Developing an Integrated Water Management Model for Simulating the River-Reservoir System Operated by Manitoba Hydro

By

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

Abstract

In Manitoba, most of the rivers traverse mid- to high-latitude regions that are vulnerable to climate change and therefore understanding the system behavior under future climate conditions is strategically very important for decision makers. Decision makers and water operating agencies must therefore have a comprehensive understanding of the system response to climate- and human-induced changes in the system. There are limitations associated with the current computer-aided models that Manitoba Hydro is using to simulate and optimize the river-reservoir system in terms of representing the complex interconnections and hydraulic relationships. Therefore, in this research, an integrated water management model is developed for the river-reservoir system operated by Manitoba Hydro. The MODSIM-DSS water management modeling tool is used for developing the simulation model with the ability of defining non-linear relationships for representing the complex backwater-affected relationship as well as the impacts of seasonality in the operation of control points in the system using the custom code editor. A large number of datasets including upstream inflow, demand, stage-storage-discharge relationship, and hydropower efficiency table are collected from Manitoba Hydro and used to set up the model. The developed model requires time-series of upstream and local inflows to simulate the system behavior under the current operating rules. The performance of the model is evaluated by analyzing the discrepancies between the simulated data and measured data. Model evaluation metrics and time series of results show a range of performance from adequate to excellent match between the simulated and historically measured data. Therefore, it is concluded that the developed model will be useful and usable for analyzing various climate- and human-induced changes in the system.

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List of Acronyms and Symbols

MH	Manitoba Hydro
SMPM	Simulation Model for hydro-Power reservoir Management
MOST	Market Optimized Short-Term
HERMES	Hydro-Electric Reservoir Management Evaluation System
SPLASH	Simulation Program for Long Term Analysis of System Hydraulics
LP	Linear Programming
SIL	Southern Indian Lake
EMMA	Energy Management and Maintenance Analysis
MINLP	Mixed-Integer Non-Linear Programming
GAMS	General Algebraic Modelling System
SA	Simulated Annealing
GEMSLP	General Energy Management by Successive Linear Programming
PSO	Particle Swarm Optimization

1 Introduction

1.1 Background

Canada, with several large-scale, inter-provincial, and international river basins, is one of the largest hydropower producers on the planet (Balat, 2006). Hydroelectric reservoirs generate more than 95 percent of the electricity in the provinces of Manitoba, Quebec, British Columbia, and Newfoundland and Labrador (Aarons and Vine, 2015). This source of energy has enabled Canadians to meet their energy demand, enhanced economic growth, and opened up remote regions (Canadian Hydropower Association, 2016).

The effective use of hydroelectric reservoirs requires a proper engineering design as well as the strategic planning for operations of the hydroelectric reservoir (Goor et al., 2011). Any operating plan includes operating constraints that are not solely focused on generating hydropower but also on water supply and flood control operations (Jager and Smith, 2008). For example, operators have to satisfy municipal and irrigation demands that conflict with the desire of storing more water to enhance the hydropower generation potential (Booker and Young, 1994; Falkenmark, 1986).

Besides operating constraints, climate change has increasingly stressed the hydropower generation and affected the flexibility of operating plans in Canadian River basins (Hamududu et al., 2012). For instance, most of the rivers in Manitoba traverse mid- to high-latitude regions and therefore are vulnerable to climate change (Milly et al., 2005; Vieira, 2016). The Nelson-Churchill Rivers basin located in Manitoba has experienced a significant increase in winter streamflow by 44 to 128 percent during the last 80 years at downstream and upstream gauges of the basin (St George, 2006). Moreover, a series of unusual hydro-climatic conditions compared to the long-term hydro-climatic pattern have caused widespread reductions in precipitation occasionally (St George, 2006).

Such changes in precipitation and runoff volume highly affect the hydropower generation. Manitoba Hydro (MH) reported a reduction in hydropower generation and sales during 2003 and 2004 as a result of widespread drought affecting the Nelson-Churchill Rivers basin (Manitoba Hydro, 2004). Conversely, a wet period happened in 2004 and 2005 which provided ample streamflow and enhanced hydropower generation (Manitoba Hydro, 2005).

Recent changes in the magnitude and timing of precipitation have raised serious concerns about the reliability of hydropower generation in this basin under future climate conditions (Déry et al., 2018, 2016, 2011). These concerns include:

- What is the extent of the impacts of future climatic conditions on hydropower generation?
- Would the current operating guidelines be reliable enough to meet the future water and hydropower demands under the future climatic conditions?
- Could the negative impacts of climate change be mitigated by changing the current operational plans?

Answering the above questions requires a comprehensive understanding of the system behavior and dynamics under different climatic conditions and time horizons that can be achieved by developing and implementing decision support systems and computer-aided modeling tools (Labadie, 2004). Therefore, this research aimed to develop a computer model for the river-reservoir system operated by MH capable of simulating the complex interconnection between the system components. MH has been developing computer-aided models, known as operational system simulation-optimization models, for understanding and optimizing the operation of the system of hydropower for the following purposes (Kubursi and Magee, 2010; Simonovic and Grahovac, 1991):

- Short-term operation with a simulation time step as fine as hourly resolution of the upcoming two weeks
- Mid-term operation with a weekly simulation time step over the next 18 months
- Long-term operation with a monthly simulation time step up to 35 years.

Some of the models that are used by MH are listed below:

- MOST: Market Optimized Short-Term
- HERMES: Hydro-Electric Reservoir Management Evaluation System
- SPLASH: Simulation Program for Long Term Analysis of System Hydraulics

These models are used for capacity and resource planning, hydropower generation scheduling, operating cost and revenue estimation, water level and flow predictions, and expanding short-term operations to long-term planning (Barritt-Flatt and Cormie, 1991a; KPMG, 2010). These models are not available for academic research purposes.

1.2 Problem Statement and Research Motivation

External reviewers have pointed out the following limitations encountered in simulation-optimization models that are used by MH (KGS, 2005; KPMG, 2010; Kubursi and Magee, 2010). These limitations are briefly summarized below and explained more in-depth in Chapter 3.

- Problem formulation and optimization approach

    - Linear Programming (LP) might be inadequate for representing the nonlinear hydraulic relationships and dependencies in the river-reservoir system.
    - Objective function might have been formulated such that LP finds a predefined desired solution. This happens when certain decision variables such as hydropower generation have higher weights (a set of numbers that is used to prioritize decision variables) compared to other decision variables so that the objective function value will be highly affected by decision variables with higher weights.
- Streamflow scenarios
    - Relying on the historical streamflow time series for operating the system might be inadequate considering the projected climate change especially for long-term operations and resource planning.
- Using multiple simulation-optimization models
    - Using multiple simulation-optimization models might result in inconsistencies between decision variables and results due to the different assumptions and structures of the models.
- Using "Perfect foresight" in SPLASH
    - Using "perfect foresight" for the operation of a river-reservoir system might not find a reliable solution under uncertain future climate condition.

1.3 Research Objectives

The aforementioned questions/concerns have motivated this study to develop an advanced Simulation Model for hydro-Power reservoir Management (SMPM) that is capable of incorporating the complex non-linear hydraulic relationships. Therefore, the main objectives of this research are to:

- Develop a simulation model that represents the non-linear hydraulic relationships at key locations of the system (Nelson West, Nelson East, and South Bay channels).
- Simulate water levels, outflow from the reservoirs, hydroelectric generation, interconnections, and flow distributions with respect to the current operational rules, physical characteristics of the system components and hydraulic relationships between them.

It can be envisioned that SMPM will be used in the future to evaluate the performance of the river-reservoir system under future climate-driven and human-driven changes. SMPM can also be coupled with an optimization package to optimize the operating plans and resource planning guidelines and improve the reliability of water and hydropower supply.

2 Study Area

The Nelson River Basin covers a large portion of the Prairie Provinces from the Rocky Mountains in the west to near Lake Superior in the east with a long-term average flow of 3933 cms at Hudson Bay. As shown in Figure 1, the Churchill River basin is located north of the Nelson River basin and diverts 776 cms of water on average at Southern Indian Lake through the Burntwood and Rat Rivers for the benefit of hydropower generation in the Lower Nelson River (Barritt-Flatt and Cormie, 1991a). The Nelson and Burntwood Rivers are the two main channels in the basin that have a confluence at Split Lake, upstream of three main generating stations in the system, Kettle, Long Spruce, and Limestone.

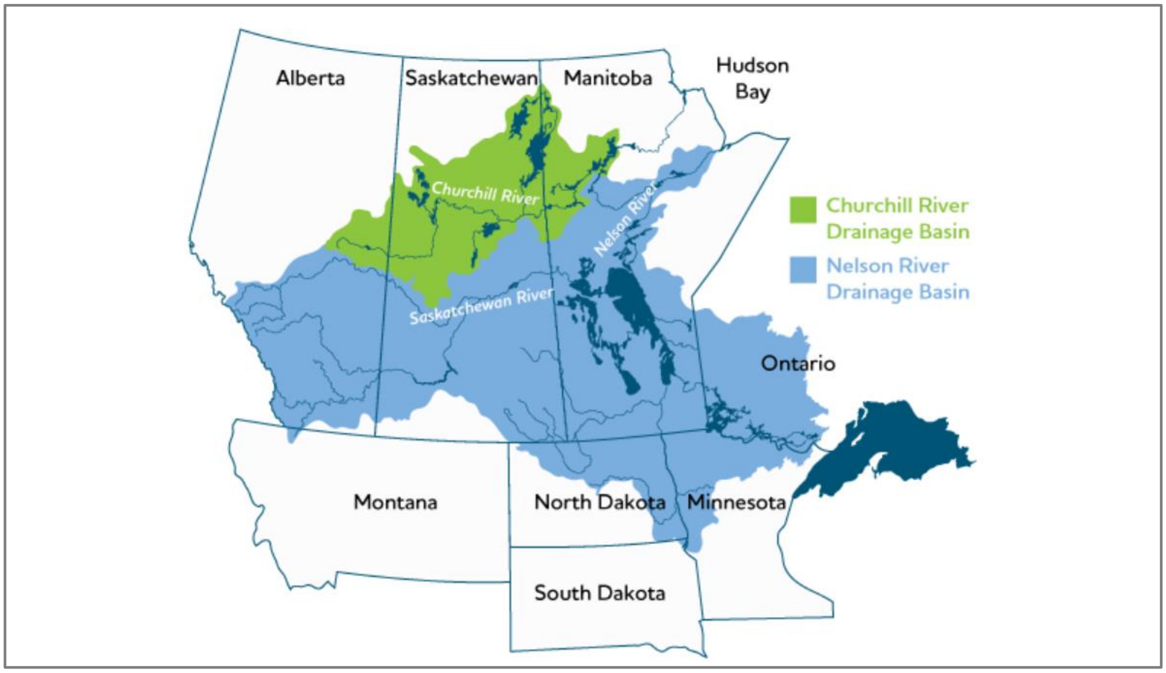


Figure 1. Nelson and Churchill River drainage basin (Manitoba Hydro, 2018)

Within the province of Manitoba, the river-reservoir system operated by MH is composed of fifteen run-of-the-river hydropower generating stations that are grouped into three sub-systems

(Barritt-Flatt and Cormie, 1991a). The name of the hydropower generating stations, capacity, and type, as well as the name of the uncontrolled and regulated lakes, are summarized in Table 1.

1) The Winnipeg River river-reservoir system that receives water from Lac Seul and Lake of the Woods
2) The Nelson River river-reservoir system that receives water from Lake Winnipeg and Southern Indian Lake
3) The Grand Rapids generation station located on the Saskatchewan River and upstream of the Lake Winnipeg

MH has a generation capacity of 5690 MW. The peak energy demand is 4460 MW and total energy load is approximately 25,000 gigawatt hours.

Table 1. Key hydraulic points in the river reservoir system operated by MH (Manitoba Hydro, 2018)

Name	**Capacity (MW)**	**Type**		**Name**	**Capacity (MW)**	**Type**
Grand Rapids	479	Hydropower		Pointe du Bois	75	Hydropower
Great Falls	129	Hydropower		Seven Sisters	165	Hydropower
Jenpeg	115	Hydropower		Slave Falls	68	Hydropower
Kelsey	286	Hydropower		Wuskwatim	211	Hydropower
Kettle	1220	Hydropower		Split Lake	-	Uncontrolled lake
Laurie River I	5	Hydropower		Sipiwesk	-	Uncontrolled lake
Laurie River II	5	Hydropower		Cross Lake	-	Uncontrolled lake
Limestone	1350	Hydropower		Wapisu	-	Uncontrolled lake
Long Spruce	980	Hydropower		Foot Print	-	Uncontrolled lake
McArthur Falls	56	Hydropower		Opegano	-	Uncontrolled lake
Pine Falls	84	Hydropower		Birchtree	-	Uncontrolled lake
Lake Winnipeg	-	Regulated lake		Southern Indian Lake	-	Regulated lake
Notigi	-	Regulated lake				

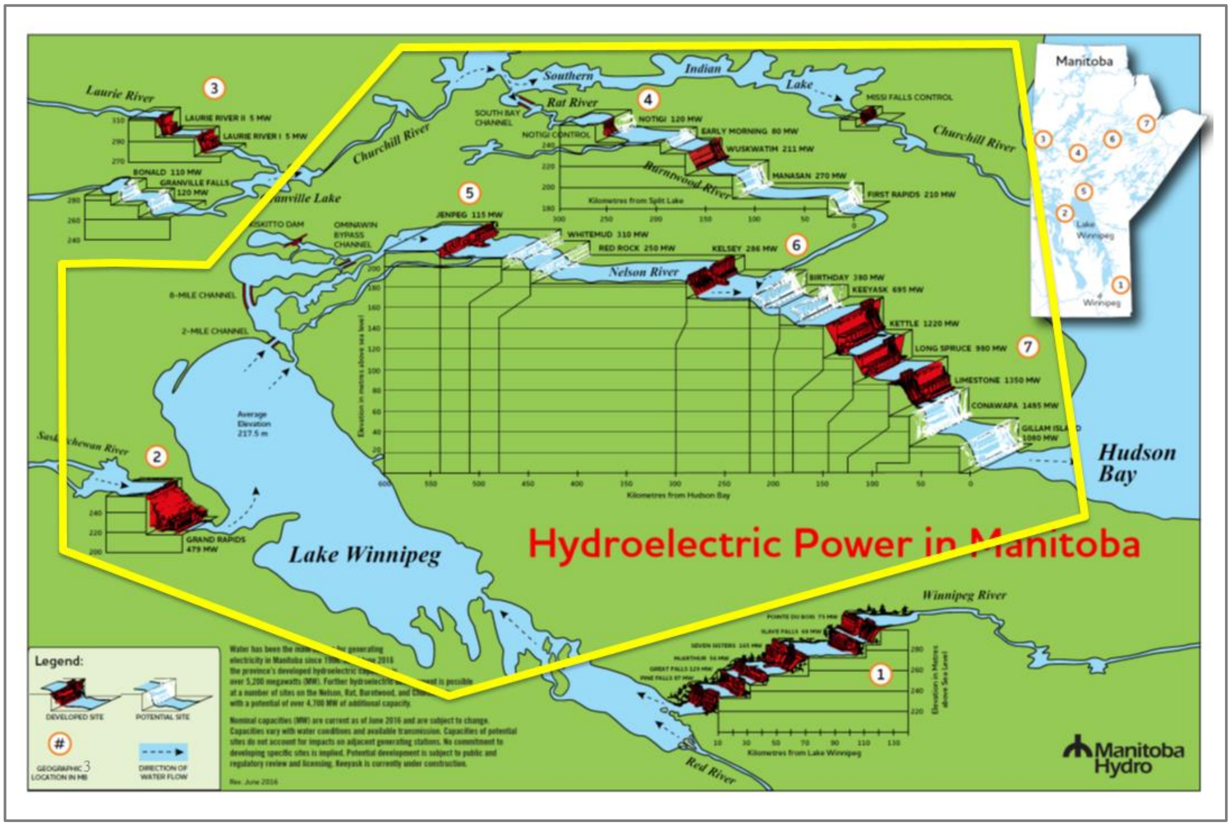


Figure 2. The schematic of the river-reservoir system operated by MH (provided by MH)

In this study, the SMPM model is developed for the area within the yellow border in Figure 2. Hydropower generating stations in this area include Grand Rapids, Jenpeg, Wuskwatim, Kelsey, Kettle, Long Spruce, and Limestone providing over 95% of the hydropower generating capacity and the uncontrolled lakes include Wapisu, Footprint, Opegano, Birchtree, Cross Lake, Sipiwesk, and Split Lake. Regulated lakes including Southern Indian Lake (SIL), Notigi, and Lake Winnipeg are controlled by the operation of their downstream controlled point.

3 MH Simulation-Optimization Models

MH has been developing simulation-optimization models for capacity and resource planning, hydropower generation scheduling, operating costs and revenues estimation, and water levels and flows predictions (KPMG, 2010; Simonovic, 1992). The following goals are considered in developing operational plans suggested by these simulation-optimization models (Simonovic and Grahovac, 1991):

- Generating sufficient energy to satisfy forecasted water and hydropower demands
- Providing and maintaining acceptable levels of system reliability
- Satisfying environmental and water supply requirements
- Operating the system economically

To meet these goals, MH uses three simulation-optimization models called MOST, HERMES, and SPLASH, as defined in this section, to efficiently make decisions in developing operational plans and improve mid-term and long-term operations.

3.1 The Market Optimized Short-Term (MOST)

MH uses MOST as a decision support system to schedule hourly power generation and reservoir operation for the entire MH generating facilities including hydropower plants (responsible for more than 95% of the total electricity generation capacity) as well as wind and thermal plants (responsible for less than 5% of the total electricity generation capacity) (Kubursi and Magee, 2010). MOST conducts a one-week optimization analysis that provides a weekly schedule for hydropower generation and system operations. Using the weekly schedule, a 24-hour-ahead schedule is provided for operators that is updated twice an hour and includes (Kubursi and Magee, 2010):

- one-day-ahead planning of capacity
- planning for committed load and transactions
- managing outages and post audits

3.1.1 MOST Structure

The water resources system components and the electrical network are defined within the LP model using an arc-node configuration to represent reservoirs, power plants, spillways, canals, river reaches, junction points, and the transmission line electrical system (Bridgeman et al., 2010). Capacity equations are defined for the hydraulic nodes to impose stage-discharge and stage-storage curves at the reservoirs.

3.1.2 MOST Input and Output

MOST requires the following data to carry out the calculations and produce the outputs:

- Hydrologic information such as forecasted inflow time series, and evaporation and infiltration rates
- Hydraulic system characteristics such as the maximum turbine flow and the storage at reservoirs
- Inflow and load forecasts
- Outage and maintenance schedules
- External and internal transmission characteristics
- Objective function cost coefficients

Using the provided input, MOST generates outputs including a 24-hour-ahead schedule for forebay elevations.

3.1.3 MOST Vista System

MOST is a Vista-based system where the Vista system has eight modules that are summarized in Table 2. Each module has a unique function but all of the modules serve to optimize allocating and scheduling electricity resources.

Table 2. Vista system modules (Olason et al., 2005)

Vista Modules	**Description**
Data Vista	To define system configuration, facilities data, and operational constraints including water levels and flows, power generation, outage or maintenance schedules
RT Data Vista	To process real-time data including weather forecasts and SCADA data
Inflow Vista	To define and derive inflow forecasts
Load Vista	To define load forecasts
Xchange Vista	To define transaction opportunities
ST Vista	To schedule short-term (real-time) operations for a two week time horizon
LT Vista	To schedule long-term generation up to 4 weeks
Vista Service	To load and process input data from external resources automatically

3.1.4 MOST Objective Function and Constraints

The objective function is formulated either to maximize the total net benefits from power generation considering the given information of market or to minimize the total cost of satisfying the system energy and load demand considering the resource availability or export and import opportunities (Kubursi and Magee, 2010).

Operational constraints in MOST include transmission, hydraulic, and water and energy supply constraints that account for operational commitments or preferences and license requirements (Kubursi and Magee, 2010), which can be summarized as:

- Physical limitations of the structures such as the maximum and minimum reservoir storage
- The limitations imposed by energy and water supply licenses and agreements
- Practical operating limitations such as spill capacities

Multiple energy or water customers are defined where short-term and long-term forecasts can be imported or generated for each customer (Bridgeman et al., 2010; Kubursi and Magee, 2010). The demand forecasts are updated multiple times hourly and fed automatically into MOST.

The large drainage area of the Nelson, Saskatchewan, Churchill, and Red Rivers and the long distances between generation stations complicate the time-specific formulation of the model and therefore, decisions for water storage in Lake Winnipeg, Kettle, and Cedar Lakes has to be made part of the short-term flow constraints and long-term water management strategies (Kubursi and Magee, 2010).

3.1.5 MOST Optimization Approach

An iterative LP approach called the successive linear approximation is used to linearize the non-linearity of the problem (Kubursi and Magee, 2010). The optimization reconciles the trade-off between the current and future power generation benefits within the system constraints and the inherent uncertainty of future prices and events such as the predicted climatic conditions.

3.2 The Hydro Electric Reservoir Management Evaluation System (HERMES)

HERMES is a decision support system and planning tool used by currently Wholesale Power and Operations group (KPMG, 2010; Kubursi and Magee, 2010). Its implementation began in 1985 with the primary goal of providing a suggested water release schedule and energy production estimates over the planning horizon of 12 to 18 months. HERMES is used to develop a reservoir and generation operation plan for the system with the following objectives:

- To ensure sufficient energy is produced to satisfy the forecasted demands
- To ensure sufficient capacity is available to satisfy the peak demands
- To maintain system reliability
- To minimize the negative social and environmental impacts of operation
- To operate the system economically

3.2.1 HERMES Structure

HERMES includes interactive graphics for its diverse sets of output and input data, extensive analytical capability, internal online documentation, data management capability, extensibility, and strong communication with other computers (Barritt-Flatt and Cormie, 1991a). HERMES Application architecture is represented in Figure 3.

Energy Management and Maintenance Analysis (EMMA) and Flow Simulation Model (QSIM) are the two main calculation modules in HERMES that are used to produce reports to support power contracts, trading decisions, and operations (Barritt-Flatt and Cormie, 1991a; Kubursi and Magee, 2010).

EMMA is the operations planning module that is used to derive the operating plans to operate generation stations, reservoirs, and transactions with neighboring utilities. EMMA has three subsystems including the power generation, hydraulic system, and maintenance system. The hydraulic system includes lakes, reservoirs, rivers, spillways, time delays, stage-storage, and outlet rating curves. The power generation subsystem describes electricity generation, load, and transmission lines. Loads are classified as fixed or price sensitive, firm or interruptible, and on-peak or off-peak time loads. The maintenance subsystem includes the maintenance of the system that can be scheduled either before the process of preparing an operating plan or assigned by the optimizing run.

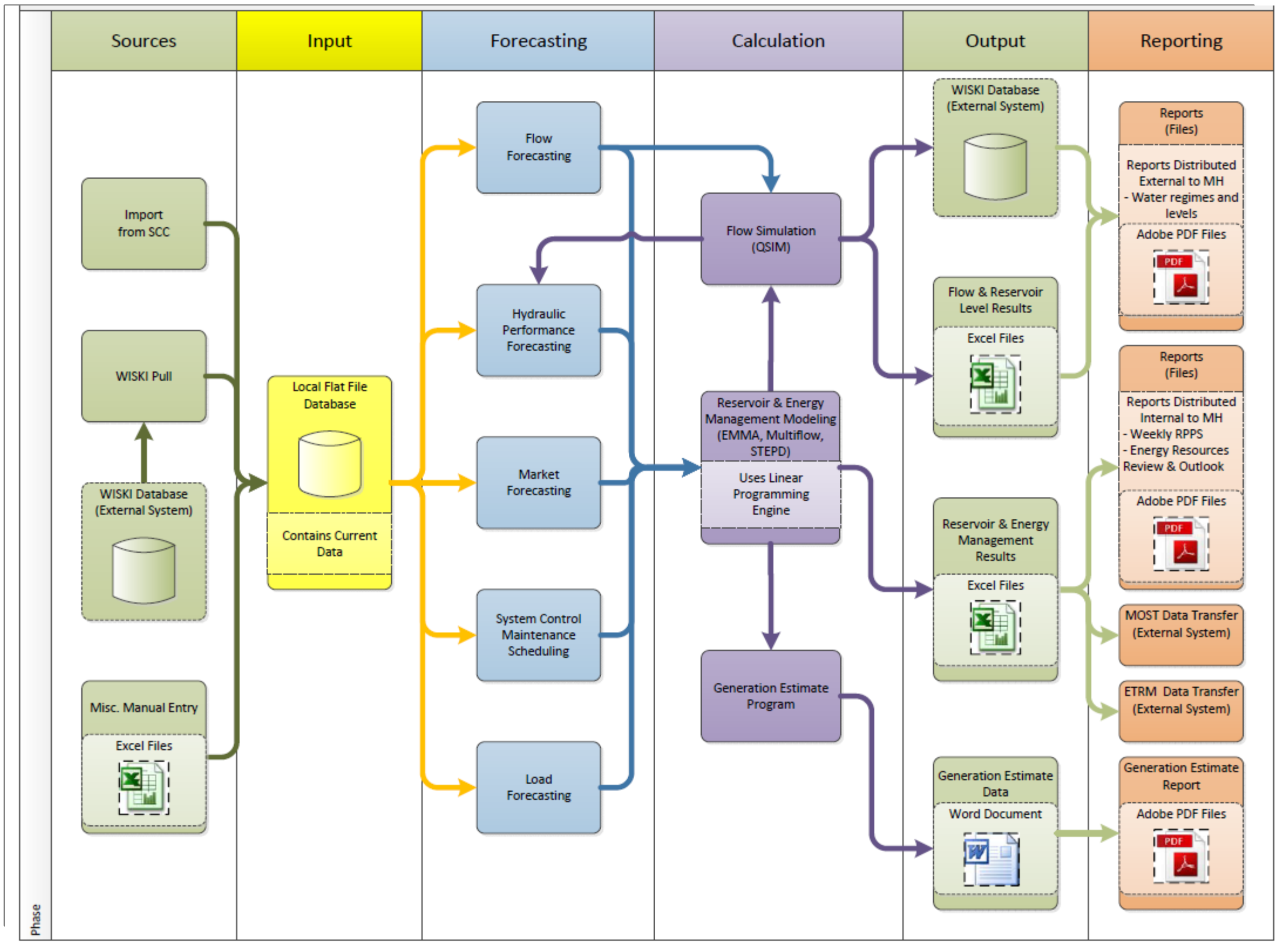


Figure 3. The HERMES application architecture (provided by MH, 2019)

EMMA is complemented by QSIM that focuses on deriving daily elevation and flow values along with the hydraulic network. QSIM estimates daily flow values compared to the weekly and monthly forecasts of EMMA. The estimated flow values are converted to energy generation and used for managing short-term energy supply.

EMMA is deterministic as opposed to stochastic, in that it generates one outcome given one set of assumptions. Stochastic models generate a range of outcomes based on a set of inputs with a probability distribution.

3.2.2 HERMES Input and Output

HERMES requires the following data to carry out the calculations and produce the outputs:

- Hydrologic information such as tributary inflows
- Generation maintenance schedule
- Load requirements
- Hydraulic system characteristics such as maximum turbine flow
- Tie line characteristics (maximum export and import load)
- Export/import energy price
- Internal transmission characteristics
- Optimization time horizon (number and length of time steps)
- Objective function cost coefficients

Using the provided input as well as the flow, hydraulic performance, load, and market forecasting, HERMES generated outputs including flow and reservoir level, reservoir and energy management, and production costs and revenues.

MH uses HERMES to update the operating plans on a weekly basis (Kubursi and Magee, 2010). These weekly updates reflect new information on changes in power efficiency coefficients, outlet rating curves, weather, water levels, and transmission capabilities and are included in the preparation of the new operating plans.

3.2.3 HERMES Objective Function and Constraints

The objective function maximizes the interruptible energy export and the final storage volume while minimizing the cost of satisfying the system requirements such as hydropower generation and spill costs (Reznicek and Simonovic, 1989).

The constraints include:

- Practical operating limitations
- Physical limitations of the structures such as maximum and minimum reservoir storage
- The limitations imposed by energy and water supply licenses and agreements
- Reservoir flow continuity equation
- Tie line load for every load duration curve strip
- Energy release relation

3.2.4 HERMES Optimization Approach

HERMES uses the successive linear programing algorithm to optimize a set of operating decisions within the operational constraints, which is programmed in FORTRAN and contains several subroutines that can be summarized as reading the input data, setting and altering the LP matrices, solving the LP, and writing the output reports.

3.3 The Simulation Program for Long-Term Analysis of System Hydraulics (SPLASH)

Implementation of SPLASH began in 1997 for all long-term resource planning studies including annual power resource plans, marginal cost analysis, integrated financial forecasts, and reviewing proposed operation of the generating plants and long-term export sales (Kubursi and

Magee, 2010; R. J. Bowering, 2005). This model helps MH to make sound decisions on the system expansion options by determining the operation costs on a monthly basis of up to 35 years with the following objectives:

- To ensure that sufficient water and energy are available to meet forecasted demands
- To operate and manage reservoirs within agreement and license limitations
- To maintain acceptable levels of system reliability
- To operate the system economically

3.3.1 SPLASH Structure

SPLASH represents the physical characteristics of the thermal, hydraulic, and transmission systems, the practical operating restrictions, and the constraints imposed on the system by agreements and licenses (R. J. Bowering, 2005).

SPLASH incorporates FORTRAN 77, C programming languages, CPLEX, PV-Wave, and UIMX and includes the following major components:

- SPLASHEM: A graphical user interface where users can view or edit input database
- GPS: A system simulation program that utilizes the CPLEX linear programming solver
- SPLASHVIEW: A graphical user interface where users can display output data for a specific run

The system simulation undertakes three distinct steps, represented below, where the first two steps provide inputs into the production costing simulation (Kubursi and Magee, 2010).

1. Dependable energy determination:

MH determines the resource requirements by utilizing the dependable criterion where sufficient energy must be available to satisfy all the firm demand under the lowest flows on record that may occur at any time in the future.

2. Rule curve determination:

   MH implements rule curve simulation to determine appropriate operating guidelines to ensure that the system will supply demands adequately over all water flow conditions.

3. Production costing:

   Production costing simulation is used to determine the system operation over the entire flow conditions range and the planning horizon.

3.3.2 SPLASH Flow Prediction

SPLASH analyzes the system operation under a range of flow conditions that may occur in the future by utilizing 86 historical years of monthly inflows to represent the current day regulation (Kubursi and Magee, 2010). Each year is chronologically cycled through 40 load years such that every flow year occurs in every load year resulting in a series of 86 flow cases accounting for the hydrologic variability (R. J. Bowering, 2005). Based on personal discussion with MH, the number of years of flow records used by MH in SPLASH simulations has increased since the time this reference was written.

3.3.3 SPLASH Input and Output

SPLASH input data is accessed through the customized graphical user interface (GUI) and is grouped as follows (R. J. Bowering, 2005):

- Hydrologic information
- Planning horizon data

- Hydraulic and thermal system characteristics such as maximum storage at reservoirs
- Inflow and load forecasts
- Outage and maintenance schedule
- Market and network data
- External and internal transmission characteristics
- Objective function cost coefficients

The SPLASH output data is accessed through the GUI and includes annual and monthly energy supply/demand values in GWh and cost or revenue values in Canadian Dollars.

3.3.4 SPLASH Objective Function and Constraints

SPLASH uses an LP to maximize the net flow related revenues or the net outcome of revenues after offsetting the related cost of energy generation subject to the following constraints (R. J. Bowering, 2005).

- Practical operating limitations
- Physical limitations of the structures
- The limitations imposed by energy and water supply licenses and agreements

Since these constraints are not linear, piecewise linear segments are used to represent nonlinear relationships using linear functions. MH uses the CPLEX linear programming software package as the problem solver.

3.4 MH Simulation-Optimization Models Limitations

3.4.1 Problem Formulation and Optimization Approach

The inclusion of nonlinear relationships in river-reservoir systems increases the complexity of the system and the models that represent and formulate these systems by mathematical or simulation approaches (Teegavarapu, 2010). Therefore in general, LP cannot accurately and adequately represent these complex hydraulic relationships (Adeyemo, 2011; Philbrick and Kitanidis, 1999; Simonovic, 1992).

MH simulation-optimization models incorporate LP to formulate and optimize hydropower generating stations, controlled and uncontrolled channels and lakes as well as the hydraulic relationships between these components. Reviewers external to MH have raised several concerns regarding the use of LP, which are summarized below.

3.4.2 Using Linear Programming for Representing Hydraulic Relationships

Simonovic and Grahovac (1991) alleged the logic behind the representation of the hydropower generation relationships with linear functions in HERMES and explained that although the shapes of the efficiency curves represent nonlinear relationships and dependencies between the hydraulic components, standard numerical adjustments are performed to linearize such nonlinear relationships. To validate this assumption, MH referred to the topography, geography, and climate conditions of hydropower generating reservoirs located in the study area and noted that these hydropower generating reservoirs have small and gradual changes in the water elevation, the reservoir water level remains relatively constant resulting in nearly constant head values (Manitoba Hydro, 2010). Therefore, MH argued that the nonlinear relationship between the head and outflow in the hydropower generation function could be represented with linear equations.

Although such operating policies, assumptions, and simplifications have been profoundly represented the river-reservoir system interconnections and hydraulic relationships, external reviewers have raised the following two main concerns:

First, it is acceptable that under the current climatic condition and system requirements, the reservoir levels can be kept at a constant elevation. However, the fluctuation in the inflow to the system is expected to increase, resulting in more variations in forebay elevations. Therefore, assuming constant elevation might not be reasonable facing climate change. (KPMG, 2010; Kubursi and Magee, 2010). For example, the annual average temperature in southern Canada increased by 1.9 ºC from 1900 to 2016, including 2.2 ºC increase in spring, 1.7 ºC increase in summer, 1.6ºC increase in autumn, and 2.8ºC in winter, (Vincent et al., 2018, 2015). It is anticipated that higher temperatures compared to the annual average temperature will become more intense and frequent (Bush and Lemmen, 2019). The warmer temperature will also impact the intensity of frequency of extreme rainfall events and therefore will increase the flood risks in southern Canada (Bush and Lemmen, 2019; Eum et al., 2012).

Second, although the nonlinearity can be tackled by advanced mathematical approaches such as successive linear programing (Barros et al., 2003; Mousavi and Ramamurthy, 2000) and separable linear programming (Crawley and Dandy, 1993), linearizing the nonlinear relationships requires mathematical adjustments such as numerical approximations, aggregations, segmentation, and other interpolations (Chunjiang Qian and Wei Lin, 2001), which increases the computational error and reduces the reliability of simulation results (Ding and Zhou, 2004).

3.4.3 Objective Function Formulation

The objective function of LP is the weighted sum of decision variables. Assigning weights to decision variables is among the standard prioritizing practices in large-scale problems (Berander and Andrews, 2005; Tamiz et al., 1998). However, inappropriate use of weights brings out the issue that users select optimum solutions near to their desired solutions (Bentley and Wakefield, 1998).

External reviewers raised concerns regarding the weights that MH uses for decision variables to form the objective function that is the weighted-sum of the decision variables. High weights are assigned to particular decision variables such as hydropower generation coefficient, which results in forced solutions where the optimal solution is near to the desired solution. Although assigning weights is a common practice in the large-scale LP problems, it is necessary to avoid forced solutions by optimizing the assigned weights or considering a combination of different weights (Kubursi and Magee, 2010).

3.4.4 Relying on the Historical Trends for Optimizing the System Operations

HERMES and SPLASH use the historical inflow trends as a predictor of future inflow trends when optimizing the operational plans. In HERMES, any given hydropower generation and release schedule are tested against the flow year 1940/41, April 1st to March 31st, that is the driest year on record (Bush and Lemmen, 2019) with 40% less flow than the long-term average in the system.

For example, a suggested water release schedule by HERMES is tested under the 1940's flow conditions, and if the ending water level at each reservoir is below the minimum level suggested for reliability purposes, the release schedule will not be implemented (KPMG, 2010). HERMES then will be rerun to find a release schedule that satisfies the system requirements.

As explained earlier, SPLASH performs the process of optimization for 86 different flow conditions (Kubursi and Magee, 2010). This approach allows consideration of possible flow trends that have happened historically and develop operating plans that satisfy the system requirements under each of these possible flow years. Relying on the historical trends as a predictor of the future climatic conditions can be acceptable for developing short-term operational and resource planning (Papalexopoulos and Hesterberg, 1990). Therefore, it is recommended that MH models are simulated or optimized under future climate conditions.

3.4.5 Inconsistency in Hydropower Generation Coefficients

Hydropower generating coefficients are numerical parameters that convert water flow into hydropower energy by capturing the relationship between water volume, head, forebay elevation, tailrace elevation, and water quantity through the powerhouse (KPMG, 2010). Equation 1 shows the hydropower energy P in Watts as a function of F_b: the forebay elevation in meter, T_w: the tailrace elevation in meter as a function of the downstream elevation (DSE) in meter and Q_T: the total outflow in cms, head $H = F_b - T_w\ (DSE, Q_T)$, Q_p: outflow through the powerhouse in cms, and e: is the unit-less power generation efficiency that is a function of H and Q_p.

Equation 1

$$P = [\ F_b - T_w\ (DSE, Q_T)] \times e(H, Q_p)/11.8^4 \times Q_p$$

In Equation 1, the water flow and head are both variables, making the equation nonlinear. An iterative process needs to be implemented to linearize Equation 1, where an initial estimate of flow calculates the generation coefficients.

HERMES and SPLASH have different simulation time steps, weekly versus monthly, which results in differences in captured flows and therefore in the calculated generation coefficients. The generation coefficients in HERMES are varied with the water volumes, because it uses shorter time steps as opposed to SPLASH where generation coefficients are averaged over one month because of the monthly time steps. These differences in generation coefficients between HERMES and SPLASH might be a big source of uncertainty in financial assessment of the system (KPMG, 2010; Kubursi and Magee, 2010). For example, when the efficiency of the turbine is underestimated due to inaccurate capture of flows, operators will release more water through the power plant, which could have been stored for subsequent use.

3.5 Overview of Suggestions to Address the Limitations

External reviewers provided the following suggestions to improve MH simulation-optimization models by addressing the above limitations:

1. Adding stochastic and nonlinear modules to the problem formulation or using dynamic programming approach where the nonlinear relationships and dependencies between the hydraulic components of the river-reservoir system can be represented, which results in more reliable simulation results (KGS, 2005; KPMG, 2010).

2. Integrating MH simulation-optimization models, which will speed up the process of simulation, eliminate the discrepancies between the modeling results, and provide the ability to operate multiple reservoirs in a stochastic multi-objective framework (Billinton and Karki, 2013; Kubursi and Magee, 2010; Loucks and Costa, 2013).

3. Reformulating the objective function to the minimization of the total cost of generation and delivery or min-max functions such as maximizing the minimum revenue obtained under the worst-case scenario such as 1940 drought or the predicted extreme flood or drought rather than

maximization of the net revenues. These changes can considerably increase the reliability of the system under extreme events (KPMG, 2010; Kubursi and Magee, 2010).

4. Developing multi-objective functions to consider multiple aspects of the system performance such as increasing the system security, reducing shortages in hydropower and water supply, and developing as-yet-unseen policies to handle future climate conditions for both high-flow and low-flow periods to improve the system operations (KGS, 2005).

It should be noted that some of the suggested approaches are not feasible when the complex interconnections and dependencies are under-represented in the model. For example, dynamic programming is not feasible if the hydraulic coupling, the relationship between forebay elevation, tailwater elevation, and releases from reservoirs, between two hydropower reservoirs are not negligible (Teegavarapu and Simonovic, 2002).

No public record exists showing that these suggestions have been tested and compared with MOST, HERMES, and SPLASH results. Literature have reported better outcomes by considering more advanced formulation and optimization approaches. Teegavarapu and Simonovic (2000) developed a short-time operation model for a series of four reservoirs on the Winnipeg River including Seven Sisters, McArthur, Great Falls, and Pine Falls and reservoirs to provide optimal hydropower generation schedules at each of these locations. The model is formulated by the Mixed-Integer Non-Linear Programming (MINLP) (Markowitz and Manne, 1957), and is solved by the General Algebraic Modelling System (GAMS) (Brooke et al., 1996). The hydraulic relationships between the power plants, which is the impact of downstream reservoir lake elevation on the upstream reservoir releases is considered in the model. The total hydropower generation is equal to the weekly hydropower demand and therefore is equal for both EMMA and MINLP models. Whereas, results represented that the distribution of hydropower generation between hydropower plants is different between EMMA and MINLP models. The hydropower generation at Seven Sister and McArthur reservoirs located on the upstream using MINLP is 4.24% and 6.71% higher than the respective hydropower generation values using EMMA. The hydropower generation at Great falls and Pine Falls located on the downstream using EMMA is 4.01% and 5.67% higher than those of MINLP model. This difference is because of the way that EMMA and MINLP consider the hydraulic coupling aspects. As EMMA is formulated by LP, the hydraulic coupling is linearized, and therefore an exhaustive representation of the backwater effect is not possible in this model.

To improve the performance of the model developed by Teegavarapu and Simonovic (2000), they applied Simulated Annealing (SA) (Kirkpatrick et al., 1983), a stochastic search technique, to the same case study (Teegavarapu and Simonovic, 2002). The objective function minimized the total hydropower generation cost. SA algorithm improved the objective function value by 1.5 percent. Besides, the computation time taken for running the model by SA algorithm (10 minutes) was much less compared to that of the MINLP algorithm (25 minutes) on the same computer system.

Reznicek and Simonovic (1992) introduced the General Energy Management by Successive Linear Programming (GEMSLP) to seek for an optimal hydropower system operation for Grand Rapids hydropower generation station, Manitoba, Canada. They used integral regression analysis to address the functional dependencies. Comparing the results of EMMA and GEMSLP clarifies that both are equally capable to model low head plants; however, only GEMSLP applies to high head plants, which is a significant advantage of this model. It is because GEMSLP is capable of taking into account the dependencies between the hydropower generation coefficients; however, in EMMA, no dependency is directly modelled. The incorporation of pertinent dependencies delve to having a more accurate description of the real system.

It is evident that incorporating a comprehensive representation of hydraulic interconnections and dependencies will result in more reliable operational planning, which requires an advanced methodology for problem formulation and optimization approaches. However, a closer look at the literature reveals the complexity of problem formulation using advanced mathematical programming techniques such as nonlinear programming as well as the high computation time taken for running the model.

This fact raises the concern about modeling large-scale case studies using mathematical programming techniques where high number of reservoirs and decision variables considerably enhance the computational effort. For example, a standard, full year HERMES EMMA LP will have over 43,000 constraints and over 100,000 decision variables.

Therefore, reformulating MOST, HERMES, and SPLASH and running them over a long period under different climatic scenarios has an extremely high computational cost.

Because of the complexities of water resources systems and different non-commensurable objectives in managing the water resources systems, using mathematical programming techniques is not proven to be widely useful and efficient for modelling the large-scale systems. Alternatively, using water management models that simulate and optimize water allocation and hydropower generation in large-scale problems is known as an effective tool for analyzing both power and water system operations, providing reliability and security within each system, and helping to provide economically viable solutions (Eichert, 1979; Labadie, 2004).

4 Water Management Models

Water management modelling tools are designed to simulate water allocation within a regulated river-reservoir system to improve water system planning and management processes (Loucks, 2006). These models can be used to test, evaluate and modify water-related planning and management issues such as operating policies, infrastructure designs, and water and power supply agreements and licenses using water management models to develop an appropriate water management approach for large-scale case studies such as the Nelson-Churchill River basin.

Water management approaches vary from case to case and include multiple operational considerations such as flood control, irrigation, water supply, navigation, recreation, water quality, and hydropower generation (Steins and Walther, 2013). Therefore, each of the generic simulation models has specific features such as simulation of hydropower generation, water pollutant distribution, and aquifer analysis that makes them suitable for advanced operating objectives. A number of water management models have combined optimization and simulation as an alternative to simulation only approach so that in cases where conflicting operating objectives exist, tradeoffs between the objectives will be identified (Assaf et al., 2008).

While each water management model has its distinct features, they all are designed to facilitate the storage, input, and a representation of hydrologic and geographic data associated with the basin of interest (Assaf et al., 2008). Input data includes operating policies that represent how water resources are being managed over time and space. The outputs describe the impacts of each operating policy on the entire basin (Assaf et al., 2008; Wood et al., 2013).

The determining factors for selecting an appropriate water management model for a study is the characteristics of the case study and research objectives (Rani and Moreira, 2010). Therefore, understanding the main features of these models and their differences is essential prior to model selection.

4.1 Model Selection

Hydropower generating reservoirs located in the Lower Nelson River Basin (LNRB) are operated as a function of multiple variables including the reservoir forebay elevation, tailwater elevation, downstream reservoirs and lake levels, forecasted inflow, and forecasted hydropower and water supply demand (personal discussion with MH). To simulate the water system operation in LNRB accurately and to address the discussed limitations in Chapter 3, the selected water management model for this research is expected to have the following capabilities:

- To simulate hydropower generating reservoirs based on the power plant efficiency table, penstock capacity, and multiple reservoir outlets and their characteristics.
- To specify separate timescales for short-term, mid-term, and long-term operation of the system
- To be open source or customizable for specialized operating rules
- To incorporate non-linear representation of complex interconnections and relationships among the river-reservoir system components.
- To define reservoir operating rules not solely as a function of the physical characteristics of reservoirs such as water level, storage, and outlet capacities, but also considering hydropower and water supply demands, downstream reservoirs and lakes elevations, water regulation and licenses, climatic conditions such as dry or wet years.

Beside these capabilities and for the purpose of research, the selected water management models should be free of charge, must be supported by peer-reviewed studies (Koch and

Grünewald, 2009; Lippai et al., 1999; Middelkoop et al., 2001), must be computationally efficient for fast simulation of multiple operating policies at different time scales (Barritt-Flatt and Cormie, 1991b, 1989), and must accurately simulate both hydropower generation and water supply systems by providing reliable solutions (Le Xie et al., 2011).

Sulis and Sechi (2013) compared the capabilities of MODSIM (Colorado State University), WEAP (Stockholm Environmental Institute), AQUATOOL (Valencia Polytechnic University), RIBASIM (Delft Hydraulics), and WARGI-SIM (University of Cagliari) models and reported MODSIM and WEAP as appropriate models for evaluating alternative operational plans and operating policies in complex water system. Razavi et al. (2018) compared WEAP, MODSIM, MIKE HYDRO Basin (DHI group), RiverWare (University of Colorado Boulder), HEC-ResSim (U.S. Army Corps of Engineers), and WRIMS also known as CalSim (California Department of Water Resources) and reported MODSIM, WEAP, and WRIMS as the most flexible models for representing complex operating policies.

Using the result of these studies as well as studying the user guide documents of these water management models, MODSIM (Labadie, 2006), WEAP (Stockholm Environment Institute, 2005), and WRIMS also known as CalSim (Draper et al., 2004) were selected as the potential water management modeling tools with the ability to simulate hydropower generation and complex operating policies. Each of these models has its unique features compared in Table 3. The evaluation criteria for this comparison are the associated price or license fees, simulation time-step, Graphical User Interface (GUI), input and output data format, input and output data units type (metric or imperial), GIS interface, user accessibility to the source code (open source or not), and ability to perform scenario analysis, reservoir operation, hydropower modeling, and customize the decision variables, parameters, and functions without changing the source code. These criteria are selected according to the highlighted features in the user guidelines and the comparison criteria suggested by peer-reviewed studies (Labadie, 2004; Sulis and Sechi, 2013; Wurbs, 2005).

Table 3. Water management models comparison

Model name	**MODSIM**	**WRIMS**	**WEAP**
Cost	Free	Free	$250 - $1000 US $ / 2yrs
Simulation time step	15 minutes–1 month	1 day or 1 month	1-365 days
GUI	Yes	No	Yes
Input data format	Time series (manual/Excel)	HEC-DDS and text file	Time series (manual/Excel)
Output data format	Graphics, ASCII, Excel	HEC-DDS and text file	Graphics, ASCII, Excel
Data unit type	Metric & Imperial	Imperial	Metric & Imperial
GIS interface	Yes	No	Yes
Open source	No	Yes	No
Scenario analysis	Yes	Yes	Yes
Reservoir operation	Yes	Yes	Yes
Hydropower modelling	Yes	Yes	Yes
Customization	Yes	Yes	Not by users

According to Table 3, WEAP is not freely available for research purposes and users need to purchase its license. Users do not have access to its source code, nor can they customize the decision variables and functions to define complex interconnection and operating policies of the real case studies. Therefore, WEAP is not recommended for simulating the MH river-reservoir system.

Both WRIMS and MODSIM are freely available for research purposes. WRIMS is open-source and users are able to define complex relationships and operating policies to improve the representation of their system of interest. Although MODSIM is not an open-source program, users have access to all its parameters, public variables, and object classes to develop any knowledge-based operating policies or rule curves through Custom Code Editor (Labadie, 2004). This user-supplied code can be written in C#.NET or VB.NET languages and at any desired strategic location such as at the beginning, in the middle, and at the end of any time step or iteration. Although WRIMS is an open source program which gives users a greater flexibility for advanced computations and designs, and problem-solving approaches, MODSIM provides the required customization flexibility for simulating complex operating policies of MH river-reservoir system.

In WRIMS, users can only insert input data or extract output data using HEC-DSS (Data Storage System) database file. However, MODSIM provides flexibility to insert data manually or from Excel database files. Graphical representation of input and output data in MODSIM helps the user to achieve a quick understanding of the simulation results.

The simulation time step in WRIMS can be selected in either a daily or a monthly basis and therefore weekly or bi-weekly time steps cannot be simulated and analyzed. However, users can select any time step between 15 minutes up to 1 month in MODSIM which makes it appropriate for MH desired short-term (hourly), mid-term (weekly), and long-term (monthly) analysis.

The GUI for MODSIM provides spatially referenced database capabilities, which allow users to create river-reservoir system components such as reservoirs, channels, and diversions on display. This feature not only speeds up the process of modeling but also provides a strong visualization capability and a better understanding of the system network for users. However, WRIMS users need to specify and define all the system components, connections, and relationships in the WRESL language.

Input data can be inserted in MODSIM in SI or Imperial system of unit or a combination of both, which highly reduces the risk of any mistake in data unit conversions. This flexibility is not provided in WRIMS as its users need to use HEC-DSS database file format that only accepts Imperial units.

4.2 MODSIM Applications

The scientific literature of water resources planning and management shows that MODSIM has been extensively applied by private and governmental organizations to complex river-reservoir system operations throughout the world (Labadie, 2004). The most significant applications of MODSIM are summarized in Table 4.

Table 4. Outstanding MODSIM applications

Case study	**Study objective(s)**
Rio Grande River Basin (Graham et al., 1986)	To determine how additional flows from planned Silva-cultural activities would be allocated to downstream users considering complex in-state water rights and agreements. In addition, the impact of possible future storage facilities are evaluated.
Upper Pampanga River Basin (Graham et al., 1986)	To improve the efficiency of the integrated irrigation system located in this basin and balance irrigation supply and hydropower generation. The possible expansion of the channel capacities for the future water distribution network is evaluated.
Colorado-Big Thompson River System (Law and Brown, 1989)	To simulate and predict the impact of a proposed reservoir on the Cache La Poudre River and determine an optimal operational management plans by investigating different management options.
Piracicaba River Basin (Azevedo et al., 2000)	Joint application of QUAL2E-UNCAS, water quality model, and MODSIM to evaluate strategic planning alternatives for satisfying water demands and providing acceptable water quality considering reliability criteria.
Klamath River Basin (Campbell et al., 2001)	Joint application of MODSIM and HEC-5Q, water quality model, to explore operating plans for improving summer and fall water quality conditions and fish habitat.
Upper Snake River Basin (Miller et al., 2003)	Joint application of MODSIM and MODFLOW, groundwater model, to quantify impacts of proposed storage rental and water allocation scenarios on water supply, reservoir recreation, wildlife, and local water uses.
Nakdong, Geum, and Yeongsan-Seomjin rivers (Yoo, 2005)	To evaluate the water supply reliability according to future the climatic conditions and disputes of water rights and licenses between inter-basins.
San Joaquin River (Marques et al., 2006)	To investigate the impact of increased water prices, changes in reservoir operations, groundwater contribution, and environmental flows and determine the best water management options.
Lower Arkansas River basin (Triana and Labadie, 2007)	Integrating GIS and MODSIM and developing GEO-MODSIM for salinity and irrigation management by incorporating different geodatabase layers.
Sirvan basin (Shourian et al., 2008)	Joint application of MODSIM and Particle Swarm Optimization (PSO) to evaluate the fitness of suggested design of dams and water transfer systems by optimizing design and operational variables.
Awash River Basin (Berhe et al., 2013)	To evaluate the impacts of four water withdrawal rate scenarios to provide a reliable water management plan under future climatic conditions.
Geum River Basin (Ahn et al., 2016)	Joint application of SWAT, watershed-scale hydrologic model, and MODSIM to evaluate the impacts of future climate change and drought threats on the irrigation facilities and agricultural water supply capacities.
Karkheh River Basin (Ashraf Vaghefi et al., 2017)	Joint application of SWAT and MODSIM to examine the water productivity of irrigated maize and wheat yield.

Overall, MODSIM seems to fit the desirable features and characteristics of a water management model due to free availability, customizable modeling capabilities, user interface, and the flexibility in defining the simulation time steps and input and output data format. Detailed information about MODSIM structure and capabilities can be found in the user guide document on the Colorado State University website (Labadie, 2004).

Components of a river-reservoir system in MODSIM are represented as a network of nodes including non-storage, storage, demand, and sink nodes. The schematic representation of the network of nodes is shown in Figure 4. Non-storage nodes are represented by blue circles and account for diversion points, river confluences, and location of demands, local flow, and other types of water contributions to the system. Storage nodes are represented by the red triangular icon representing groundwater basins, reservoirs, lakes, and storage right accounts. Links or arcs are represented by black lines, which also sets the flow direction for that link. Water demands in MODSIM are represented by purple square icons representing consumptive or flow through demands. A consumptive demand results in consumption of a portion of the diverted flow to the demand whereas in a flow through demand, the diverted flow will come back to the system at another location specified by the users. The green square icon represents the river basin outlet where all the flows will eventually drain into. Detailed explanation about the functionality and features of these nodes can be found in MODSIM user manual uploaded on the University of Colorado website.

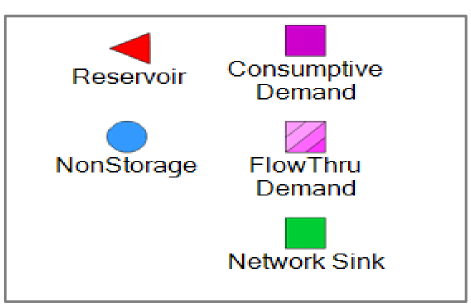


Figure 4. MODSIM node palette

5 Methodology

5.1 Data provided by MH

Reliable input data is the key to a successful MODSIM model development. MH as the operator of the river-reservoir system in Manitoba is the main source of data for this research. Experts from the Energy Operations and Technology Department of MH provided the following data sets:

5.1.1 Inflow time series

MODSIM requires forcing inflow to a system that is the sub-basin of a larger basin. The river-reservoir system simulated in this research is the downstream sub-basin of the Nelson-Churchill Rivers basin. Therefore, inflows from the upstream system is required to develop its MODSIM model. MH provided the following key inflow datasets:

- Time series of inflows for the period of 1980/01/01 to 2018/01/01 to the system including upstream inflow at Grand Rapids and SIL, which are the main forcing of the MH river-reservoir system
- Local inflows for the period of 1980/01/01 to 2018/01/01 to upstream of the reservoirs

5.1.2 Uncontrolled and Regulated Lakes

The main driver of uncontrolled and regulated lakes is the stage-storage-discharge relationship that is among the following datasets provided by MH.

- Daily lake elevations for the period of 1980/01/01 to 2018/01/01
- Daily local inflow time series to the lakes for the period of 1980/01/01 to 2018/01/01
- Daily releases from the lakes for the period of 1980/01/01 to 2018/01/01

- Stage – Storage curves that describe the relationship between the lake elevation and storage volume. These curves are provided for SIL, Notigi, Wapisu, Footprint, Opegano, Birchtree, Cross Lake, Sipiwesk, and Split Lake. An example of the stage-storage curves is provided below in Table 5.

Table 5. An example of a stage-storage curve

Elevation (ft)	**Storage (kcfs-days)**
778.00	0.00
778.72	2.83
779.44	6.96
780.17	11.80
780.89	17.13
781.61	22.88
782.33	28.99

- Stage – Discharge rating curves that describe the relationship between the lake elevation and the outlet discharge rate. An example of these curves is shown in Table 6:

Table 6. An example of a stage-discharge rating curve

Elevation (ft)	**Discharge (kcfs)**
778.21	0.09
780.31	1.09
781.56	2.07
782.61	3.10
783.53	4.14
784.38	5.22
785.20	6.35

5.1.3 Hydropower Generating Reservoirs

- Daily reservoir elevations for the period of 1980/01/01 to 2018/01/01
- Daily local inflow time series to reservoirs for the period of 1980/01/01 to 2018/01/01

- Daily releases from the reservoirs for the period of 1980/01/01 to 2018/01/01
- Daily hydropower generation at each reservoir for the period of 1980/01/01 to 2018/01/01

  It should be noted that, Wuskwatim and Limestone came into service in 2012 and 1991, respectively, and their data sets start respectively from 2012 and 1991.
- Stage – Storage curve for Wuskwatim, Grand Rapids, Jenpeg, Kelsey, Kettle, Long Spruce, and Limestone.
- Efficiency curves that describe the relationship between head at the hydropower generating station, flow through the powerhouse, and power plant efficiency. Head is defined as the forebay elevation minus tailrace elevation. Efficiency curves are provided for Wuskwatim, Grand Rapids, Jenpeg, Kelsey, Kettle, Long Spruce, and Limestone.

5.1.4 Additional data

- Lake-outlet mapping file that represent the schematic of the system network.
- Backwater-affected rating curves that describe the relationship between the lake elevation, downstream elevation, and outlet discharge. The relationship is provided for Nelson East, Nelson West, and South Bay channels. An example of the backwater-affected curve is given in Table 9.

5.2 MODSIM Implementation for the River-Reservoir System Operated by MH

Two versions of the SMPM model are set up for the MH river-reservoir system: the “mass-balance” and the “operational” models. The mass-balance model is developed to simulate the historical scenarios including historical inflow to the reservoirs, outflow from the reservoirs, water levels, and hydropower generation at hydropower reservoirs. Implementation of the mass-balance model helps to validate the input data and simulation logics. The name “mass-balance” is chosen because the components of the mass-balance equation including the storage targets at the reservoirs and inflow time series to the system are set in the model based on the historical information. The model therefore meets the storage targets and releases the rest of the water as outflow from the reservoir. Considering that the historical inflows and storage values are known (data provided by MH), if the mass-balance model is set up properly with the correct system hydraulic representation, it is expected to simulate the historical system behavior very accurately.

Because storage targets are not available for future climate scenarios, the mass-balance model cannot be applied for simulating and evaluating the system under future climatic conditions. Therefore, the “operational” model is developed to represent the operations without the need for specifying storage targets based on daily measured data over the whole simulation period. The main difference between the mass-balance and operational models is therefore the representation of storage targets. A similar river-reservoir network schematic is set in both models. The outcome of this research is the operational version of SMPM.

5.2.1 Implementation of River-Reservoir Network

A schematic diagram of SMPM developed in MODSIM for the MH river-reservoir network is shown in Figure 5. Red triangular nodes account for controlled points and uncontrolled lakes in the system. Downstream and upstream points at each reservoir are represented by adding DS and US after the name of the reservoir. For instance, LW_US and LW_DS represent the upstream and downstream points at Lake Winnipeg, respectively. This way of representation allows defining the exact location of the local inflows to the system as well as regulating inflow and outflow. Local inflows to the system are represented by adding LF after the name of the reservoirs or lakes. For example, Footprint_LF accounts for the local inflow coming to the system at the upstream of Footprint. Local demands in the system are specified by adding LD after the name of reservoirs. The local demands are not actual water supply demands but account for water losses in the system. Hudson Bay is the outlet of the system provided by MH where all the water eventually drain into.

Because of the limitations imposed by data availability and operating details, adequate representation of the operations at SIL, Notigi, and Grand Rapids was challenging that will be explained in Chapter 6. Since these points are located upstream of the system, they have a significant contribution to the simulation of all other nodes in the system. Therefore, as shown in Figure 5, the outflow from these locations is drained into "Sink3" and "Sink", respectively. The historical outflow from Notigi and Grand Rapids are considered as inflow nodes to the system. In addition, "LWF_Calib" and "LWD_Calib" are inserted to calibrate the outflow from Lake Winnipeg based on the historical records by subtracting and adding water to the system.

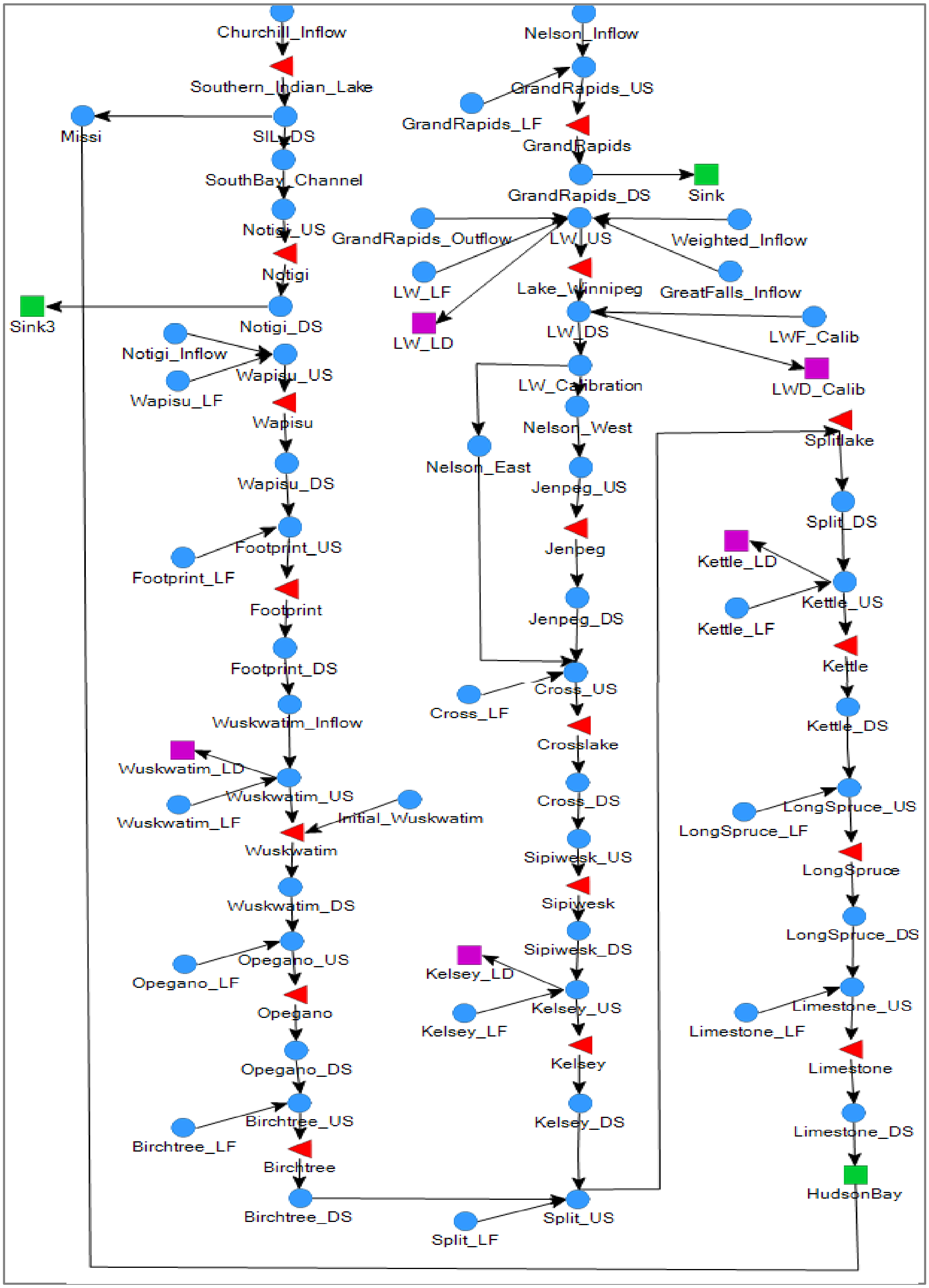


Figure 5. Schematic of SMPM configured in MODSIM for the river-reservoir system operated by MH

5.2.2 Similarities and Dissimilarities between MH Simulation-Optimization Models and SMPM

Complexity is a characteristic of any water resources system and arises under the interaction between the hydraulic components of the system (Paul Cilliers et al., 2013). The simulation of the complex interconnection between the river-reservoir components therefore requires large computational budgets, highly functional water management simulation-optimization packages, and the availability of accurate data for representing both hydrological processes as well as the system operations. Therefore, the simplification of the complicated hydraulic relationships between the network components is a common practice for simulating the water resources systems (Labadie, 2006; Paul Cilliers et al., 2013; Sulis and Sechi, 2013). The following simplifications are made by MH to set up the simulation-optimization models:

5.2.2.1 Lake Winnipeg Downstream Components

The system network hydraulics between Lake Winnipeg and Jenpeg is very complex and includes the Two-Mile Channel, Eight-Mile Channel, Ominawin Bypass Channel, Kisipachewuk Channel Improvement, and Jenpeg to control water flows as well as Kiskitto Lake Inlet Control Structure, Black Duck Control Structure and Stan Creek Diversion to limit the forebay flooding (Manitoba Hydro, 2014). The location of these components is shown in Figure 6. Based on personal communications with MH, these system components are simplified into three reservoirs including Lake Winnipeg, Jenpeg, and Cross Lake, and three outlets including Nelson West Channel, Nelson East Channel, and Jenpeg outlets in the simulation-optimization models. Therefore, outflow from Lake Winnipeg is controlled by the Jenpeg forebay level that has a backwater effect on the outflow from Lake Winnipeg through the Nelson West and East Channels. For the Nelson East channel, the outflow relationship is represented by Jenpeg forebay as the downstream condition and Lake Winnipeg as the upstream condition. Following MH system configuration, it is assumed in this thesis that the Nelson West and Nelson East Channels are two separate outlets of Lake Winnipeg where Nelson West Channel flows into Jenpeg and Nelson East Channel discharges into Cross Lake. The backwater effect relationships for these channels are formulated in the MODSIM custom code editor.

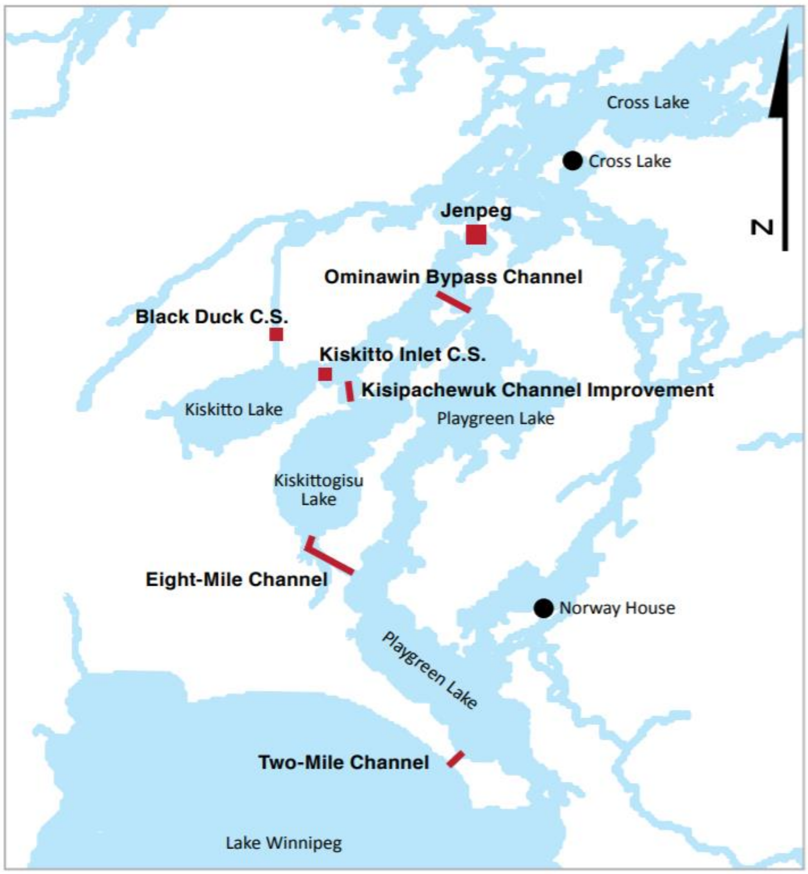


Figure 6. Lake Winnipeg downstream components (Manitoba Hydro, 2014)

5.2.2.2 Lake Winnipeg Inflows Routing

Lake Winnipeg receives inflows from Pigeon River, Bloodvein River, Dauphin River, Gunisao River, Lake Winnipeg local inflows, Poplar River, Red River, Pine Falls releases, and Grand Rapids releases. The historic inflow time series as well as inflow factor for each inflow into Lake Winnipeg are provided by MH. Inflow factors for Pigeon River, Bloodvein River, Fairford

River, Gunisao River, Lake Winnipeg local inflows, Poplar River, Red River, and Bird River are 1.81, 1, 1, 2.18, 1, 1.38, 1, 1.14, respectively. The inflow time series at each location is multiplied by the corresponding inflow factor. The total inflow from these locations is inserted in "Weighted_Inflow" node shown in Figure 5.

According to the personal communication with MH, inflows routing in the Lake Winnipeg is simplified assuming all inflows accumulate into the lake on arrival date, without considering any travel time. Local inflows are also calculated based on an averaged, wind-eliminated Lake Winnipeg elevation from multiple gauges. In this thesis, an instantaneous accumulation into the lake is assumed for all inflows, regardless of their location.

5.2.2.3 Southern Indian Lake (SIL) Outlets

Two outlets convey the water out of SIL, one of which is called South Bay Channel that flows to Notigi and another outlet at Missi Falls Control Structure. South Bay Channel is backwater-controlled by the water elevation in Notigi forebay. Based on the personal communication with MH, adequately representing the hydraulics of the Notigi-South Bay Channel-SIL location has been challenging for MH. To improve the representation of the complex hydraulic relationships, instead of following the assumption by MH, the operation of South Bay channel is customized in MODSIM, and therefore both outlets are represented in the MODSIM river-reservoir network configuration.

5.2.3 SMPM Model Configuration

In the following, the configurations of uncontrolled lakes, hydropower generating reservoirs, and channels that are similar in both mass-balance and operational models are explained.

5.2.3.1 Lakes

Cross Lake, Sipiwesk, Split Lake, Wapisu, Footprint, Opegano, and Birchtree are uncontrolled (natural) lakes in the river-reservoir system. Lake Winnipeg, SIL, and Notigi are regulated lakes. Forebay of Grand Rapids, Wuskwatim, Jenpeg, Kelsey, Kettle, Long Spruce, and Limestone hydropower generating stations are considered as controlled lakes in the model. The following general steps are taken for setting up lakes in MODSIM. Additional steps that are required to set up controlled lakes in MODSIM are explained in Section 5.3 and Section 5.4.

1. Specifying of the maximum, minimum, and initial storage volume
2. Based on the personal communication with MH, there is no actual "maximum volume" for uncontrolled reservoirs as if more water were to inflow than it can outflow, the water elevation would continue to rise. However, the stage-storage relationships provided by MH contain elevations higher and lower than the historic elevations that are used for setting up the maximum and minimum storage volume in SMPM. The minimum storage volume represents the lowest active storage volume above the dead storage volume. The initial storage volume is defined as the historic storage volume in the first day of the simulation period in the mass-balance model. This value is defined as the long-term average of the historic storage volumes in the operational model setup.
3. Evaporation from the surface and water seepage from the bottom of the lakes

The data set provided by MH for this research includes the net streamflow time series to the system where losses from the system including evaporation, seepage, and other types of water losses are already considered in the inflow time series. Therefore, the simulation of evaporation and groundwater seepage losses are turned off in SMPM.

Table 7. Maximum, minimum, and initial storage values at reservoirs

	Maximum storage ($1000m^3$)	**Minimum storage ($1000m^3$)**	**Initial storage ($1000m^3$)**
Kettle	1933288	72159	867279
Long Spruce	112676	5687	111925
Limestone	386803	10520	0
Kelsey	6000977	728	54009
Wuskwatim	696298	782	0
Jenpeg	415817	16632	246816
Grand Rapids	15870865	475890	7429059
Split Lake	1696727	82595	932704
Sipiwesk	5089838	175868	2450581
Cross Lake	3333876	90501	1427126
Lake Winnipeg	118972661	7318692	31953410
SIL	10586634	115083	4830618
Notigi	2423400	506609	1633769
Wapisu	452458	1907	602261
Footprint	1055257	732	538575
Opegano	25829	446	16292
Birchtree	41516	956	31472

4. Area/Capacity/Elevation/Hydraulic capacity

Stage-storage and stage-discharge relationships provided by MH are used to define relationships between the reservoir forebay elevation, storage, area, and the maximum hydraulic capacity of the outlet. For some of the reservoirs such as Jenpeg and Long Spruce, only the minimum and maximum elevation and storage are provided. A linear interpolation between these values is implemented to extend the table and include more data points. Based on the personal communication with MH, the rating curves act as outflow capacity for uncontrolled outlets and therefore can be considered as hydraulic capacities. However, the hydraulic capacity of outlets at controlled lakes tend to be much larger (at least 20%) than the historical inflows and therefore a large hydraulic capacity (10000 cms) is defined for controlled lakes. The simulation results are analyzed and compared to the historic outflow for reasonableness. A similar approach is taken in MH operations modeling as flows do not typically approach the capacity limits. An example of A/C/E/Hydraulic capacity table is provided in Table 8.

Table 8. An example of A/C/E/Hydraulic capacity table

Area (m2)	**Capacity (m3)**	**Elevation (m)**	**Hydraulic capacity (cms)**
0	0	237.13	0
3088.58	732611	237.20	2
29044.81	6893898	237.35	9
71849.54	17069532	237.57	19
121491.86	28890255	237.80	28
132030.90	31402232	237.84	30
175831.69	41850628	238.02	43
230686.18	54954085	238.22	59
234740.19	55923266	238.23	60
297451.98	70928669	238.45	80

5.2.3.2 Hydropower Generating Reservoirs

Grand Rapids, Wuskwatim, Jenpeg, Kelsey, Kettle, Long Spruce, and Limestone are the hydropower generating reservoirs in the MH river-reservoir system modeled in MODSIM. The model configuration in terms of the maximum, minimum, and initial storage volumes, and evaporation and groundwater seepage rates for these lakes are similar to those for the uncontrolled lakes.

1. Hydropower generation setup

MODSIM requires the specification of power plant efficiency relationship, head, maximum power plant capacity to generate hydropower, and generating hours to calculate the generated hydropower. The power plant efficiency relationships and maximum power plant capacities are provided by MH. Head is defined as the difference between forebay elevation and tailwater elevation where forebay elevations are calculated based on the water volume in the reservoir at the end of the time step converted to the elevation using A/C/E/Hydraulic capacity relationship. Plant elevation values are defined as constant elevation and are calibrated manually to match the historical head values. The calibrated plant elevation at Grand Rapids, Jenpeg, Kelsey, Wuskwatim, Kettle, Long Spruce, and Limestone are 220, 207.79, 168.5, 208, 109, 84, and 42 meters above sea level, respectively.

2. Hydropower generation targets

Hydropower generation targets or demands in MODSIM can be specified by using the advanced hydropower extension. This extension is newly developed in MODSIM and has not been included in the MODSIM user manual. However, Dozier (2012) provided a helpful explanation of this feature. Hydropower generation targets are set based on the historic hydropower generation time series provided by MH.

5.2.3.3 Channels Setup

Based on personal discussion with MH, the channel capacities to convey water tend to be much larger than the historical flow time series, and therefore no upper bound is defined for the channels. Because the provided flow time series are net flow time series where the water losses are included in the data, the water losses from the channels are set to 0.

5.2.3.4 Backwater-affected Channels Setup

Nelson West and East Channels located in the outlet of Lake Winnipeg as well as the South Bay Channel located in the outlet of the SIL are backwater-affected by the downstream reservoirs. Therefore, an adequate representation of the complex hydraulic relationships can only be achieved by customizing the model setup through MODSIM custom code.

Backwater-affected relationships at these channels represent the relationship between the downstream reservoir forebay elevations, upstream reservoir elevation, and flow rate in the channel. A portion of an example of the backwater-affected stage-discharge relationships is provided in Table 9.

Table 9. Part of an example backwater-affected (3D) stage-discharge relationship

US_lvl (m)	**Q (cms)**	**US_lvl (m)**	**Q (cms)**	**US_lvl (m)**	**Q (cms)**
DS_lvl = 213.51(m)		**DS_lvl = 213.81 (m)**		**DS_lvl = 214.12(m)**	
213.51	0	213.82	0	214.12	0
213.64	283	213.84	109	214.16	142
213.94	566	213.88	187	214.24	283
214.12	708	213.93	273	214.36	425
214.30	850	214.01	364	214.50	566
214.49	991	214.15	501	214.66	708
214.68	1133	214.25	591	214.83	850
214.87	1274	214.41	726	216.42	2210
215.07	1416	215.56	1642	216.81	2556

A similar table is provided for different downstream elevation and therefore to simulate the hydraulic relationships accurately, the discharge rate should be calculated based on the downstream and the corresponding upstream elevation-discharge table.

A Visual Basic script is developed in the MODSIM custom run editor to emulate the operation of Nelson West Channel, Nelson East Channel, and South Bay Channel in SMPM. Lake Winnipeg outflow is controlled by Nelson East channel and Nelson West channel and an adequate representation of operations in one of the channels leads into a proper simulation of operations in another channel. Therefore, the script is developed for simulating the backwater relationships at Nelson East and South Bay channels.

The following steps are taken to code the operations in Nelson East Channel. Similar steps and logic are followed to emulate the backwater relationships at South Bay Channel. These scripts are kept the same in the mass-balance and operational versions of SMPM.

Step 1: Regression equations are developed to represent the relationship between the upstream elevations and discharge rate with respect to the downstream elevations. According to Table 9, each downstream elevation corresponds to a table representing upstream elevation – discharge relationships. Therefore, multiple regression equations are developed to represent the three dimensional (3D) stage-discharge relationships. For instance, ten tables are provided by MH for Nelson East channel. Each table represents the relationship between Lake Winnipeg forebay elevations and discharge from the lake at a specific Jenpeg forebay elevation. To develop the regression equations, the following nonlinear equation is fitted to each one of those tables independently.

$$Y = a(X - c)^\wedge b \quad \text{Equation 2}$$

Where Y represents the discharge rate in cms, X represent the upstream lake forebay elevation in meter (e.g. Lake Winnipeg forebay elevation for Nelson East channel), and a, b, and c are the nonlinear regression coefficients that are calibrated by function of MATLAB with 100 independent trials to minimize the sum of absolute error (SAE) between the fitted curve and the data provided by MH, see Equation 3. As shown in **Error! Reference source not found.**, the fitted curves simulate the data provided by MH very accurately, so it is concluded that SAE is a proper metric for this curve fitting experiment.

$$SAE = \sum_{i=1}^{N} |x_i - y_i| \quad \text{Equation 3}$$

Where N is the number of data points, x_i is data in the backwater-affected rule curves, and y_i is the estimated data by the regressions. The SAE values at Nelson East channel and South Bay channel are less than 0.24, which indicates a very accurate representation of the hydraulic relationships by regressions. The calibrated regression functions are considered confidential and therefore the calibrated value of a, b, and c are not reported in this thesis.

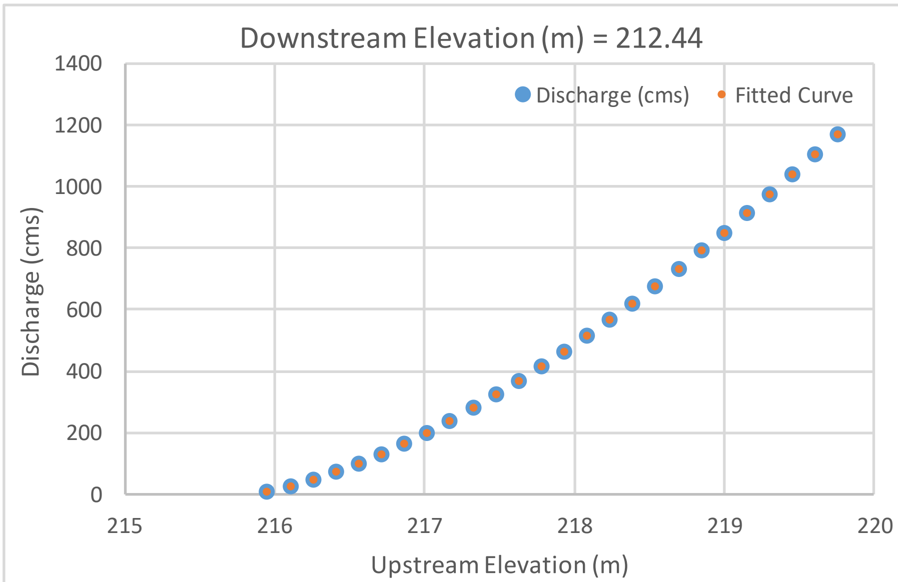


Figure 7. An example of a non-linear curve fitted to a backwater-affected stage-discharge relationship

Step 2: Backwater-affected rule curves are coded in MODSIM custom code editor. The code is developed in Visual Basics (VB) based on the following steps:

1. The Jenpeg forebay elevation at the current time step is read.
2. The Lake Winnipeg forebay elevation at the current time step is read.
3. A set of if-then statements are coded in VB that specifies the corresponding regression equation to each downstream forebay elevation.
4. The discharge rate from Lake Winnipeg is calculated using the regression equation from step 3.
5. The minimum channel capacity is set to the calculated discharge from step 4. The maximum channel capacity is set equal to the minimum channel capacity plus 5 cms as

assigning the same upper and lower bounds for channels capacities may result in infeasibility.

6. The Jenpeg forebay and Lake Winnipeg forebay elevations for the next time step are updated based on the end of the time step water level at Jenpeg and Lake Winnipeg.

MODSIM users have to specify the precision level for its internal calculations. Through some trial and error experiments, the regression functions are revised to make sure that these internal processes are properly performed on the regression functions by MODSIM. Since a precision level of two decimal places is selected in the model, constant value of 100 is used as shown in the sample of VB script below, where numbers highlighted in red are the multiplier. Part of an example script coded in MODSIM custom editor is shown in Figure 8 where DS_lvl and US_lvl are respectively downstream and upstream water elevation, and Discharge.lo and Discharge.hi respectively represent the lower and upper bound of the channel flow capacities.

```
IF DS_lvl <= (213.6648×100) THEN
Discharge.lo = (148.77×((((US_lvl-(215.8×100))/100)^1.5)×100))
Discharge.hi = (148.77×((((US_lvl - (215.8×100))/100)^1.5)×100)) + 5×100
ELSEIF DS_lvl <= (213.8111×100) AND DS_lvl > (213.6648×100) THEN
Discharge.lo = (156.03×((((US_lvl - (215.8×100))/100)^1.5)×100)
Discharge.hi = 156.03×(((( US_lvl - (215.8×100))/100)^1.5)×100) + 5×100
ENDIF
```

Figure 8. Part of an example VB script coded in MODSIM for backwater-affected rule curves.

5.2.3.5 Ice Impacts on Backwater-affected Rule Curves

In cold regions such as the study area of this research, rivers and reservoirs can be covered by ice in a relatively large portion of each year (Manitoba Hydro, 2005). The ice cover increases the friction against streamflow and therefore affects the shape of the stage-storage, stage-discharge, and efficiency curves (Gebre et al., 2014). For example, the ice cover at the outlet of Lake Winnipeg reduces the capacity of the channels to convey water and therefore the amount of outflow from this lake (Manitoba Hydro, 2014). In addition, as winter progresses the ice cover becomes thicker gradually and reduces the discharge rate more significantly (Manitoba Hydro, 2014).

As discussed earlier, the flow rate is one of the critical elements in the hydropower generation equation, which motivated this study to investigate whether the impact of the ice cover is addressed in the 3D stage-discharge relationships. To this end, a MATLAB script is developed that reads the historical forebay elevation at Jenpeg and Lake Winnipeg and simulates the corresponding discharge rates using the 3D stage-discharge relationship at Nelson East channel. The simulated discharge rate at Nelson East channel is then compared to the historical discharge rates to investigate if the backwater-affected rule curves represent the ice formation impact on the discharge rate. Similar MATLAB scripts are developed for the South Bay Channel and Nelson West Channel. The simulated and historical discharges are plotted in Figure 9 for the period of 1980 – 1985 and 2013 – 2018, respectively. These periods are selected as representative of the whole simulation period starting from 1980 until 2018. Comparing the grey line and blue line in Figure 9 illuminates that the 3D stage-discharge curves provided by MH adequately represent the outflow in spring, summer, and fall; however, they are not representative for the ice-on (winter) season. To improve the winter outflow representation in Nelson East channel, Nelson West channel, and South Bay Channel, seasonal calibration is implemented by taking the following steps:

1. The measured (historical) discharge is divided by the simulated values calculated by the 3D stage-discharge curve for the whole simulation period, 1980 until 2018.
2. The Box and Whisker plot is developed for the 365 days of a year (see Figure 9).
3. The median value of the coefficients in the box plots is selected as the ice-on correction factor.
4. The simulated discharge is divided by the ice-on correction factor.

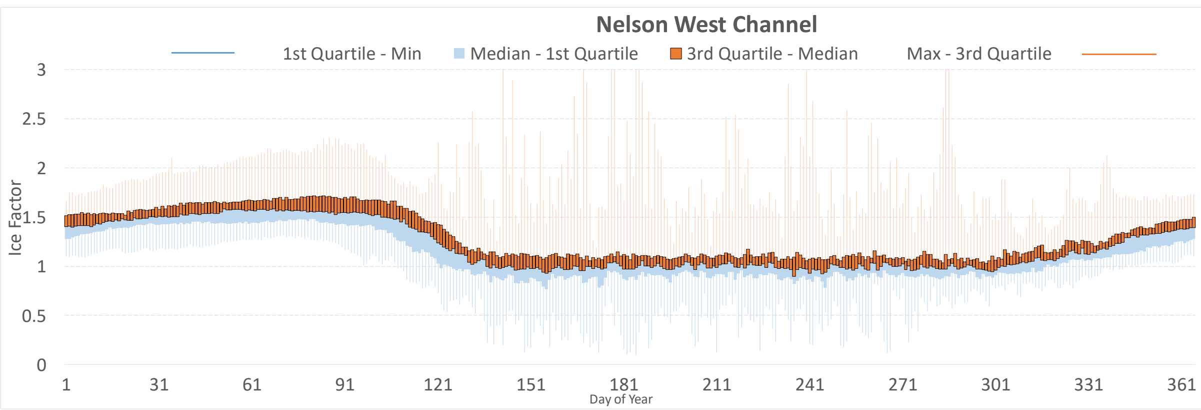


Figure 9. The Box and Whisker plot developed for ice factor in Nelson West Channel

Figure 9 suggests that, the median of the ice factor is around 1.5 during ice-on season in the beginning of each year and gradually starts to decrease around the end of March when the ice starts to break up. The ice coefficient stays around 1.0 in the ice-off season and gradually increase as ice cover starts to form in the beginning of November. The deviation from 1.0 in the ice-off season is primarily due to the wind effect and vegetation that causes resistance against flow.

The seasonal ice factor is developed at Nelson East and South Bay channels to incorporate the ice-on condition in backwater-affected rule curves. The MATLAB simulation result of the hydraulic relationships at Nelson East channel after applying the seasonal ice factor is shown by the orange line in Figure 10. This simulation results show a better representation of historic flow trends in ice-on condition is expected after applying the seasonal ice factor, which will be discussed further in Chapter 0. A similar approach is used by MH to adjust the rating curves during the ice-on season.

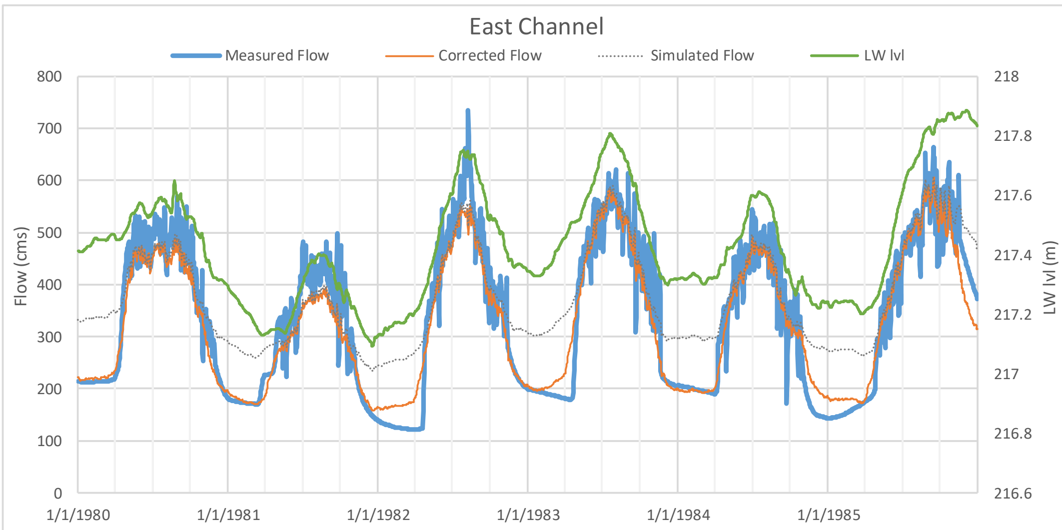


Figure 10. Nelson East Channel backwater-affected rule curve simulation from 1980 until 1985

As shown in Figure 11, the time series of the ice-on correction factors are included in MODSIM as nodes that are separate from the system hydraulics but can be accessed during the custom run simulation.

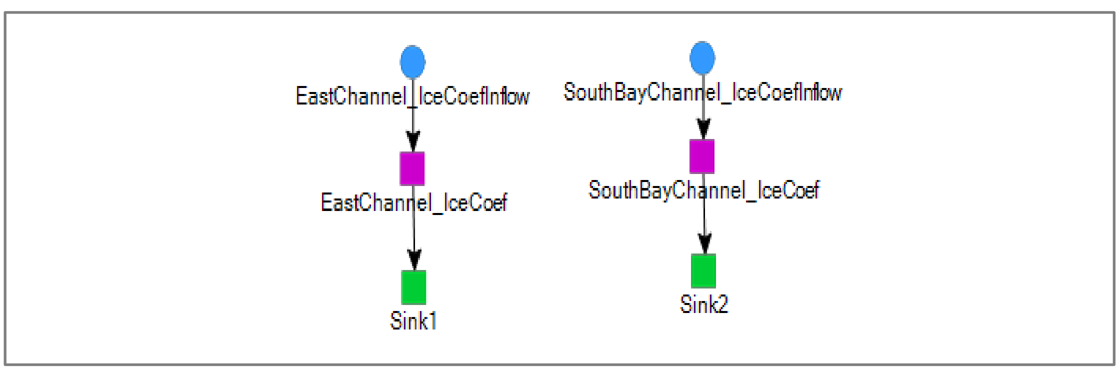


Figure 11. Seasonal calibration coefficient implementation in MODSIM

The regression developed in the custom code editor (see section 5.3.3.4) are then divided by the daily ice coefficient.

5.3 Mass-Balance Model Setup

The mass-balance model is developed to validate the current setup of the river-reservoir network including uncontrolled lakes, hydropower generating reservoirs, and channels compared to the historic observed system behavior. This model ensures that data provided by MH as well as the assumption made to configure SMPM are representative of the physical characteristics of system components and the existing hydraulic relationships.

To develop the mass-balance model, target storage levels are defined for forebay elevation at each controlled point and uncontrolled lake based on the historic (measured) water elevation. The reservoir target storage levels in MODSIM represent the top of the active storage of the reservoir and determine the volume of water that should be stored in the reservoir at each time step. The amount of outflow at each time step is therefore calculated by following the mass-balance concept. For instance, if t represents the time step, I_t represents the amount of inflow to a reservoir, Q_t represents the amount of outflow from the reservoir, and S_t represents the storage in the reservoir which is equal to the reservoir target storage level at this time step, the mass-balance equation is:

$$Q_t = I_t + S_{t-1} - S_t \qquad \text{Equation 4}$$

Because the inflow to a reservoir and the target water storage time series are the measured values of these components of the mass-balance, the mass-balance model is expected to perform very well in simulating the measured historical records.

5.3.1 Reservoir Target Levels

MH provided the historical water surface elevations as well as the stage-storage curve for each reservoir. MODSIM requires target storage (volume of water) rather than water level. Therefore, the historical water storages are calculated by converting the historical water elevations to the water storage values. To this end, the stage-storage relationships are plotted in Excel and a regression equation is fitted to the curve with R^2 value between 0.99 and 1. For instance, Figure 12 shows the fitted curve to the stage-storage relationship at the Cross Lake, where x represents the water elevation in meters and y represents the amount of storage in the reservoir in 1000 m^3. Similar regression functions are developed for all the reservoirs and the target storage levels are calculated by applying the regression to the historical water elevations.

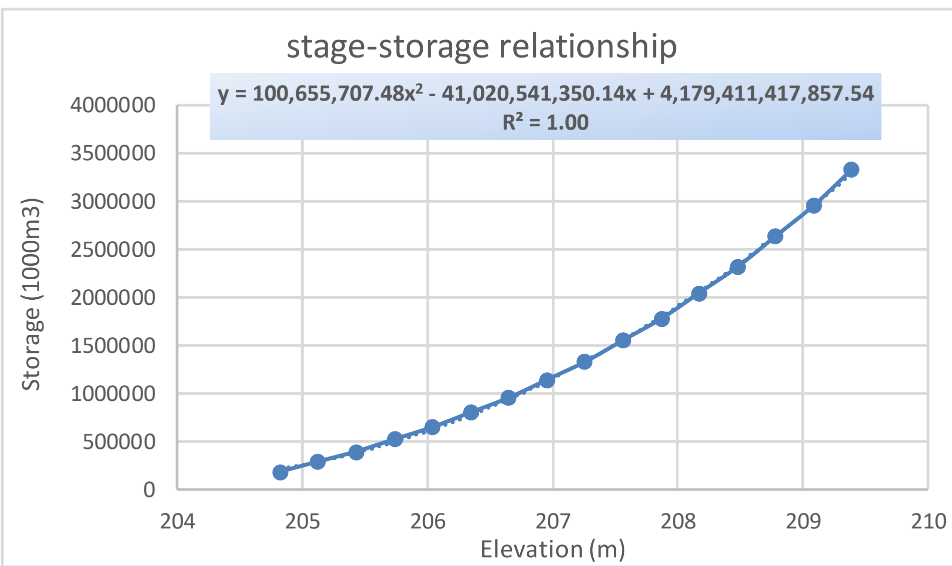


Figure 12. Fitted curve to the stage-storage curve at Cross Lake

5.4 Operational Model Setup

Specifying daily storage targets is not applicable when evaluating system performance against future climatic scenarios. Therefore, generic storage target values need to be developed to represent the typical operation of reservoirs in the system. The following steps are taken to develop the seasonal storage targets:

1. Daily historical forebay elevations from 1980 until 2018 are used to develop the box and whisker plots at all reservoirs in the system. An exception is Wuskwatim that became operational in 2012 and therefore the period of 2012-2018 is considered to develop its box plots.
2. The daily median values are selected as the daily target elevation at each reservoir.
3. The daily target levels are converted to daily target storages using the stage-storage relationship at each reservoir (see section 5.4.1).

Daily storage targets are developed for each reservoir and are incorporated in MODSIM. Figure 13-a shows the Box and Whisker plots at Jenpeg. One can see a clear seasonal pattern in the water surface elevation upstream of Jenpeg in order to increase the hydraulic gradient between Jenpeg and LW to increase the flow in the Nelson West Channel. Figure 13-b shows that unlike at Jenpeg, MH strives to keep the storage upstream of Kettle at its maximum operational level throughout the year. A similar operational policy is observed at Kelsey, Long Spruce, and Limestone. Therefore, the target storages in the operational SMPM for these controlled points are more representative of the system behavior compared to that at Jenpeg.

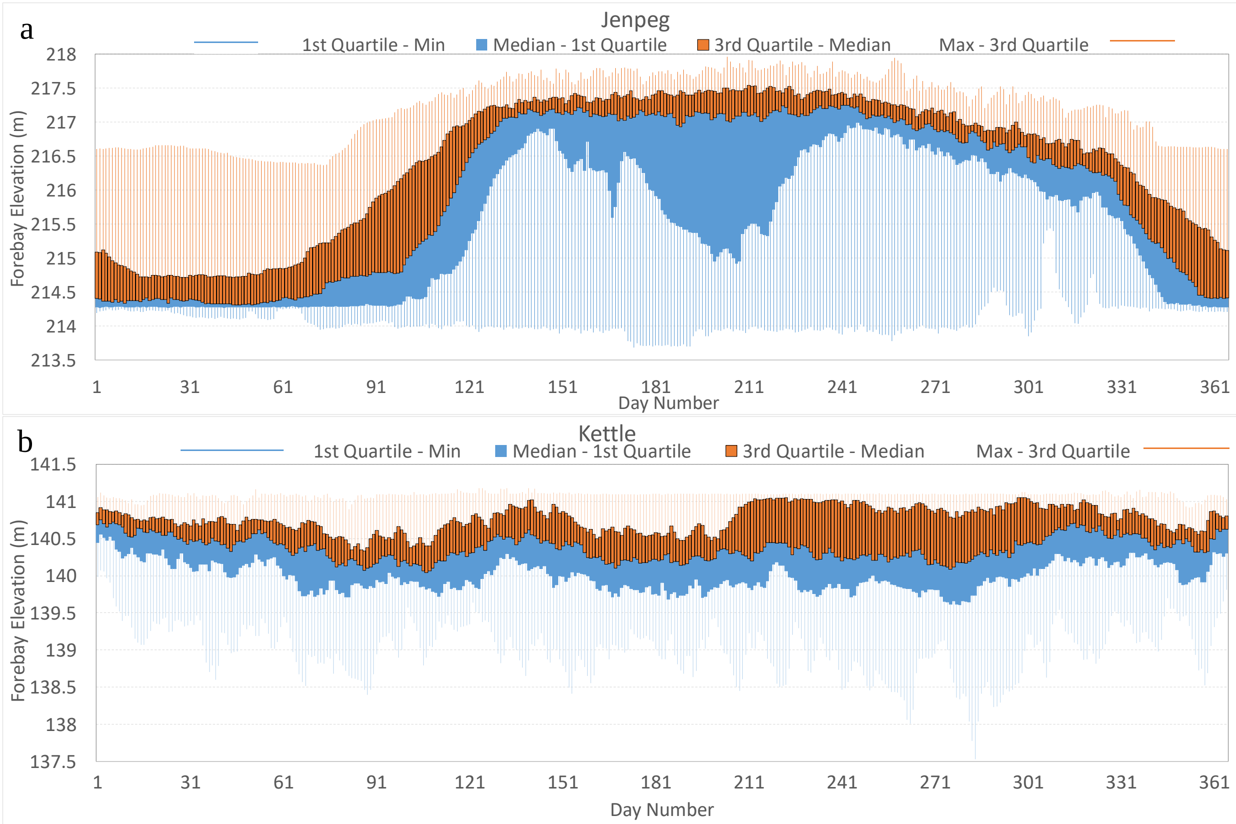


Figure 13. The Box and Whisker plots for forebay elevation at (a) Jenpeg and (b) Kettle

5.5 Performance Evaluation

Evaluating the model performance is necessary prior to relying on model projections for future assessment. The most basic and fundamental model evaluation is performed through visual comparison to the time series of the simulated values against the measured values. In addition, a more objective evaluation is performed by some of the well-known metrics in the area of model evaluation, including the Nash-Sutcliffe Efficiency, percent bias and correlation coefficient. These metrics evaluate different aspects of the model performance; therefore, they are good compliments to the visual evaluation.

5.5.1 *Performance Evaluation Metrics*

As noted by Gupta et al. 1998, there is no single metric that can comprehensively represent the distribution of the error between a simulated and measured time series. For example, the Nash-Sutcliffe Efficiency (NSE) metric is very sensitive to high error values that usually happen in high-flow periods, while NSE of the logarithm of the error is more sensitive to very small errors that usually occur in low-flow periods. On the other hand, percent bias (PBIAS) is very sensitive to the total volumetric error because it measures the total error between simulated and measured values relative to the total measured value. Table 10 shows different model performance evaluation metrics used in the literature to evaluate river-reservoir simulation models.

In this thesis, Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and Pearson product-moment correlation coefficient (Cor) (see Equation 5, Equation 6, and Equation 7) are selected to evaluate the model performance in representing the historical outflow and hydropower generations as shown by the following equations. In addition, minimum, maximum, and average values are used to evaluate the simulation of the forebay elevations compared to the historical elevations.

Table 10. Summary of performance evaluation metrics used by researchers to evaluate the performance of river-reservoir simulation models

Model	Application	Performance Evaluation	Reference
AQUATOOL	Developing an integrated model by combining aspects of water resource allocation and water quality assessment for the Llobregat River Basin	Statistical: Mean squared error Graphical Time series	(Momblanch et al., 2015)
Wase-Tana hydrological model	Analyzing the future scenarios of water supply and demand as well as an assessment of trade-offs for water allocation in the upper Blue Nile basin	Statistical: Root mean squared error Nash-Sutcliffe efficiency	(Dessie et al., 2017)
Applying PSO-SA on FKNN, M5P, ANFIS, BN, SVR	Developing an optimization model for water and waste load allocation in reservoir–river systems considering the existing uncertainties in reservoir inflow, waste loads and water demands.	Statistical: Root mean squared error Root mean relative error Bias Correlation coefficient Scatter index	(Nikoo et al., 2014)
WEAP	Assessing the impacts of human activities on water level fluctuations of Urmia Lake	Statistical: Root mean squared error Nash-Sutcliffe efficiency Coefficient of determination	(Dariane and Eamen, 2017)
	Evaluating and analyzing the existing balance and expected future water resources management scenarios in watersheds western Algeria	Statistical: Root mean square error Correlation coefficient Graphical Time series	(Hamlat et al., 2013)
	Evaluating the current water management scenario and the effect of proposed water development projects in Perkerra catchment	Statistical: Mean square error Mean error Model coefficient of efficiency	(Mugatsia, 2010)
	Developing a model of the role of Andean glaciers in the hydrology of their associated watersheds in the Rio Santa watershed (Peru)	Statistical: Root mean square error Bias Nash-Sutcliffe efficiency	(Condom et al., 2011)
RIBASIM	Developing guidelines for optimization of the water resources system in Egypt.	Statistical: Root mean square deviation	(Omar, 2013)
MODSIM	Evaluating agricultural water supply capacity in Geum river basin	Statistical: Root mean square error Coefficient of determination Nash-Sutcliffe efficiency	(Ahn, 2013)
RSOCM	Presenting the River Simulation and Optimization Coupled Model (RSOCM) for the optimal operation of regulated river systems in real-time conditions.	Statistical: Nash-Sutcliffe efficiency Graphical Time series	(León and Kanashiro, 2010)

$$NSE = 1 - \frac{\sum_{t=1}^{T}(S_t - M_t)^2}{\sum_{t=1}^{T}(M_t - \mu_M)}$$ Equation 5

$$PBIAS = \frac{\sum_{t=1}^{T}(S_t - M_t)}{\sum_{t=1}^{T}(M_t)} \times 100$$ Equation 6

$$Cor = \frac{\sum_{t=1}^{T}\left((S_t - \mu_S) \times (M_t - \mu_M)\right)}{\sqrt{\sum_{t=1}^{T}((S_t - \mu_S)^2 \times (M_t - \mu_M)^2)}}$$ Equation 7

Where T is the total number of time steps, S_t and M_t are the simulated and measured values at time step t, μ_M and μ_S are the average of the observed and simulates values, respectively. NSE is dimensionless, being scaled into the interval $[-\infty, 1]$ with an ideal value of 1. It is very sensitive to higher error values, because it squares the error between the simulated and measured data. $PBIAS$ measures the tendency of the simulated values to under- or over-estimate the measured values, with an ideal value equal to 0%; however, $PBIAS = 0\%$ does not necessarily mean that the model perfectly simulates the measured data, it rather means that the average of the error is 0. Cor assesses the strength of a possible two-way linear association between two variables, defined as time series here, being scaled into the interval $[-1, +1]$. The stronger the correlation, the closer the Cor comes to -1 or 1; whereas, the closer values to zero, the greater variation exists between the two variables sets. Cor equal to zero indicats that no linear relationship exist between the two variables. In the context of the evaluation of a simulation model, the ideal value for Cor is +1, because the model is expected to result in a higher value for time steps when the measured value is higher. This relationship is expected to be linear to make sure that the model can accurately simulate the differences observed between two measured data points. The simulation period in this research is from 1980 until 2018 that correspond to the provided data by MH.

6 Results and Discussion

The simulation results for mass-balance and operational versions of the SMPM model are presented in this chapter, and their similarities and differences with historical trends are discussed. The model performance is evaluated by comparing simulated and measured forebay elevation at each reservoir, outflow from each reservoir, and hydropower generation at hydropower generating stations. The model performance is evaluated using well-known metrics and visual comparison of the time-series graphs.

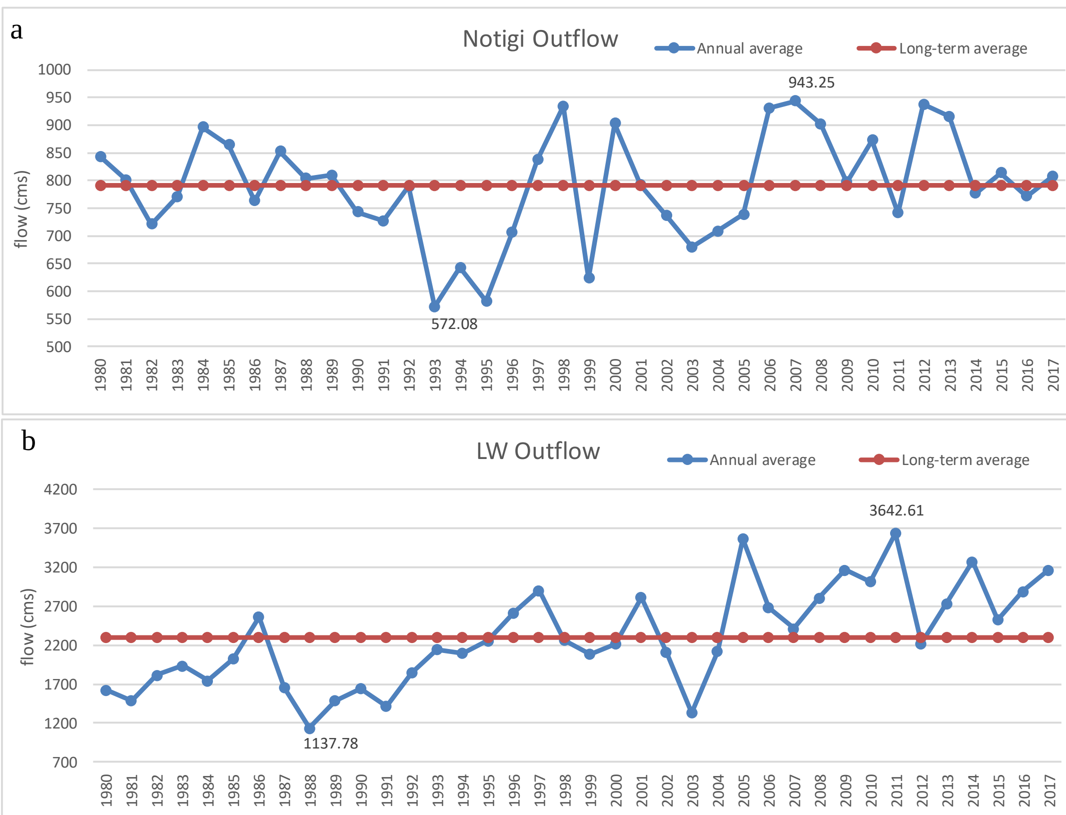


Figure 14. Annual average outflow (cms) from (a) Notigi and (b) LW

The simulation period in this research starts from 1980 and ends in the beginning of 2018, including 39 years of simulation. The driest and wettest years are selected for plotting the time series to demonstrate the model performance in different flow conditions. According to Figure 14, 1988 and 2011 as well as 1993 and 2007 are considered as the driest and wettest years at the Nelson River and Churchill River, respectively. Therefore, results for the system components located on Churchill River are presented for the periods of 1992-1995 and 2006-2009, and for the components located on Nelson River are shown for the periods of 1986-1989 and 2010-2013.

6.1 Mass-balance model

In order to develop an efficient mass-balance model, it was attempted to avoid any customization in the model. However, as discussed in Appendix A, the corresponding model failed to adequately simulate the system performance mainly due to the under representation of the backwater- and ice-affected rule curves at the outlet of Lake Winnipeg and SIL. Therefore, these curves are custom-coded in the mass-balance version of SMPM that is evaluated here. Section 6.1.1 shows the significant improvement in the model performance when the backwater-affected rule curves and the ice factor are custom-coded in the model.

6.1.1 Model Improvement after Customization

According to Table 11, when the model is custom-coded for the backwater effect in the Nelson East and South Bay Channels, it performs better compared to the results shown in Appendix A. NSE value of 0.68 for Nelson East and 0.83 for Nelson West show adequate simulation of flow in these channels. However, over the whole simulation period, this model under-estimates the flow in Nelson West and over-estimates that in Nelson East with about 15% bias, suggesting significant room for improvement in the model. Based on the PBIAS value of +5.52%, the model tends to slightly over-estimate the flow in South Bay channel while. The NSE score of 0.32 indicates an inadequate simulation of the flow in the South Bay Channel. Cor values in Nelson East and Nelson West channels are greater than 0.92 indicating a strong linear relationship between the simulated and measured streamflow, and therefore the model adequately simulates the streamflow timing.

Cor value 0.78 for the South Bay channel indicates that the model performance is weaker in simulating streamflow timing in this channel.

Table 11. Model performance metric values for Nelson East, Nelson West, and South Bay channels after customizing SMPM for the backwater-affected rule curves and ice cover effect

	Customization Level	**Nelson East**	**Nelson West**	**South Bay**
NSE	Backwater	0.68	0.83	0.32
	Backwater + Ice Cover	0.89	0.99	0.46
PBIAS	Backwater	14.87%	-15.79%	5.52%
	Backwater + Ice Cover	-4.89%	0.88%	-3.80%
Cor	Backwater	0.92	0.99	0.78
	Backwater + Ice Cover	0.95	0.99	0.79

According to Table 11, after considering the ice-cover impact on flow in the Nelson East and South Bay Channels, NSE and PBIAS scores are significantly improved in these three channels. The PBIAS scores are improved from 14.86% to -4.89% for Nelson East channel and from -15.79% to 0.88% for the Nelson West channel indicating that the overall volume of water in these two channels is adequately simulated. Since these two channels sum up and become the main source of inflow to the Split Lake, underestimating the flow in one channel and over estimating the other channel are expected to compensate each other and result in a better estimation of inflow to the Lower Nelson system. As shown in Figure 15(c) and (d), and Table 11, although the NSE and PBIAS scores at South Bay channels have improved by adding the ice impact coefficients to the model, low flow values can still be found among the simulated streamflow values.

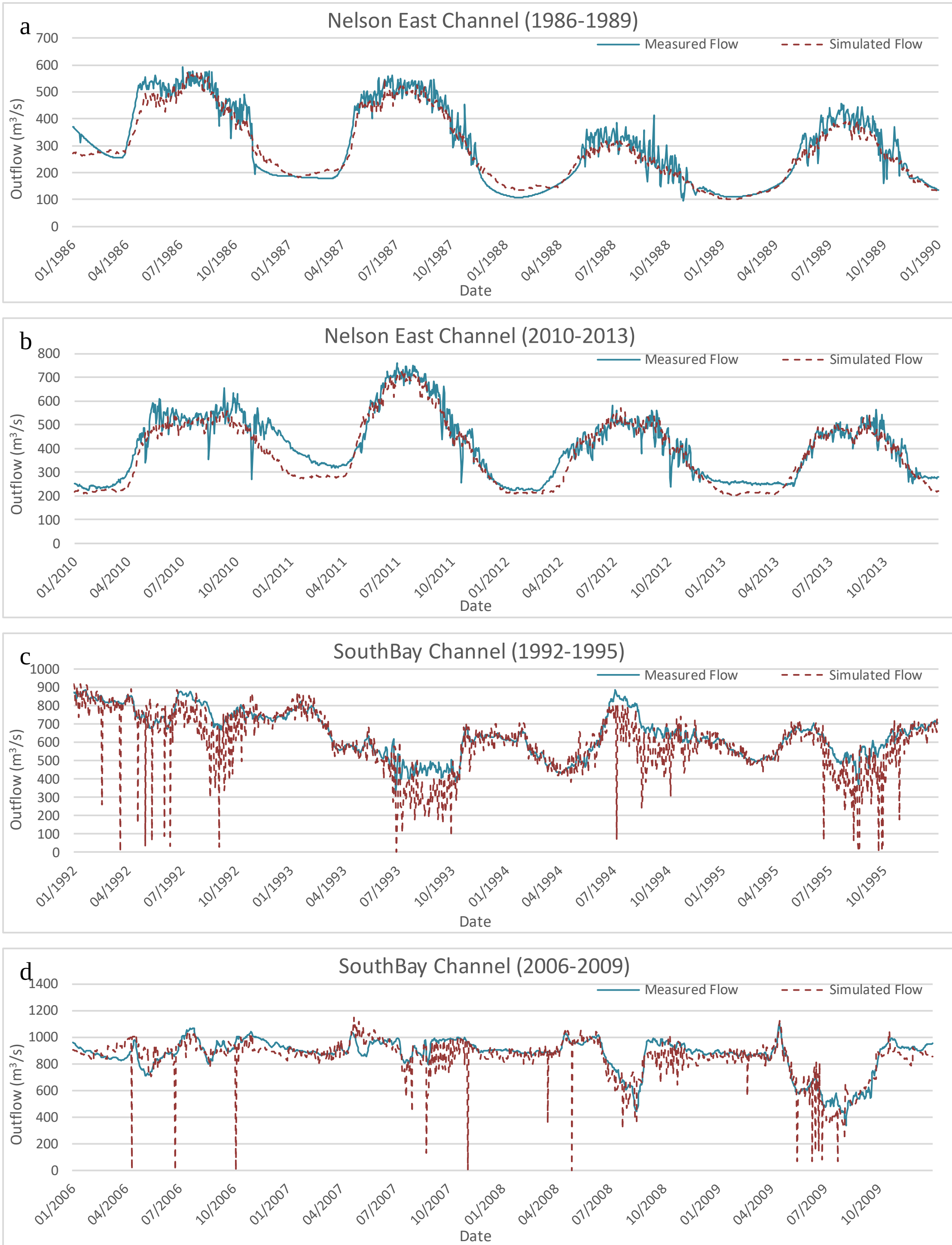


Figure 15. Time series of measured and simulated flow by mass-balance SMPM after customizing for backwater and ice-cover effects in (a) & (b) for Nelson East Channel in (1986-1989) & (2010-2013) and (c) and (d) for South Bay Channel in (1992-1995) & (2006-2009).

6.1.2 Reservoir Releases

The performance metrics scores associated with the controlled and natural reservoir releases are summarized in Table 12. In general, all performance metrics show excellent simulation of releases from all reservoirs, except for the Grand Rapids and Notigi. The correlation coefficient scores show strong linear relationships between the measured and simulated releases from the reservoirs. Kettle, Long Spruce, Limestone, Kelsey, Jenpeg, Sipiwesk, Cross Lake, Split Lake, Birchtree, Opegano, Footprint, Wuskwatim, Wapisu, SIL, and Lake Winnipeg have NSE > 0.91 and -1.4 < PBIAS < 2.52 indicating that the measured and simulated releases from these reservoirs are in an almost perfect match in the case of both timing and volume.

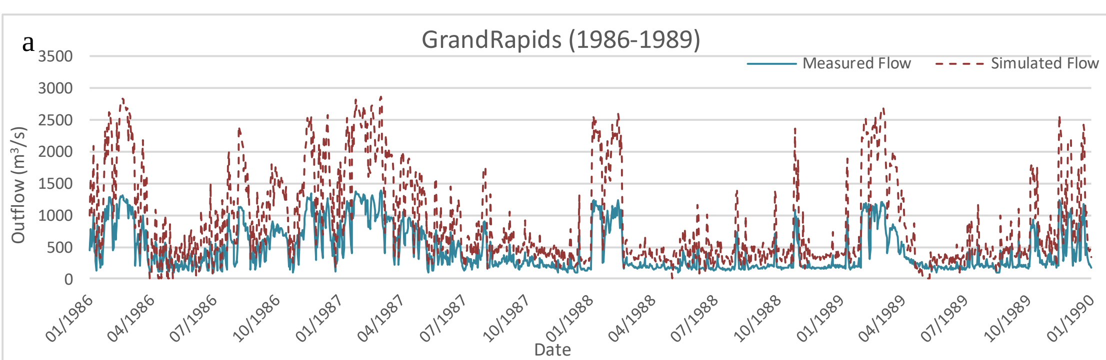
Table 12. Performance metric scores for the reservoir releases

Evaluation Point	NSE	PBIAS (%)	Cor
Kettle	0.94	-0.86	0.97
Long Spruce	0.91	-0.85	0.96
Limestone	0.96	-0.53	0.98
Kelsey	0.96	2.52	0.98
Wuskwatim	0.96	-1.40	0.98
Jenpeg	0.99	0.54	0.99
Split Lake	0.97	-1.03	0.98
Sipiwesk	0.98	1.29	0.99
Cross Lake	0.98	1.29	0.99
Lake Winnipeg	0.99	-1.1	0.99
SIL	0.91	0.00	0.95
Wapisu	0.99	-0.01	0.99
Footprint	0.99	-0.01	0.99
Opegano	0.98	-0.80	0.99
Birchtree	0.98	-0.78	0.99
Notigi	0.50	-5.58	0.81
Grand Rapids	-2.44	101.09	0.98

According to Table 12, the model has a relatively low performance in simulating outflow from Grand Rapids and Notigi. The main reason for inadequate performance at Notigi is that streamflow in the South Bay channel that flows into Notigi is poorly simulated. Improving the streamflow simulation in the South Bay channel will result in an adequate simulation of Notigi releases, which will be explained in the recommendation section.

NSE and PBIAS values at Grand Rapids are -2.44 and 101.09%, respectively. NSE score less than zero represents that the observed mean would be a better predictor than the model and the difference between the model and measured data is larger than the variation observed in the measured data. PBIAS of more than 100% confirms the poor simulation of the flow out of the Grand Rapids. Figure 16(a) and (b) confirm that the flow out of Grand Rapids is consistently over estimated by the model. This poor simulation is the result of the inappropriate stage-storage curve used in the model. This stage-storage curve is derived for Cedar Lake, immediately upstream of Grand Rapids. Cedar Lake with the surface area of 1353 km^2 is considered a medium to large size lake. Changes in the storage to meet the daily forebay level targets results in adding or removing a considerable amount of water at each time step and therefore a poor simulation of the releases from Grand Rapids.

The nearly perfect simulation of reservoir releases from Split Lake suggest adequate simulation of flow releases at other reservoirs as the Churchill River and Nelson River streamflow merge at Split Lake and provide the inflow to the downstream reservoirs.



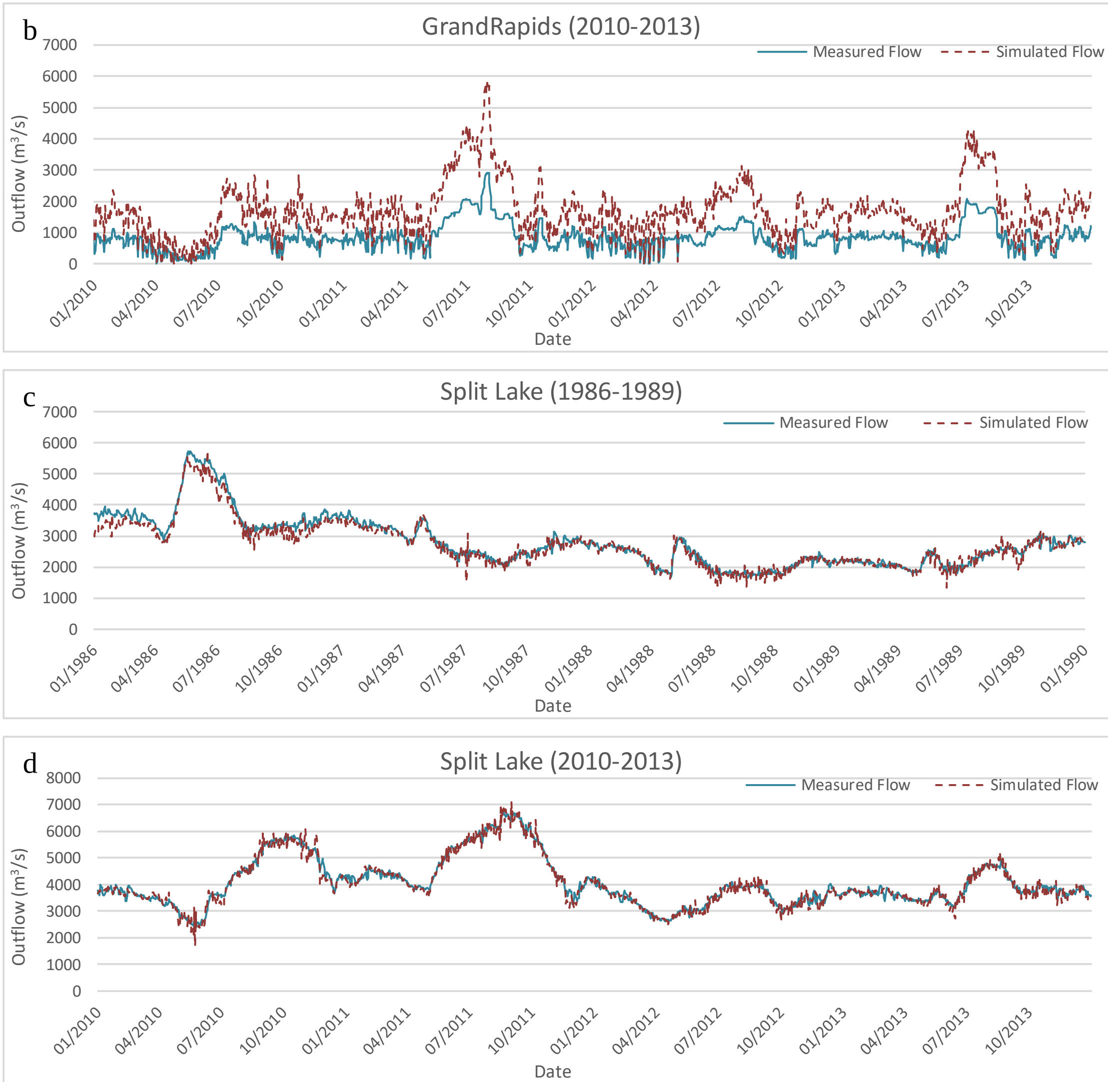


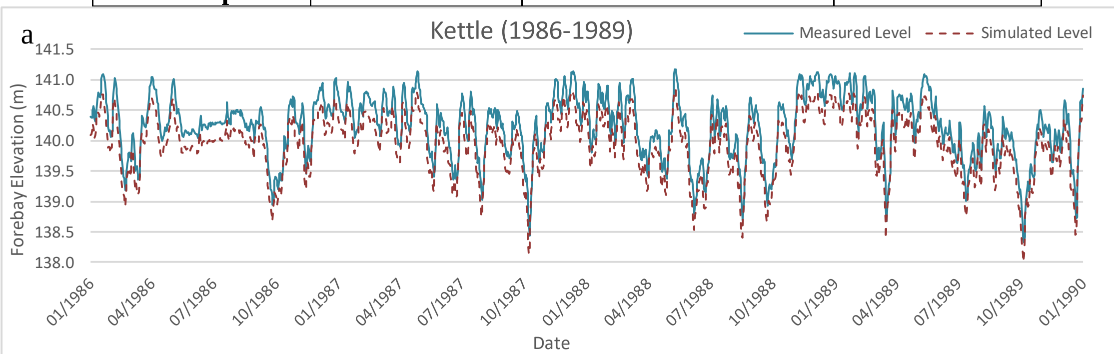
Figure 16. Time series of measured and simulated flows by mass-balance SMPM at (a) & (b) Grand Rapids in (1986-1989) & (2010-2013) and (c) & (d) for Split Lake in (1986-1989) & (2010-2013).

6.1.3 Forebay Elevations

The differences between the maximum, long-term average, and minimum simulated and measured forebay elevations are reported in percentage and are summarized in Table 13. In this table, negative and positive values indicate under- and over-estimation of the measured values, respectively. Differences between the maximum, long-term average, and minimum simulated and measured forebay elevations at each reservoir are less than 1% indicating an excellent match between simulated forebay elevations to their measured values. Minor differences are the result of the existing errors in the stage-storage curves and the way that forebay elevation are converted into storage targets in this research.

Table 13. Percentage difference between measured and simulated forebay elevations by mass-balance SMPM in terms of maximum, minimum and long-term average

	Maximum (%)	Long-term average (%)	Minimum (%)
Kettle	-0.24	-0.21	-0.11
Long Spruce	0.22	0.36	0.37
Limestone	-0.32	-0.32	-0.32
Kelsey	0.00	0.00	0.00
Wuskwatim	-0.11	-0.11	-0.11
Jenpeg	0.00	0.00	0.00
Split Lake	-0.91	0.87	0.00
Sipiwesk	0.00	0.00	0.00
Cross Lake	0.00	0.00	0.00
Lake Winnipeg	0.00	0.00	0.00
SIL	0.00	0.00	0.00
Wapisu	-0.01	0.01	-0.03
Footprint	-0.01	-0.02	0.00
Opegano	-0.01	0.00	0.02
Birchtree	0.00	0.00	0.00
Notigi	-0.02	0.01	-0.03
Grand Rapids	0.03	0.04	-0.14



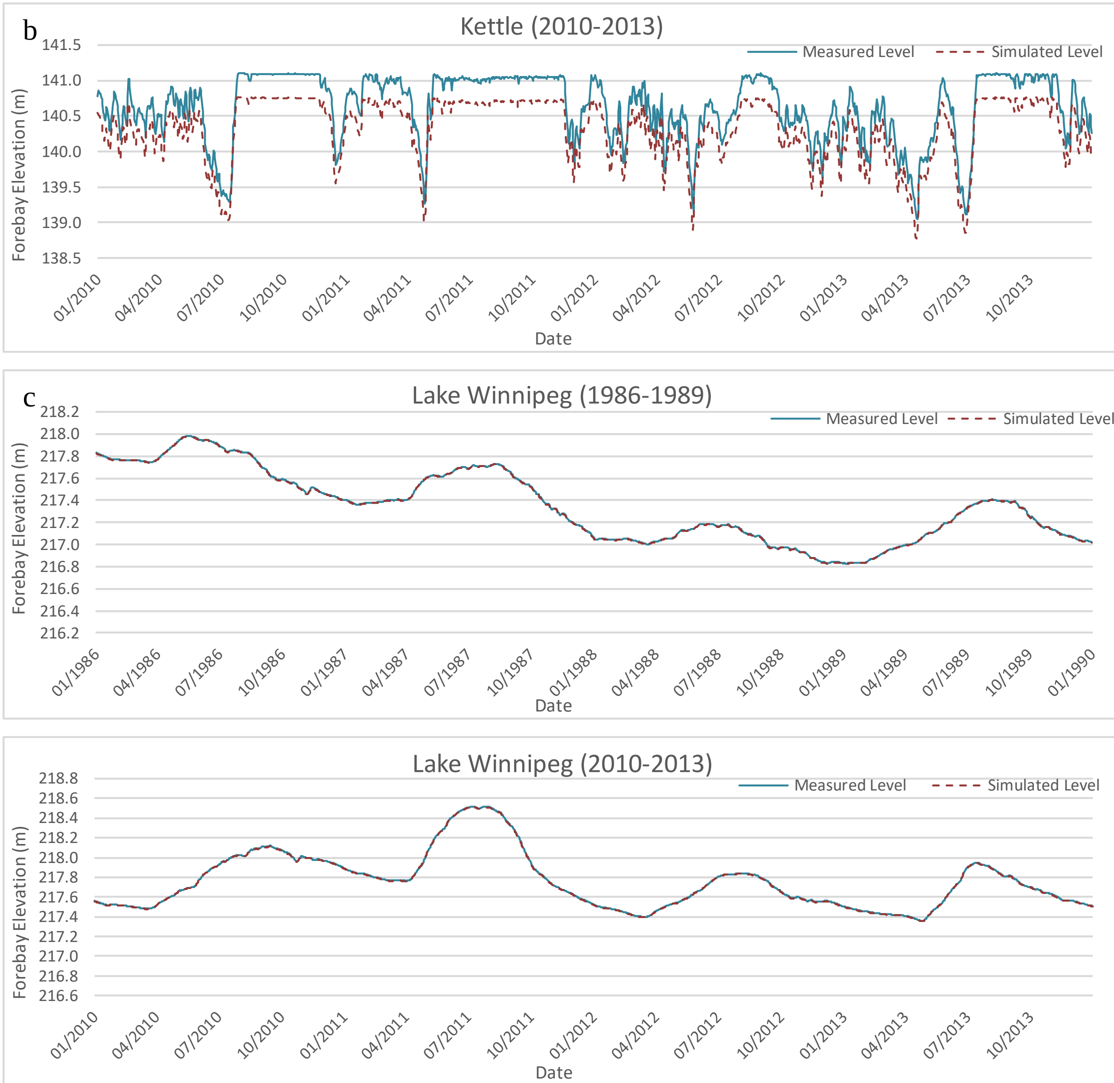


Figure 17. Time series of measured and simulated forebay elevation by mass-balance SMPM upstream of (a) & (b) Kettle in (1986-1989) & (2010-2013) and (c) & (d) Lake Winnipeg in (1986-1989) & (2010-2013).

Forebay elevation time series at Kettle and Lake Winnipeg are shown in Figure 17 as representatives of hydropower generating reservoirs and uncontrolled lake, respectively. According to Figure 17, mass-balance SMPM almost perfectly simulates forebay elevation at Lake Winnipeg. However, the estimated forebay elevation at Kettle is slightly but constantly underestimated. This error could be caused by converting the historical forebay elevation to storage targets using the fitted regression equation to the stage-storage rule curve not only at Kettle but also at all other key hydraulic points upstream of it.

6.1.4 Hydropower Generation

Table 14 presents the performance metric scores at the hydropower generating stations. NSE scores range between 0.96 and 0.99 represent a nearly perfect match between simulated and measured hydropower generation. The high correlation coefficient values confirm this high model performance showing a strong linear relationship between the simulated and measured hydropower generation values. Moreover, small value of PBIAS confirms the exceptional performance of the mass-balance SMPM for simulating historical generations.

Table 14. Performance metric scores for hydropower generation by mass-balance SMPM

	NSE	**PBIAS (%)**	**Cor**
Limestone	0.99	-0.02	0.99
Long Spruce	0.98	-0.46	0.99
Kettle	0.98	-0.60	0.99
Kelsey	0.99	-0.15	0.99
Wuskwatim	0.99	-0.07	0.99
Jenpeg	0.99	-0.42	0.99
Grand Rapids	0.96	-1.92	0.99

The simulated hydropower generation at Grand Rapids has the lowest NSE and PBIAS scores compared to other hydropower generating reservoir but still a great representation of the historical generation. This is because simulating the releases from Grand Rapids was challenging in this research which is discussed in section 6.1.2. The simulated and measured hydropower generation time series at Wuskwatim, and Kettle are shown in Figure 18 as an example of an upstream and downstream evaluation point, respectively. The hydropower generation data provided by MH for the purpose of this research are confidential and there the hydropower generation values on the vertical axis are eliminated from the graphs.

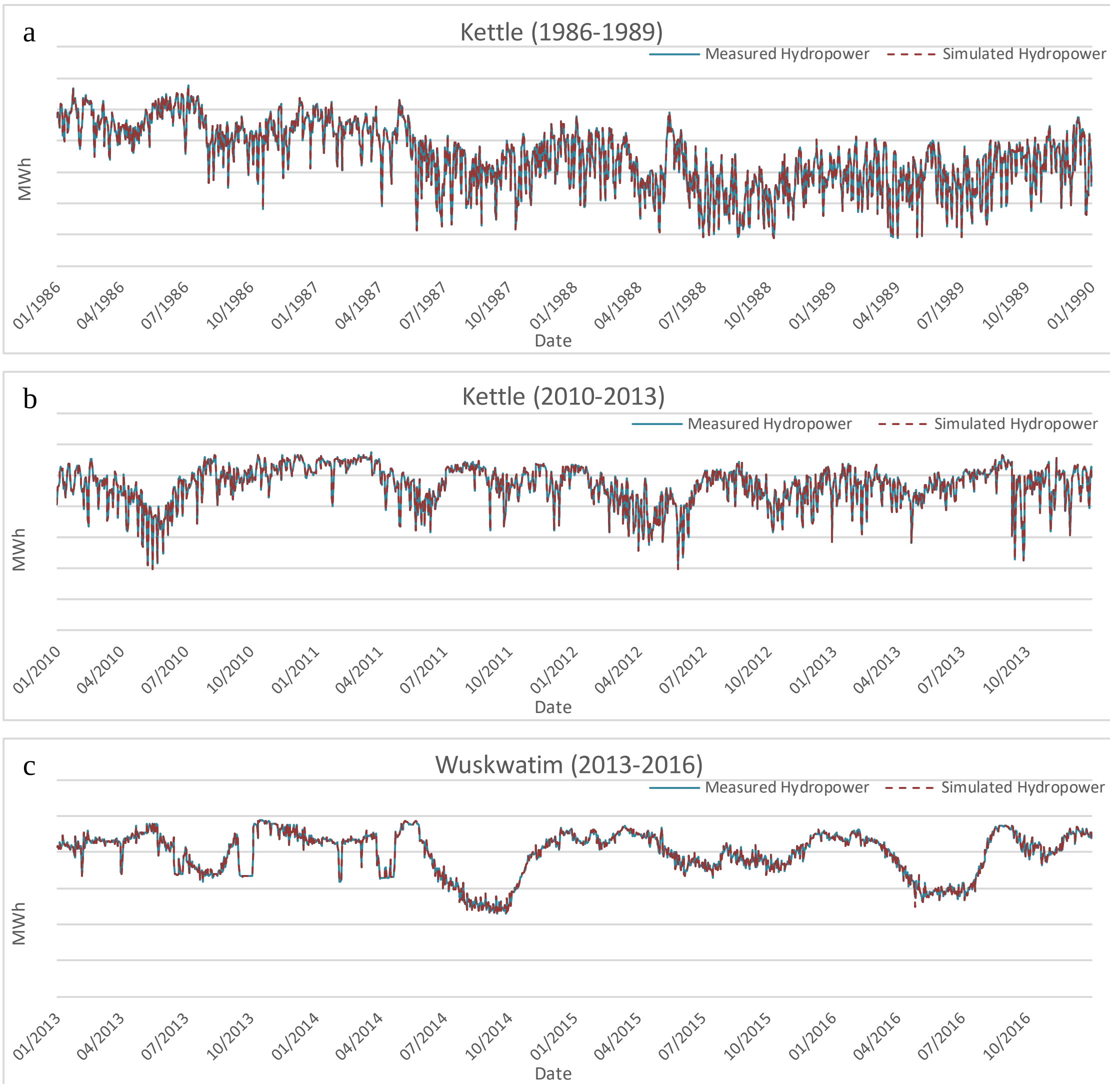


Figure 18. Time series of measured and simulated hydropower generation by mass-balance SMPM at (a) & (b) Kettle in (1986-1989) & (2010-2013) and (c)Wuskwatim in (2013-2016).

6.2 Operational model

6.2.1 Streamflow Timeseries at Channels after Applying the Ice Impacts

Figure 19 presents simulated and measured streamflow time-series in Nelson East and South Bay channels using the operational version of SMPM that incorporates the ice impact on backwater-affected rule curves. According to Table 15, NSE scores at Nelson East channel has decreased from 0.89 in the mass-balance SMPM to 0.56 in its operational version. Whereas, NSE scores at Nelson West and South Bay channels are 0.97 and 0.46 in the operational model, respectively, with almost no change from their values in mass-balance model. PBIAS scores at three channels using operational SMPM are almost similar to that using the mass-balance model. Cor value at Nelson East channel has decreased from 0.95 to 0.76 showing that the strong linear relationship between the two series has decreased. This change in timing can be seen in Figure 19.

Table 15. NSE, PBIAS, and Cor values for Nelson East, Nelson West, and South Bay channels after incorporating the ice impacts on Nelson East and South Bay channels customization.

	Nelson East channel	**Nelson West channel**	**South Bay channel**
NSE	0.56	0.97	0.46
PBIAS	-5.00%	0.89%	-3.80%
Cor	0.76	0.99	0.79

Figure 19 (a) and (b) show that the simulated streamflow time series at Nelson East channel follow the long-term observed seasonal pattern in the measured data. Daily storage targets in operational SMPM remains the same every year and because the discharge rate in the backwater-affected channels are a function of forebay elevations, the streamflow at these channels follow a seasonal pattern as well. Daily storage targets are the median values over 39 years of data, and therefore it is expected to have an adequate estimation volume of water, which is the reason that PBIAS score represents an adequate simulation of the volume of water. However, differences between the simulated and measured peak and low flow streamflow values have reduced the NSE score about 0.30 in the operational model compared to that for the mass-balance model.

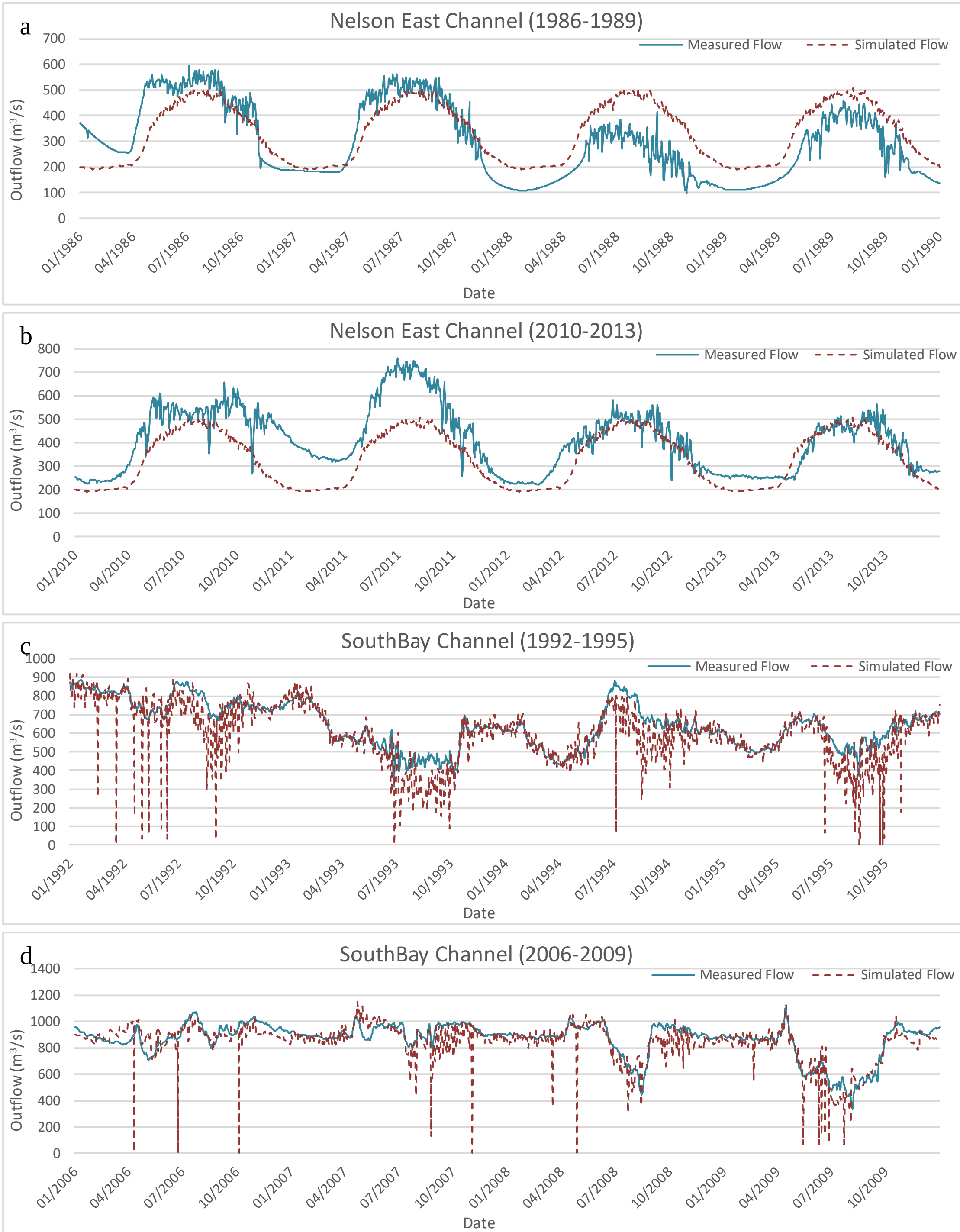


Figure 19. Time series of measured and simulated flow by operational SMPM after customizing for backwater and ice-cover effects in (a) & (b) for Nelson East Channel in (1986-1989) & (2010-2013) and (c) and (d) for South Bay Channel in (1992-1995) & (2006-2009).

PBIAS and NSE scores at Nelson West channel in the operational model remained almost the same to their values in the mass-balance model. The streamflow ranges from 96 cms to 759 cms in the Nelson East channel, while this range starts from 127 cms to 4649 cms in the Nelson West channel. Therefore, gradual changes in the streamflow do not considerably affect the NSE and PBIAS scores in the Nelson West channel when moving from the mass-balance version to the operational version of SMPM. Moreover, the model is still capable of simulating low flows in the South Bay channel.

6.2.2 Reservoir Releases

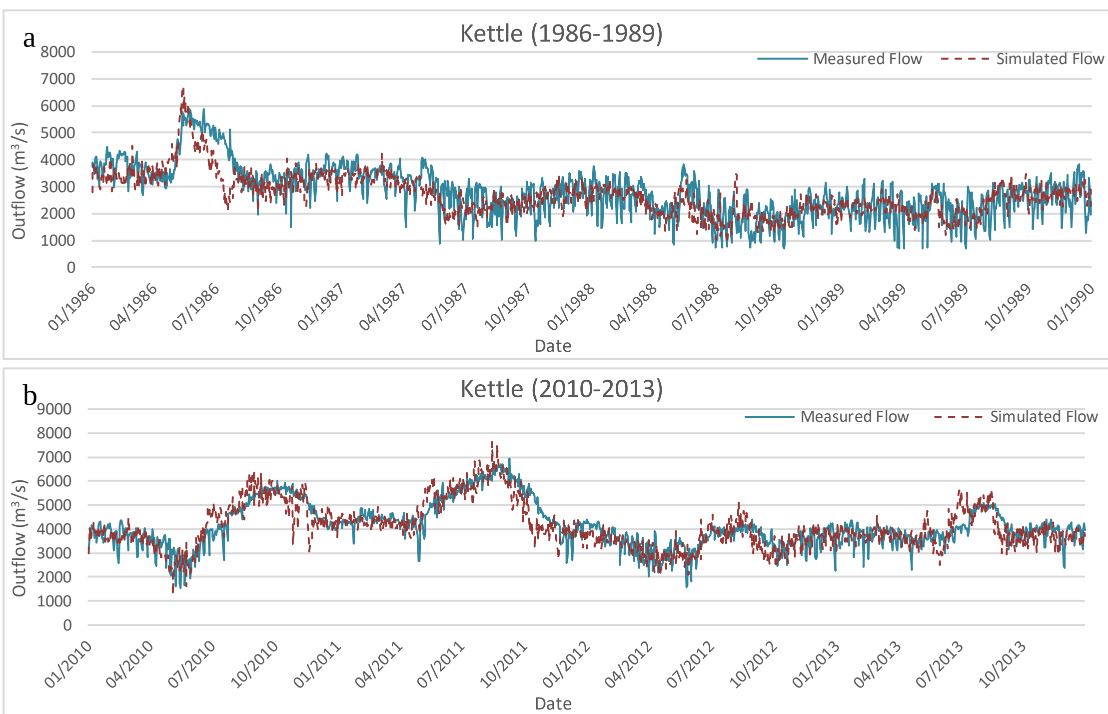
The performance metric scores calculated for reservoir releases are summarized in Table 16. The correlation coefficient scores show that the linear relationship between the measured and simulated releases from the reservoirs has slightly reduced compared to the mass-balance SMPM. Except for the Grand Rapids and Notigi, the NSE and PBIAS scores in the rest of the system for reservoir releases ranges from 0.62 to 0.98 and -1.66% to 2.53%, respectively indicating a range of adequate to excellent performance of the operational model. Moving from the upstream control points such as Wapisu and Jenpeg to the downstream points such as Kettle, Long Spruce, and Limestone, the NSE scores are decreased compared to their values in the mass-balance model, suggesting that simulation error adds up from upstream to downstream. Although the daily storage targets are replaced with annual storage targets in the operational model, the PBIAS scores illustrate that still the volume of water is adequately simulated. The reason is that in the river-reservoir system operated by MH, most of the reservoirs are run-of-the-river, and therefore the storage contribution to the releases from the reservoirs are not considerable.

Table 16. Performance metric scores for the reservoir releases estimated by operational SMPM

Evaluation point	**NSE**	**PBIAS (%)**	**Cor.**
Kettle	0.68	-1.66	0.83
Long Spruce	0.62	-1.65	0.82
Limestone	0.70	-1.21	0.84
Kelsey	0.82	2.53	0.92
Wuskwatim	0.88	-1.50	0.95

Jenpeg	0.96	0.58	0.98
Split Lake	0.83	-1.02	0.91
Sipiwesk	0.83	1.30	0.92
Cross Lake	0.93	1.30	0.97
Lake Winnipeg	0.98	0.00	0.99
SIL	0.63	0.03	0.83
Wapisu	0.98	-0.01	0.99
Footprint	0.91	-0.01	0.96
Opegano	0.89	-0.80	0.94
Birchtree	0.89	-0.78	0.95
Notigi	-0.33	1.09	0.41
Grand Rapids	-2.44	101.08	0.98

Figure 20 shows the time series of simulated and measured releases from Lake Winnipeg, Split Lake, and Kettle. Lake Winnipeg and Split Lake are selected as indicators of the uncontrolled reservoirs and Kettle represents the hydropower generating stations. The accurate simulation of reservoir releases from Split Lake indicate that streamflow in its upstream from Nelson and Churchill Rivers are adequately simulated by the operational model.



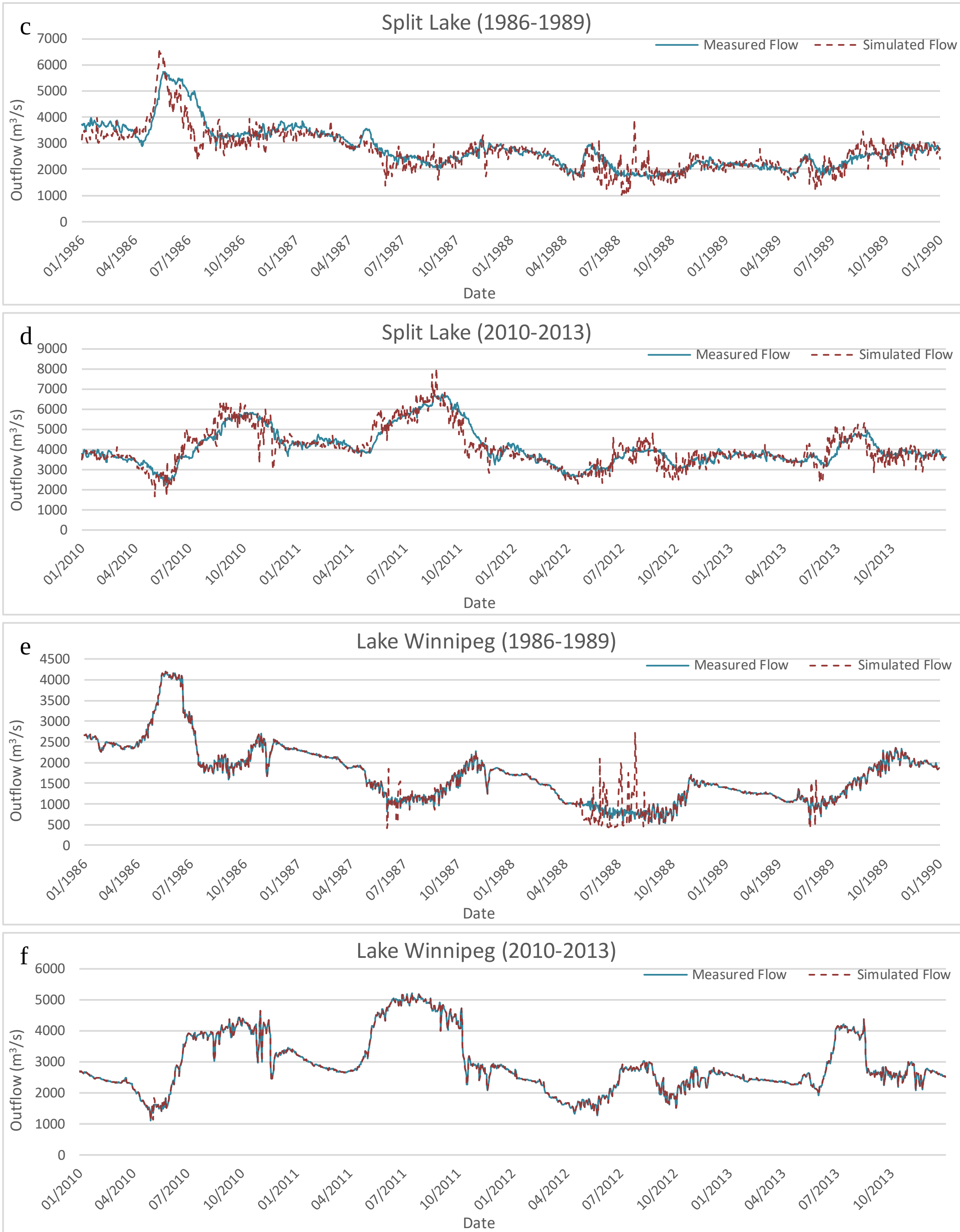


Figure 20. Time series of measured and simulated reservoir releases by operational SMPM at (a) & (b) Kettle in (1986-1989) & (2010-2013) and (c) & (d) Split Lake in (1986-1989) & (2010-2013) and (e) & (f) Lake Winnipeg in (1986-1989) and (2010-2013).

According to Figure 20 (a) and (b), the simulated releases at Kettle are smoothened out compared to the measured values, which is the reason that NSE score has decreased in the operational model. Although NSE = 0.98 and PBIAS = 0.00 at Lake Winnipeg indicate an almost perfect match between the simulated and measured releases during 39 years of simulation, Figure 20 (e) and (f) show that the simulation performance has decreased slightly in the driest year, which is due to the ranges of data provided in the backwater-affected rule curves. In addition, a closer look at the simulated high-flow values at Kettle and Split Lake illustrate that high–flow values are over-estimated in the simulated releases compared to their historical ones. A seasonal calibration of the backwater-affected rule curves as well as the ice impact coefficients for both dry and wet years could improve the model performance during both low and high flow periods. In addition, multiple annual storage targets can be developed by setting different hydrological conditions such as dry, normal, and wet conditions. Because the streamflow in the backwater-affected channels is a function of forebay elevations, defining annual storage targets based on the hydrological conditions can lead to a better simulation of streamflow and reservoir releases.

6.2.3 Forebay Elevations

The differences between the maximum, long-term average, and minimum simulated and measured forebay elevations are reported in percentage and are summarized in Table 17. According to Table 17, the operational model adequately simulates the forebay elevations across the system. The long-term average, maximum, and minimum differences between the simulated and measured forebay elevations are less than 0.40%, 1.83%, and 3.20%, respectively.

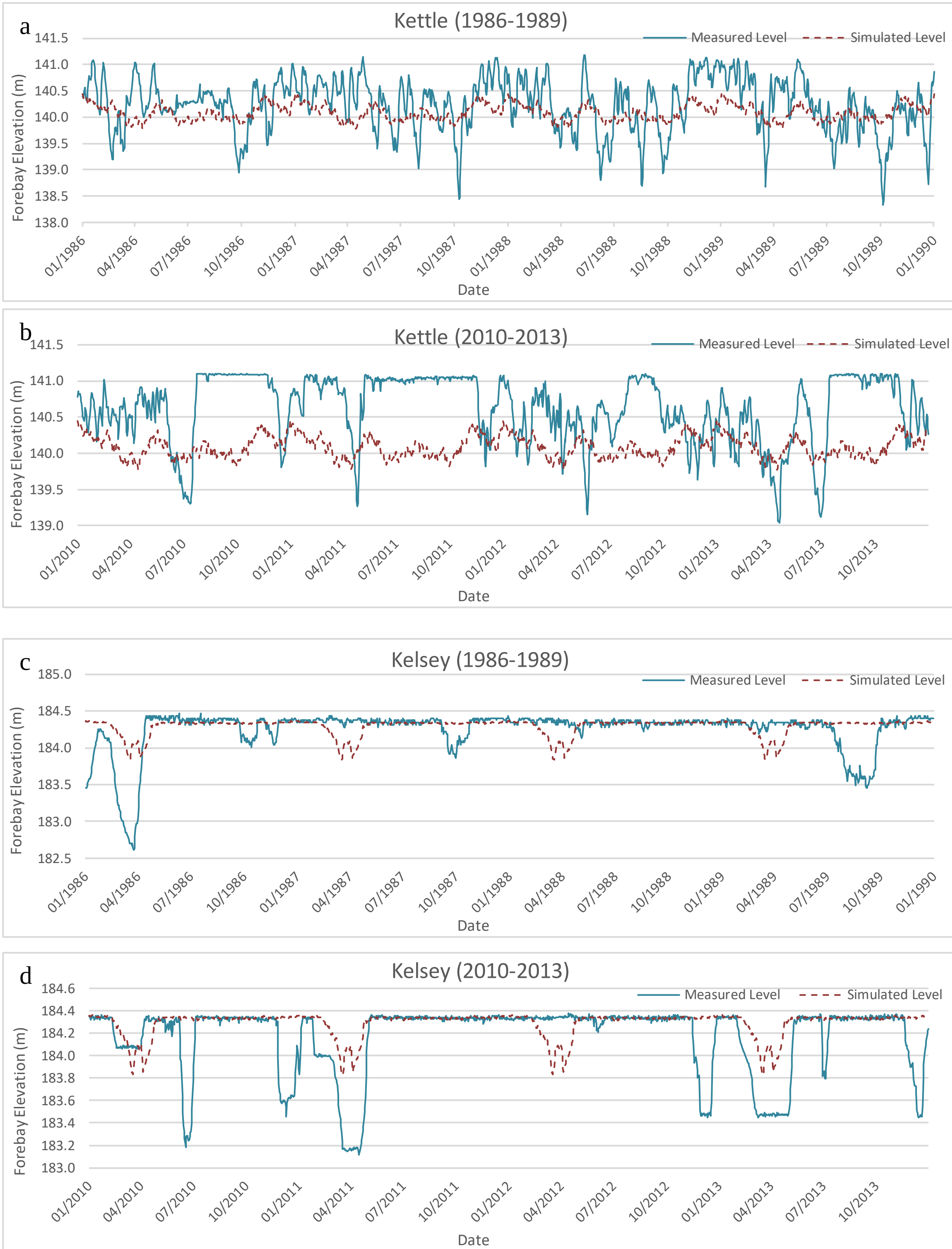
Table 17. Percentage difference between measured forebay elevations and simulated values by operational SMPM

	Maximum (%)	**Long-term average (%)**	**Minimum (%)**
Kettle	-0.52	-0.17	1.63
Long Spruce	0.15	0.39	3.20
Limestone	-0.32	-0.32	-0.32

Kelsey	-0.12	0.06	0.84
Wuskwatim	-0.11	-0.11	-0.11
Jenpeg	-0.33	0.06	0.29
Grand Rapids	0.03	0.04	-0.14
Split Lake	-0.91	0.00	0.87
Sipiwesk	-1.83	-0.40	0.53
Cross Lake	-0.61	0.00	0.94
Lake Winnipeg	-0.34	0.00	0.25
SIL	-0.13	0.03	0.10
Notigi	-0.02	0.01	-0.03
Wapisu	-0.28	0.04	0.65
Footprint	-0.22	0.03	0.62
Opegano	-0.01	0.00	0.02
Birchtree	0.00	0.00	0.00

Forebay elevation time series at Lake Winnipeg, Kelsey, Split Lake and Kettle are shown in Figure 21. Comparing the simulated and measured time series illustrate that the simulated forebay elevations are not an excellent representation of their measured values although the long-term average error values are close to the zero. In addition, annual storage targets are the median values of the 39 years record resulting in the long-term average scores being close to zero. In addition, small variations between the maximum and minimum simulated and measured forebay elevations can be found.

To improve the model representation of forebay elevation, multiple storage targets can be developed for different hydrological conditions. In addition, incorporating the operation policies in development of the storage targets can improve the performance of the model. For example, comparing Figure 21 (a) and (b) represent changes in the operation trends such as a constant higher forebay elevation during the summer.


a
Kettle (1986-1989)
Measured Level
Simulated Level
Forebay Elevation (m)
141.5
141.0
140.5
140.0
139.5
139.0
138.5
138.0
01/1986
04/1986
07/1986
10/1986
01/1987
04/1987
07/1987
10/1987
01/1988
04/1988
07/1988
10/1988
01/1989
04/1989
07/1989
10/1989
01/1990
Date
b
Kettle (2010-2013)
Measured Level
Simulated Level
Forebay Elevation (m)
141.5
141.0
140.5
140.0
139.5
139.0
01/2010
04/2010
07/2010
10/2010
01/2011
04/2011
07/2011
10/2011
01/2012
04/2012
07/2012
10/2012
01/2013
04/2013
07/2013
10/2013
Date
c
Kelsey (1986-1989)
Measured Level
Simulated Level
Forebay Elevation (m)
185.0
184.5
184.0
183.5
183.0
182.5
01/1986
04/1986
07/1986
10/1986
01/1987
04/1987
07/1987
10/1987
01/1988
04/1988
07/1988
10/1988
01/1989
04/1989
07/1989
10/1989
01/1990
Date
d
Kelsey (2010-2013)
Measured Level
Simulated Level
Forebay Elevation (m)
184.6
184.4
184.2
184.0
183.8
183.6
183.4
183.2
183.0
01/2010
04/2010
07/2010
10/2010
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Date

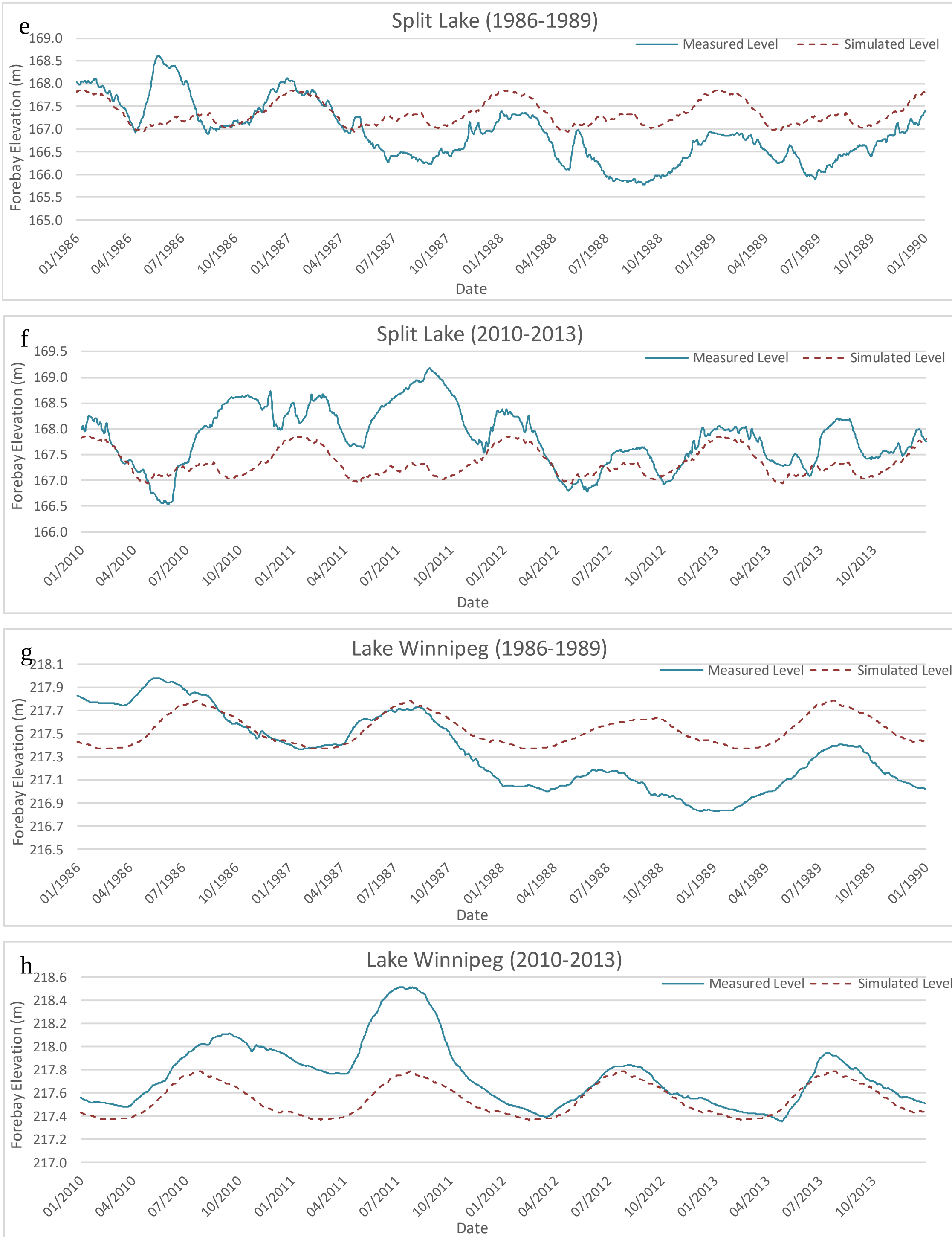


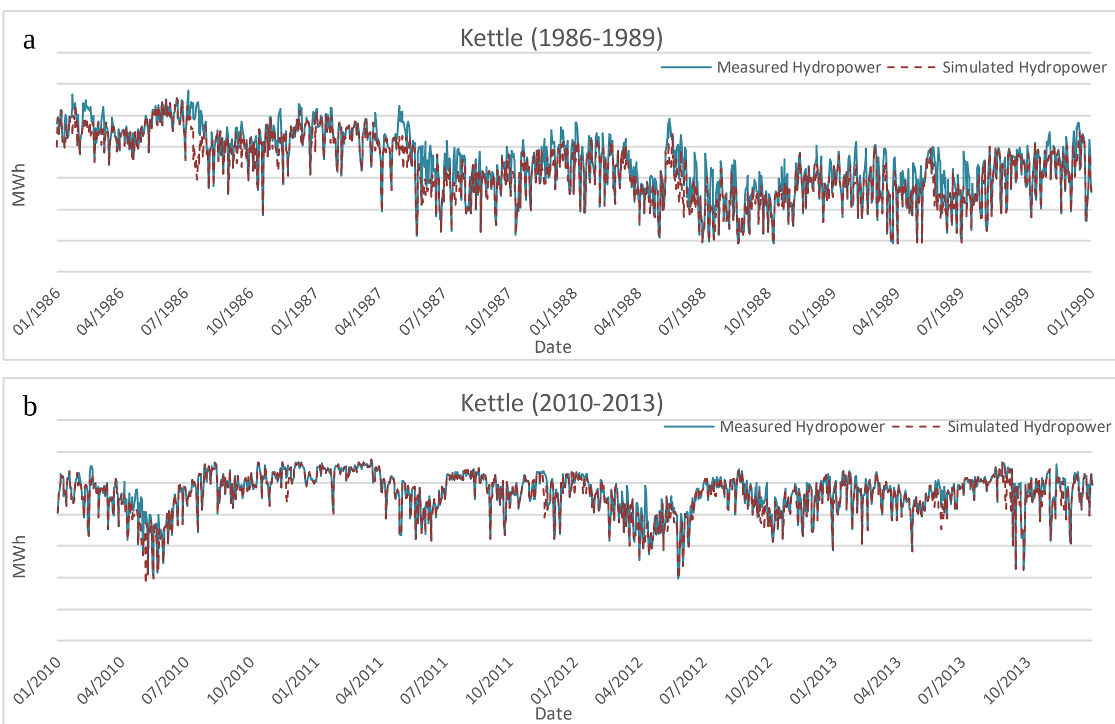
Figure 21. Time series of measured and simulated forebay elevations by operational SMPM at (a) & (b) Kettle in (1986-1989) & (2010-2013), (c) & (d) Kelsey in (1986-1989) & (2010-2013), (e) & (f) Split Lake in (1986-1989) & (2010-2013), and (g) & (h) Lake Winnipeg in (1986-1989) & (2010-2013).

6.2.4 Hydropower Generation

Table 18 presents the performance metrics scores at the hydropower generating stations. NSE scores range between 0.79 and 0.99 representing a range from adequate excellent match of simulated hydropower generation to the observed data. Correlation coefficient values show that there is a strong linear relationship between the simulated and measured hydropower generation values so that two trend lines are adequately match. Cor value at Kelsey has decreased as a reason of simulation performance in drought conditions.

Table 18. Performance metrics scores at the hydropower generating stations

	NSE	PBIAS (%)	Cor
Limestone	0.99	-0.13	0.99
Long Spruce	0.92	-1.96	0.96
Kettle	0.90	-2.73	0.96
Kelsey	0.79	-1.09	0.90
Wuskwatim	0.99	-0.14	0.99
Jenpeg	0.95	-1.63	0.96
Grand Rapids	0.95	-4.09	0.97



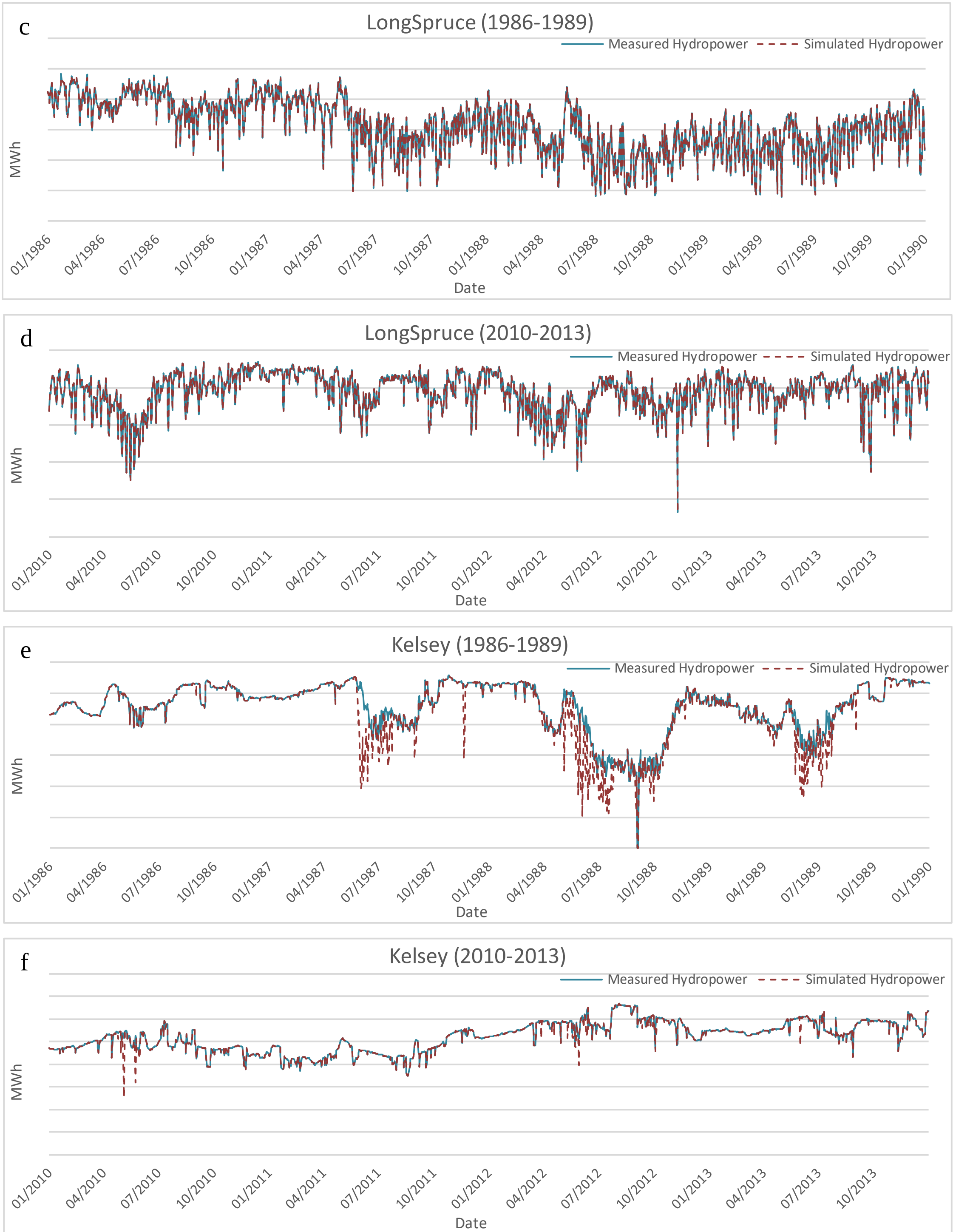


Figure 22. Time series of measured and simulated hydropower generation by operational SMPM at (a) & (b) Kettle in (1986-1989) & (2010-2013), (c) & (d) Long Spruce in (1986-1989) & (2010-2013), and (e) & (f) Kelsey in (1986-1989) & (2010-2013).

The simulated hydropower generation at Kettle, Long Spruce, and Kelsey has decreased in the operational model. According to Equation 1, the hydropower generation is a function of discharge rate and head. According to Table 16, Table 17, Figure 20, and Figure 21, the simulated releases and forebay elevations in the operational models are smoothened out as the result of annual storage targets. Thus, a similar trend is expected to occur in simulated hydropower generation, which is shown in Figure 22, causing minor discrepancies between the simulated and measured hydropower generation. Improving the regulation of the backwater-affected channels and annual storage targets can lead to a better representation of the hydropower generation.

7 Conclusions and Recommendations for Future Work

7.1 Summary of Major Findings

The MODSIM-DSS integrated water management model is successfully set up for the river-reservoir system that Manitoba Hydro operates. The model, called SMPM incorporates the non-linear relationships in the system including the hydropower generating equation, and the stage-storage-discharge curves that are affected by backwater and ice cover as well as the seasonality in the operation of key control points in the system, e.g. Jenpeg. Preliminary results of this work show that SMPM fails to adequately backwater-affected distribute water between the East and West Channels that are backwater and ice-on affected channels.

The seasonality is most evident between the ice-on and ice-off conditions and highly affect the model estimations of winter streamflow and therefore the distribution of water between the backwater-affected channels such as Nelson East and Nelson West channel. Incorporating backwater rules and ice-cover factors through the custom code noticeably improves model performance. Evaluating the model performance using performance metrics including NSE, PBIAS, and Cor as well as visual comparison of time series plots for upstream and downstream elevations, and streamflow of the backwater-affected channels show that SMPM adequately simulates the seasonal pattern observed in the measured data.

Results show that the mass-balance version of SMPM scores an excellent performance for simulating streamflow, hydropower generation and storage levels in the Lower Nelson River, downstream of Jenpeg. This high performance is not a surprise, because the mass-balance model is restricted by daily target levels that are set in the model based on the daily historical records. In order to advance SMPM toward its operational version, these target storages are replaced by the median of daily water levels and outflows are restricted by regression equations developed based on stage-discharge equations provided by Manitoba Hydro. Unlike its mass-balance version, the operational SMPM can be used to analyze climate- and human-induced changes in the system.

Results show that the performance of SMPM degrades moving from its mass-balance version to its operational version. On average. NSE, PBIAS, and Cor scores of streamflow decrease by 0.2, 2%, and 0.1, respectively. However, the model performance metric values show a range of adequate to excellent simulation of hydropower generation, forebay elevations, and streamflow time series indicating that the operational version of SMPM can be used to investigate the impacts of future climatic conditions on the river-reservoir system operated by Manitoba Hydro such as hydropower generation and to optimize the current operating guidelines to mitigate the negative impacts of the climatic conditions. The most significant degradation in the model performance in terms of streamflow simulation occurs at Kettle where NSE is reduced from 0.94 in the mass-balance model to 0.68 in the operational model. However, NSE for hydropower generation at Kettle is reduced from 0.98 in the mass-balance model to 0.90 in the operational model.

7.2 Study Limitations

The major limitation of this study is the simulation of the operation of the most upstream control points in the system. Due to the stage-storage curve of Cedar Lake, immediately upstream of Grand Rapids, SMPM is unable to simulate the operation of Grand Rapids adequately. Moreover, all attempts made in this thesis failed to simulate the operation of SIL, adequately. The data related to the operation of SIL were reviewed by experts from MH, and the model was reviewed multiple times to confirm that it is consistent with the data. According to personal communication with experts in MH, modeling the operation of SIL is challenging even for MH models such as HERMES. Since Grand Rapids and SIL are upstream of the system operated by

MH, it is decided to disconnect them in the simulation model from the rest of the system and feed the system by the measured historical outflow from these control points.

7.3 Recommendations and Future Research

This research has identified the following areas that require further investigation and can improve the model performance.

- Input Data

The data quality is the key to the successful application of integrated water management models. The following suggestions can improve the estimation of streamflow, forebay elevations, and hydropower generation.

  - Inflow routing in Lake Winnipeg

The inflow routings in Lake Winnipeg is simplified assuming all inflows accumulate into the lake on arrival, without considering travel times. Considering the large area of the lake, it is suggested to study travel times and incorporate them in future water management models. The reason is that Lake Winnipeg is located on the upstream of the system and therefore improving the model estimations of outflow from this lake can highly influence the simulation performance in the downstream components as well.

- Backwater-affected rule curves and ice impact coefficients

The same daily ice impact coefficients are repeated every year in the model. To improve the streamflow simulation, a different set of ice impact coefficients can be developed considering the characteristics of the water year, winter, and advanced operating guidelines. For instance, the rate of inflow to the system and the start date of the freeze up period highly affects the ice formation in winter and its impact on the reservoir and channel operations. Studying the seasonal influences on the operating procedures and considerations can lead to a better simulation of the streamflow in backwater-affected channels. In addition, calibration of the backwater-affected rule curves or low flow values can improve the estimation of streamflow under drought conditions. Improvements in the representation of the backwater-affected curves can lead to a better estimation of streamflow in the Nelson East channel and therefore improving the overall performance of the operational model. Moreover, the calibration of backwater-affected rule curves under drought conditions will result in a better estimation of streamflow in low flow periods.

- Storage targets

Multiple hydrologic conditions can be defined in MODSIM-DSS to classify dry, normal, and wet years. Different storage targets can also be developed at the hydrological conditions. It is recommended to define multiple hydrological conditions by studying the forebay elevations trend lines and inflow time series to the system and define different storage target for each condition. Defining multiple storage targets can highly improve the representation of forebay elevations in the operational model.

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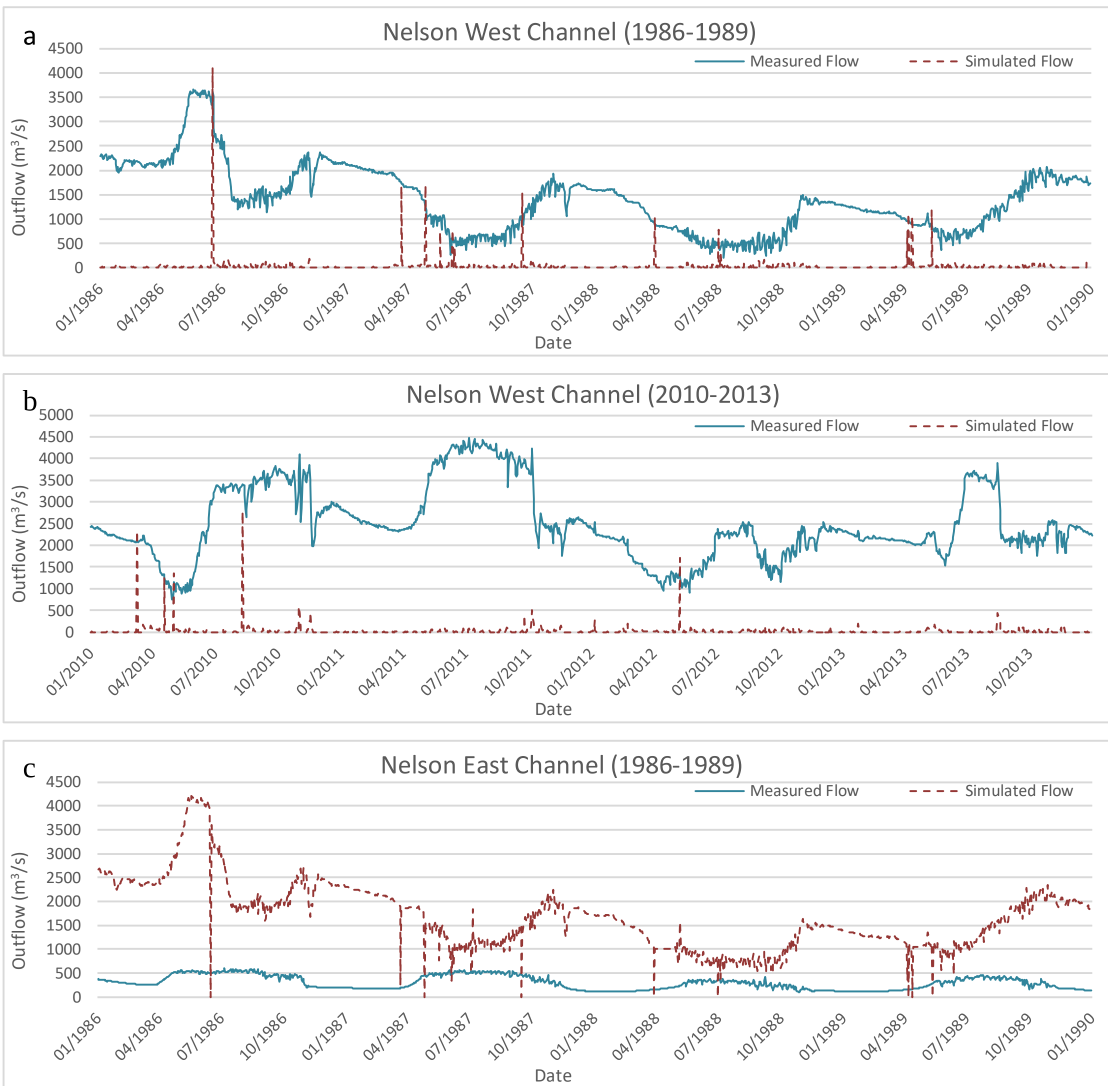
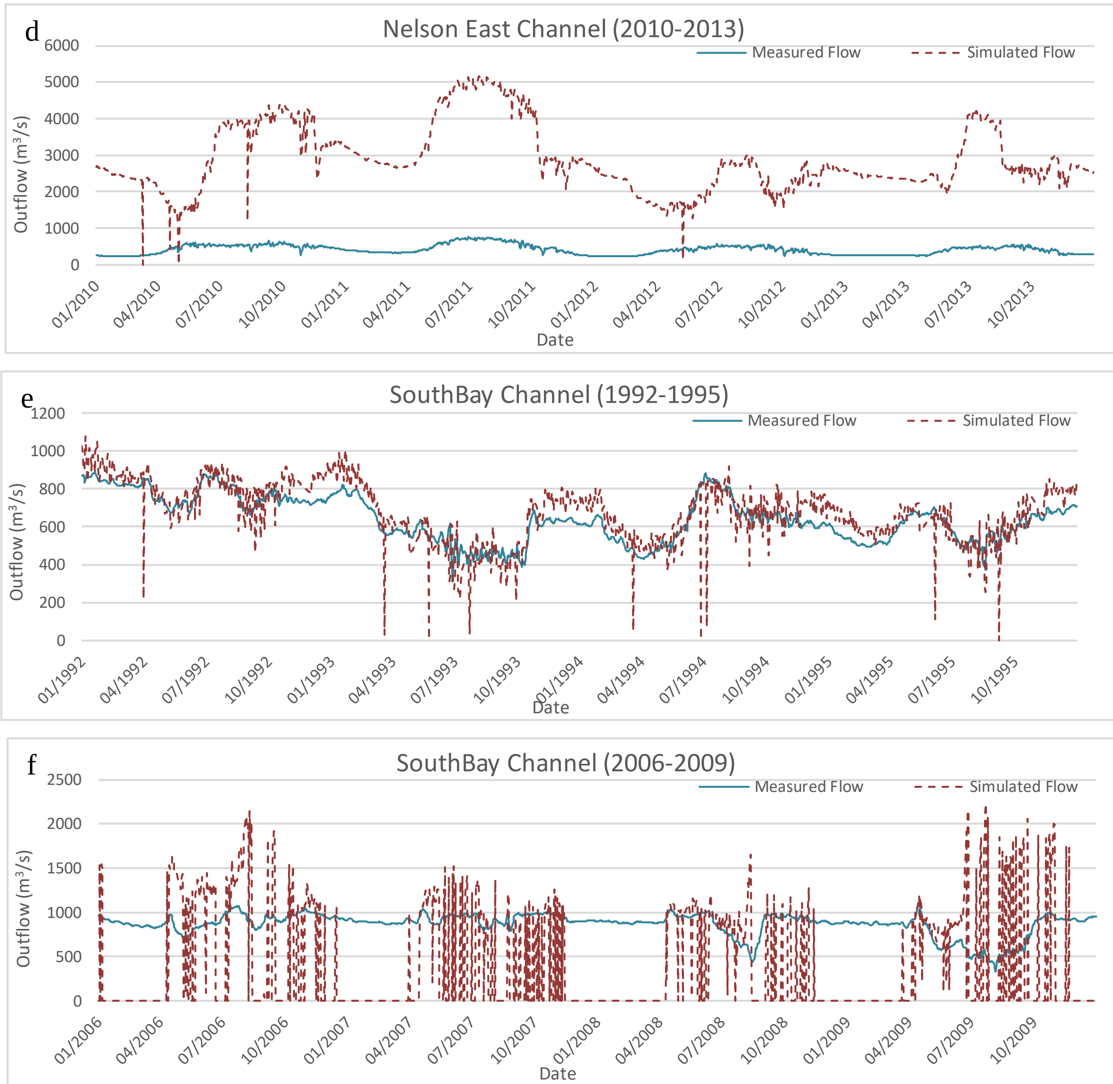
Appendix

The following figure presents the simulated and measured streamflow time-series in Nelson East, Nelson West, and South Bay channels before incorporating the backwater-affected rule curves through the custom code. These figures show that the model fails to adequately represent the water distribution through channels by only following the mass-balance equation. The backwater-affected rule curves represent the physical characteristics of the system which affects the streamflow at each channel and therefore an adequate representation of these characteristics is necessary for an acceptable estimation of streamflow in these channels.





The mass-balance model simulation result without customizing Nelson East and South Bay channels. (a) Nelson East channel streamflow (1986-1989). (b) Nelson East channel streamflow (2010-2013). (c) Nelson West channel streamflow (1986-1989). (d) Nelson West channel streamflow (2010-2013). (e) South Bay channel streamflow (1992-1995). (f) South Bay channel streamflow (2006-2009).