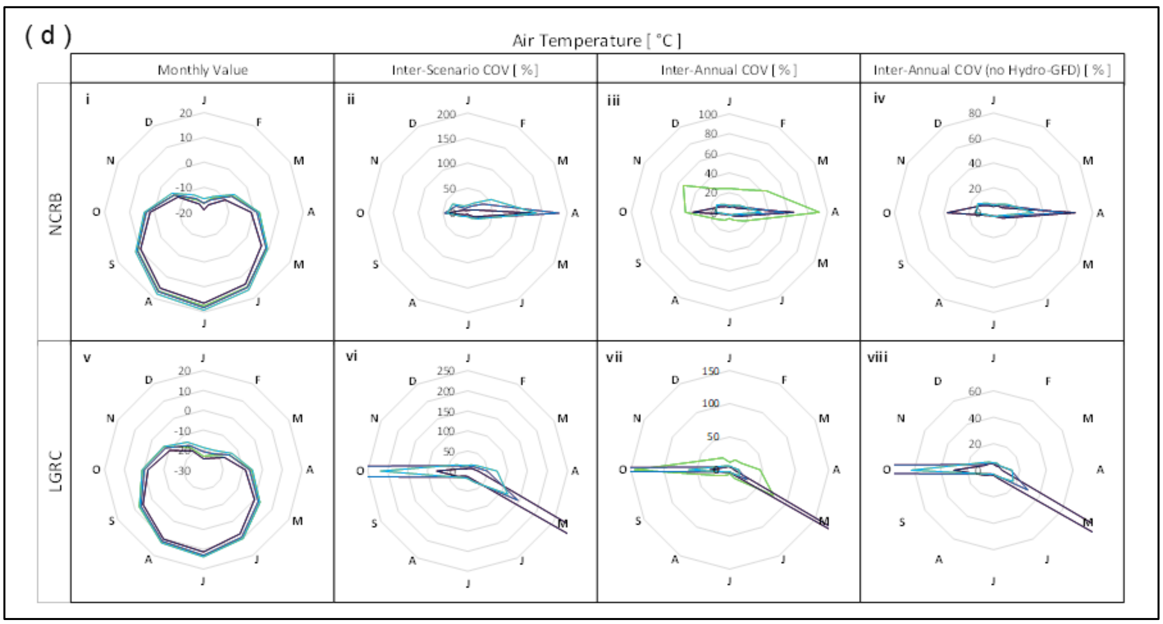


Figure H-1: *Inter-scenario coefficient of variation (COV) maps by (vertical) year and (horizontal) month for NCRB (top) and LGRC (bottom) for various inputs and variables. Given in percentage.*

6.9 Appendix I: Radial Plots of Period-Mean Values for Regulated Basins




(c)
Total Precipitation [mm]
Monthly Value
Inter-Scenario COV [%]
Inter-Annual COV [%]
Inter-Annual COV (no Hydro-GFD) [%]
NCRB
LGRC
i
ii
iii
iv
v
vi
vii
viii


(d)
Air Temperature [°C]
Monthly Value
Inter-Scenario COV [%]
Inter-Annual COV [%]
Inter-Annual COV (no Hydro-GFD) [%]
NCRB
LGRC
i
ii
iii
iv
v
vi
vii
viii

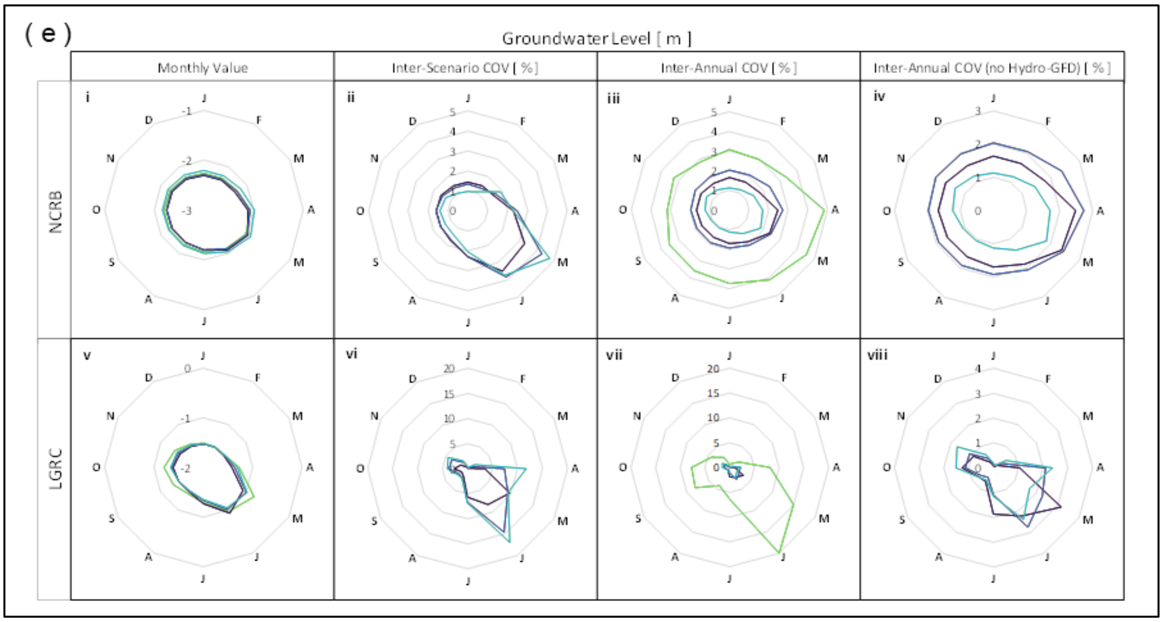
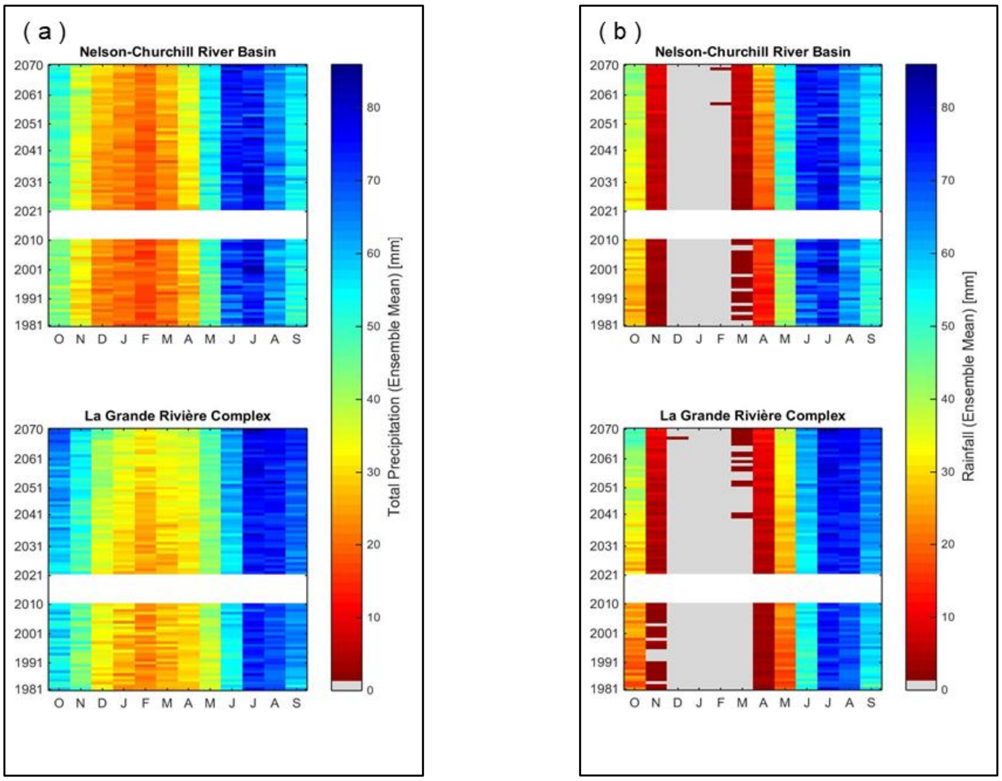
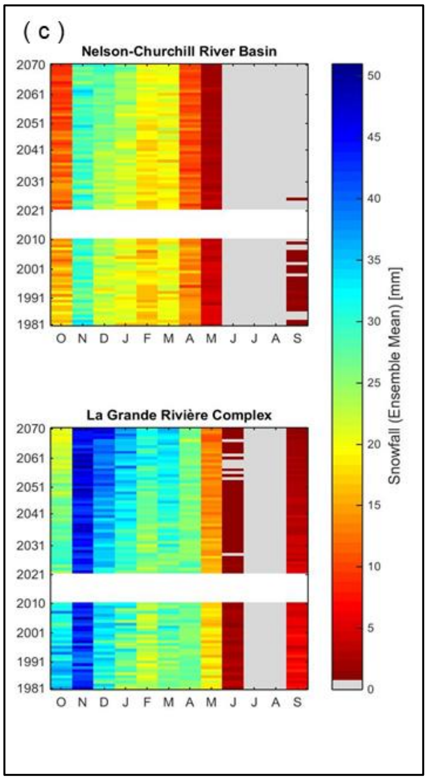
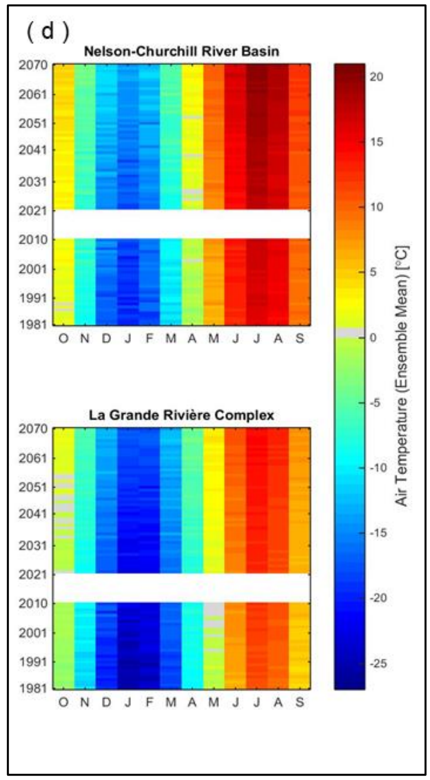


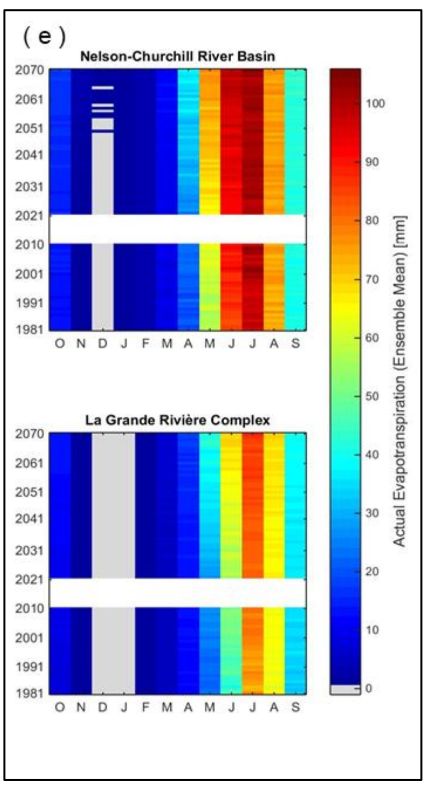
Figure I-1: *Monthly radial plots by period/model configuration for (i, ii, iii, iv) NCRB and (v, vi, vii, viii) LGRC for (i, v) 30-year ensemble average value, (ii, vi) inter-scenario COV, (iii, vii) inter-annual COV and (iv, viii) inter-annual COV with reanalysis products excluded. Units vary by plot.*

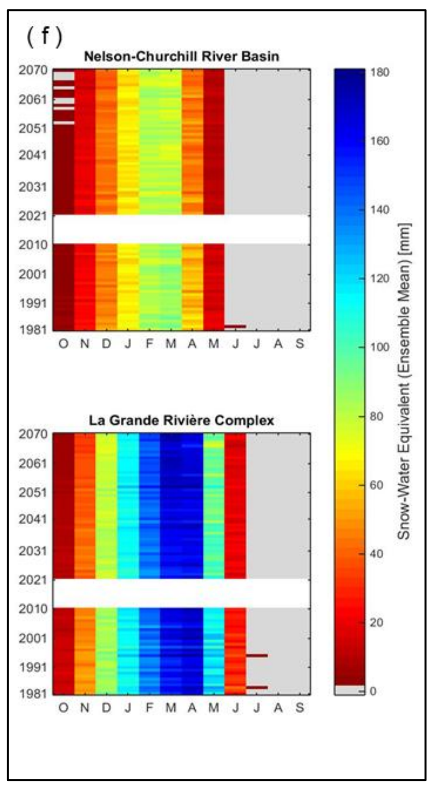
6.10 Appendix J: Heatmaps of Monthly Value for Regulated Basins




(c)
Nelson-Churchill River Basin
La Grande Rivière Complex
2070
2061
2051
2041
2031
2021
2010
2001
1991
1981
O N D J F M A M J J A S
Snowfall (Ensemble Mean) [mm]
0 5 10 15 20 25 30 35 40 45 50


(d)
Nelson-Churchill River Basin
La Grande Rivière Complex
2070
2061
2051
2041
2031
2021
2010
2001
1991
1981
O N D J F M A M J J A S
Air Temperature (Ensemble Mean) [°C]
-25 -20 -15 -10 -5 0 5 10 15 20


(e)
Nelson-Churchill River Basin
La Grande Rivière Complex
2070
2061
2051
2041
2031
2021
2010
2001
1991
1981
O N D J F M A M J J A S
Actual Evapotranspiration (Ensemble Mean) [mm]
0 10 20 30 40 50 60 70 80 90 100


(f)
Nelson-Churchill River Basin
La Grande Rivière Complex
2070
2061
2051
2041
2031
2021
2010
2001
1991
1981
O N D J F M A M J J A S
Snow-Water Equivalent (Ensemble Mean) [mm]
0 20 40 60 80 100 120 140 160 180

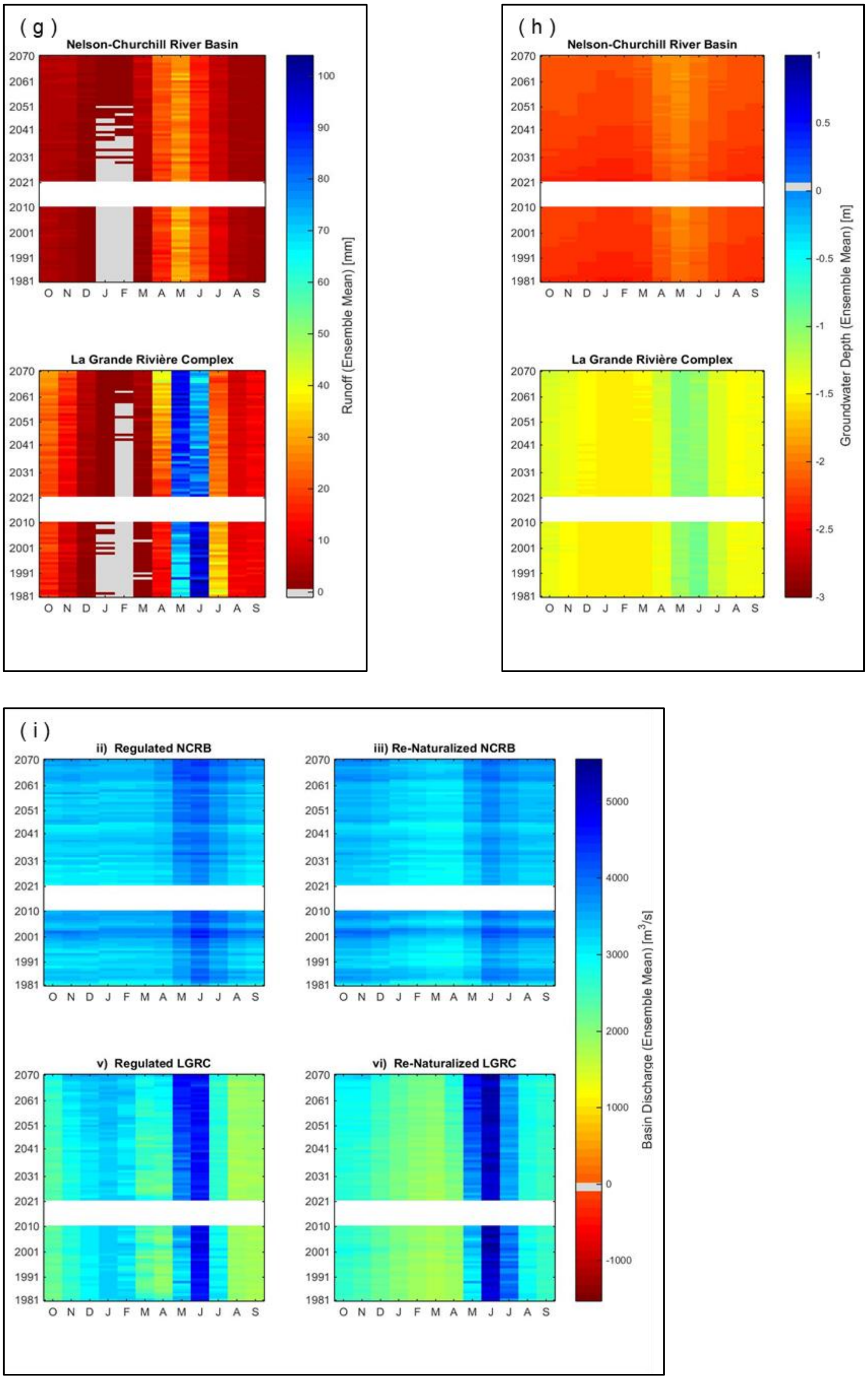


Figure J-1: *Heat maps by (vertical) year and (horizontal) month for NCRB (top) and LGRC (bottom) for model input and output variables. Units shown in title at right.*