COLUMBIA RIVER TREATY RENEGOTIATION: POTENTIAL IMPACTS ON AGRICULTURE, FLOOD RISK, HYDROPOWER AND INSTREAM FLOWS IN THE CONTEXT OF AN ALTERED CLIMATE

By

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Dedication

To all 1971 liberation war martyrs of Bangladesh

because of whose sacrifice I lived in a free country, got subsidized education and be an entity to compete in this world.

COLUMBIA RIVER TREATY RENEGOTIATION: POTENTIAL IMPACTS ON AGRICULTURE, FLOOD RISK, HYDROPOWER AND INSTREAM FLOWS IN THE CONTEXT OF AN ALTERED CLIMATE

Abstract

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The Columbia River Treaty (CRT), signed between Canada and the United States in 1964 is important for flood control and hydropower generation in the Columbia River Basin (CRB). Starting from 2014, with 10 year notice the treaty can be terminated or modified. With the possibility of renegotiating the terms of the treaty in the horizon, it is timely to assess impacts of possible treaty alternatives on water resources of the region. The CRB region is projected to have increased temperature resulting in earlier snowmelt and shift in the stream-flow timing. Thus the objective of the study is to assess the impacts of possible changes in the CRT on agriculture, flood control, hydropower production and environmental flows under projected climate change. A biophysical modeling system, VIC-CropSyst, a reservoir operation modeling tool, ColSim, and a curtailment model is implemented under two alternative treaty scenarios and ten climate change scenarios in this study. Treaty alternatives consider operation of the treaty storages to augment flow during low flow months. These two treaty alternatives are run separately under two different flood flow targets (13,000 m^3/s and 17,000 m^3/s) at The Dalles.

Climate change projections centering 2030s and 2060s show increased flow during spring with a shift in peak supply earlier in the season, greater flood risk, better production of firm hydropower energy, and improved reliability of meeting instream flow targets in most of the reservoir locations compared to the historic period.

Future climate is projected to shift agricultural demand earlier in the irrigation season, causing an increase in water rights curtailment beginning of the irrigation season in those locations where the supply shift is occurring faster than the demand shift. The alternative treaty scenarios benefit irrigated agriculture in the future by reducing water rights curtailment. However, in terms of flood risk, hydropower and environmental flows, CRT alternatives result in mixed impacts when considered along with climate change. This study will help in guiding policy makers to provide stable and flexible treaty provisions that consider benefits to numerous water-use sectors in the long-term.

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Chapter 1: Introduction

Over 200 international water agreements were signed for shared water boundaries between two or more countries (Wolf 2002). One significant treaty between the U.S. and Canada was ratified in 1964 and is known as the Columbia River Treaty (CRT) (Hyde 2010). The CRT was implemented primarily to help both countries with flood control and hydropower generation. Starting from 2024, U.S. or Canada can terminate or bring changes in the treaty provisions with a 10-year advance notice leading to potential changes in reservoir operations and water resource availability. With the possibility of renegotiating the terms of the treaty in the horizon, it is timely to assess treaty alternatives that consider the more complex conditions that currently influence water resources decision making in the basin, including climate change. Hydropower and flood control are the two most widely emphasized sectors in the treaty because of their economic impacts and risk factors (Dunn et al. 2014; Johnson 2016). There is an emerging demand to bring more provision to the treaty that considers ecosystems and other aspects of the environment, agriculture, and climate change (Brady et al. 2015, Cosens et al. 2014). There are few recent studies that consider current concerns regarding unmet instream flow requirements and environmental flows supporting fish and ecosystems (Kruger 2014; Mamun et al. 2015); however, not much attention has been paid to the agricultural sector regarding the treaty.

Climate change has a great influence on Columbia River hydrology and water resources of both Canada and the U.S. Pacific Northwest (PNW) region is projected to have increased temperature which will result in earlier snowmelt and shift in the stream-flow timing. Climate change projection in the pacific northwest area shows increase in mean annual temperature 1.1 to 4.7 °C (2 to 8.5 °F) from 1950–1999 to 2041–2070 by 2050 (Rupp et al. 2016). This change in temperature is expected to shift the spring snowmelt peak earlier with increased flow during the winter and decreased summer streamflow. These predicted changes will have impacts on water resources and CRB operations. Thus several studies have addressed this issue and analyzed the future impacts of climate change in water resources management sectors such as hydropower (Payne et al. 2004), flood control (Lee et al. 2009) and irrigation (Vano et al. 2010) in the PNW. Due to these probable altered climate conditions, it is timely to consider CRT alternatives that incorporate future climate change and its uncertainties (Cosens 2010).

Our long-term objective is to guide policy makers to provide stable and flexible treaty provisions that are beneficial in the long-term through examination of the combined effects of proposed CRT alternatives and climate change on hydropower generation, flood risk, irrigated agriculture, and environmental flows. The objective of this particular study is to assess the impacts of alternative CRT scenarios under climate change on agriculture, flood protection, hydropower and environmental flow targets, and to examine the relative tradeoffs among alternative CRT scenarios. The specific aims are to 1) examine how climate change is projected to impact agricultural water availability, flood risk, and hydropower and environmental flow targets; 2) determine how CRT alternatives mitigate or exacerbate these climate change impacts, and 3) quantify trade-offs between CRT alternatives to guide policy makers. This study is unique because we examine impacts on agriculture through curtailment of interruptible water rights, in addition to the instream water uses of hydropower generation, environmental flows, and flood risk reduction.

Chapter 2: Background

2.1 Physical Geography of the Columbia River Basin

The Columbia River is the fourth largest river of North America based on average annual flow (Payne et al. 2004). Originating from British Columbia in Canada, the Columbia River Basin (CRB) covers about 672,100 square kilometers area in total (in Figure 2.1, marked in black line). The watershed area of the Columbia River comprises seven western and north-western states of the United States (U.S.) and British Columbia of Canada; 85% of this basin area falls in the U.S.

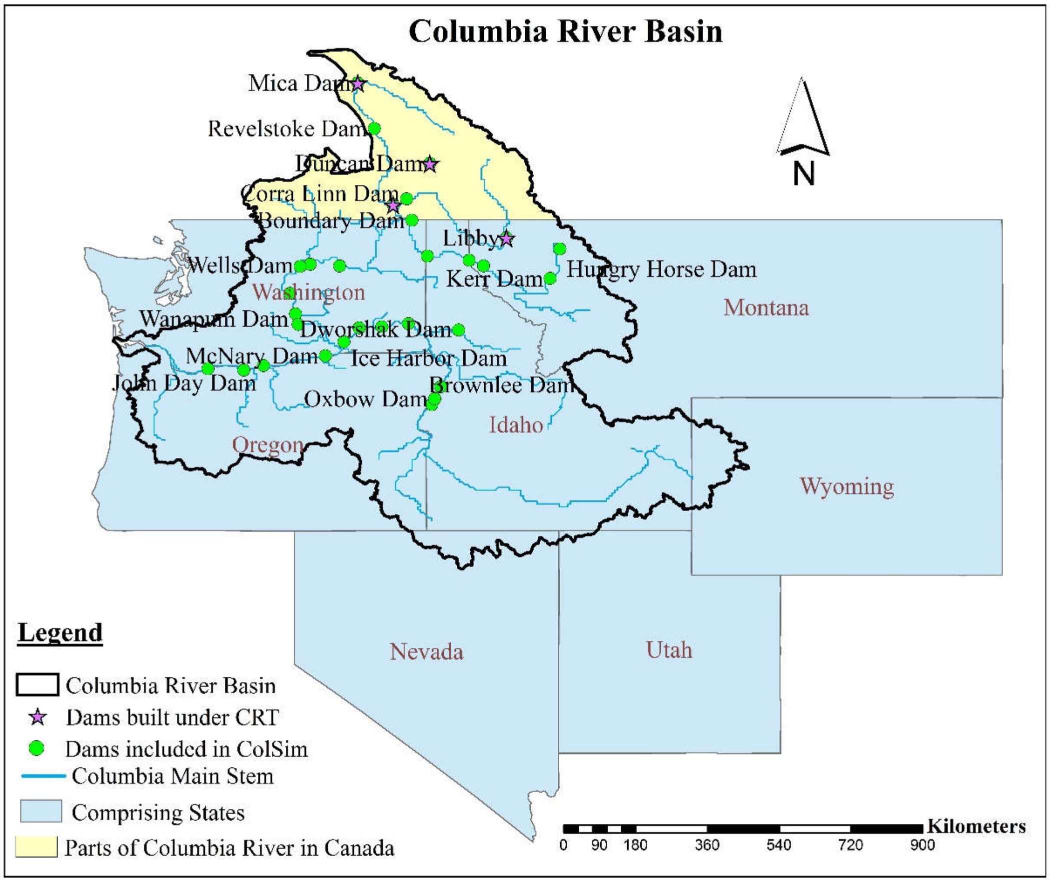


Figure 2.1: Columbia River Basin. Purple stars indicate location of dams built under CRT. Green dots indicate dams available in ColSim for simulation.

2.2 Columbia River Water Uses

2.2.1 Hydropower Uses

Hydropower from the CRB is a major source of energy in the PNW, contributing 77% of the power demand within the basin and 40% of the western regional power grid (Hamlet et al. 2002). Greater than 15,000 megawatts (MW) of energy are generated from 75 major dams in the CRB with roughly market value of $1.42 billion per year (as per 2002 estimation at $25 per MW-hour) (Hamlet et al. 2002, Northwest Power and Conservation Council 2010).

2.2.2 Flood Control

Major floods (e.g. floods of 1876, 1894, 1948 and 1964) in this river occurred before major dams were built. Flood control is a major concern in the CRB and is prioritized in the reservoir operation system. Flood usually occurs in this basin during spring and early summer time. Thus, seasonal filling of the reservoirs generally starts during the spring continues through summer months as possibility of flooding occurrence (Pulwarty and Redmond 1997).

2.2.3 Environmental Flows

The Columbia River basin is habitat of a variety of fish and other wildlife important for the economy, culture and environmental wellbeing of the region. Due to heavy management of the river water and construction of dams for hydropower generation, the fish population has been greatly affected (Raymond 1988). In 1991, twelve specific type of fish species including species from salmon, steelhead and sturgeon have been listed for protection under the Endangered Species Act (ESA). To protect these endangered species and other declining fish species, state regulatory agencies have adopted minimum instream flows in several watersheds. Beside these flow regulations, administrative low flow restrictions, known as surface water source limitations (SWSLs), have been established on several surface water sources in the Washington state (HDR 2005).

2.2.4 Irrigated Agriculture

Water supply for irrigated water use represents a major portion of the out of steam demand from the river. Water from this river is vital for the economy of Washington. Agriculture related services in this basin account for approximately 10% of the basin's employment (NRC 2004). Water diverted from the Columbia River for agriculture purposes are approximately 6% of the total river flow (BPA et al. 2001). The Columbia Basin Project, which uses water from the Columbia River as a main source, alone has the capacity of irrigating up to 1,600 square kilometers (Golder and Anchor 2006). During the years of water shortages, water for irrigation gets curtailed at first. Curtailment program along the mainstem is triggered to provide water for other sectors with higher priority. (See section 3.1.3 for details).

2.2.5 Other uses of Columbia River Water

Other sectors that represent a much smaller portion of the water use from this river are municipal, industrial and recreation. Although municipal use draws very small portion of the water from the river, it is important for serving daily household water needs in the region. About 4% of the total surface water diverted from the Columbia River is used by municipalities and industries (NRC, 2004).

2.3 Climate Change and the CRB Region

Several studies have been conducted on the climate change impacts on the Columbia River (Hamlet et al. 2001, Hamlet 2003, Hamlet et al. 2013, Lee et al. 2009, 2011, Payne et al. 2004). Hamlet et al. (2013) performed a comprehensive study to examine the climate change impact assessment and future adaptation procedures in 300 river locations in the PNW region. Major findings are as follows: significant changes in spring snowpack, shifts from snow and mixed-rain-and-snow to rain-dominant behavior, increases in instream flow during the winter season, and a rise in temperature in the summer. In another study, Murdock et al. (2013) projected a 1.8 to 2.7 °C increase in the temperature for the mid of the 21^{st} century as compared to the 1971-2000 period in the

Canadian part of the Columbia basin. This study also predicted an overall 1-9% increase in the annual precipitation.

The streamflow in the Columbia River is managed for various water resources purposes, resulting in significant change in the natural flow characteristic of the river. A major portion of the flow from this river is diverted for irrigation use in the PNW region. Besides out-of-stream demands a certain level in-stream flow must be maintained for flood control, hydropower generation and fish habitat. The water supply from the river is limited and it varies year to year depending on the climatic condition. Because it is anticipated that climate change will bring a significant shift in the magnitude and timing of the flow in the Columbia River, efforts are required to assess the effect of climate change on water resources operations. This is vital to secure the future water supply in this region and to make provisions for climate change in the treaty as required.

Lee et al. (2009, 2011) assessed reservoir refill timing and evacuation requirements for flood control in the CRB. The authors found that storage deficit phenomenon were observed for Mica, Keenleyside, Hungry Horse, Libby, Duncan, Grand Coulee and Dworshak Dams. Out of these dams Mica and Libby are used for storage control under the CRT. Lee et al. (2009) projected that a 2 C increase in temperature in this region will affect the refill timing and evacuation requirements for flood control in the CRB areas, and created an optimized flood rule curve that reduces storage deficits without increasing flood risk. Lee et al. (2011) further showed that proper adjustment and optimization in the flood control curve can also benefit the hydropower sector. Payne et al. (2004) considered three different future climate conditions and proposed reservoir policy to reduce the adverse impacts of climate change on hydropower production, flood protection, and environmental flows. They showed that a moderate climate change will disrupt the basin's "safe-yield" of hydropower. Cohen et al. (2000) performed a study primarily focusing on the trans-boundary flow in the Columbia Basin which predicted that hydropower generation, fisheries and irrigation will face more challenging situations under projected climate changes. However, they did not find much effect on flood risk.

2.4 The Columbia River Treaty

The Boundary Waters Treaty, signed between the U.S. and Canada in 1909 addressed the disputes of cross-boundary water problems (Hyde 2010). Despite some short-comings, this treaty resulted in the formation of the International Joint Commission (IJC) to deal with issues which might arise from the disputes (Hyde 2010). In 1944 IJC was requested to investigate the feasibility of increased water use from the river. In 1948 a devastating flood in the Columbia River affected a large area. The Grand Coulee Dam on the Columbia River in Washington State could not protect downstream areas from the flood. The need for a combined effort became obvious between the two countries to increase the flood control capacity. The process was further influenced by rising power demand for post-World War-II damage recovery. After formal negotiation, based on a detailed study by IJC published in 1959, the Columbia River Treaty was signed in 1964 for flood control and hydropower generation. The CRT is one of the most significant and ground-breaking agreement both for the U.S. and Canada in terms of flood control and power benefits. With 14 major dams under its operation, the CRT controls a major part of the Columbia River water.

2.4.1 Main Features of the CRT

Duncan Dam, Mica Dam, Keenleyside Dam in Canada and Libby Dam in the U.S. were constructed according to the CRT (Figure 2.1, marked in purple star). The two main objectives of these reservoirs and dams are flood control and hydropower generation. Important segments of the Treaty projects are shown in Table 2.1 (Hyde 2010, Mamun 2012). In total, treaty storage is 25 cubic kilometers. Except Duncan Dam, the three dams together have power houses with annual generation 9,548,000 Megawatt-hour (Mamun 2012).

Table 2.1: Important segments of the Treaty projects

Dam Name	Duncan	Mica	Keenleyside	Libby
Reservoir Formed	Duncan Lake	Kinbasket Lake	Arrow Lake	Koocanusa Lake
Reservoir Area	72.5 km^2 (28 $mile^2$)	435 km^2 (168 $mile^2$)	528 km^2 (204 $mile^2$)	189 km^2 (73 $mile^2$)
Maximum Reservoir Depth	38.7 m (127 ft)	184.1 m (605 ft)	52.1 m (171ft)	112.8 m (370 ft)
Powerhouse Capacity	–	1792 Mega-Watt	180 Mega-Watt	600 Mega-Watt

2.4.2 Flood Protection

2.4.2.1 Assured Operating Plan (AOP)

As part of the CRT, Canada operates at least 10.4 cubic kilometers of storage to prevent flood damages in the U.S. as well as in Canada. In exchange, the U.S. repays Canada with a certain portion of these benefits monetarily. Until 2014, Canada has received $64.4 million in three installments (Mamun 2012).

2.4.2.2 On-call flood protection

On-call flood protection must be provided to the U.S. by Canada in the case of potential floods because of peak discharges of greater than 61.3 million cubic meter per hour at The Dalles (Mamun 2012). The Columbia River Treaty Flood Control Plan (FCOP) provides the basis for current Columbia River system flood control operation. According to system flood control operations, storage reservoirs throughout the Columbia River Basin are operated during the months of January through April. The basic objective of the Columbia River system flood control operation is to operate reservoirs to prevent flood damage as well as insuring that reservoirs are refilled at the end of the spring runoff season. These reservoirs are also being regulated in a way that the storages do not fill in too soon causing the system to be under unfavorable condition (USACE 2003, Cosens 2010).

2.4.4 Impacts of the Columbia River Treaty

2.4.4.1 Social Impacts

To implement CRT, Columbia River tribes were forced to migrate and their land was brought under the government land-acquisition program. More than 1700 people were relocated for the implementation of CRT losing their livelihood, and long-borne heritage associated with the land (Loo et al. 2011). According to the Columbia River Inter-Tribal Fish Commission (CRITFC), the opinion of the tribes and tribal fishing interests were not taken into account while first finalizing the treaty. As arable land permanently went under water, the livelihood pattern of the local people was completely changed (Loo et al. 2011).

2.4.4.2 Economic Impacts

The U.S. Army Corp of Engineers found that due to the CRT, the U.S. has saved $260 million, $306 million and $379 million have been saved fromdue to U.S. flood damage reduction in 1972, 1974, and 1997, respectively (Sopinka et al. 2014). Besides direct economic benefits from hydropower generation and indirect economic benefits from flood protection, the CRT has generated employment in the form of dam-building, maintenance, power generation and development of new tourist attractions using entitled treaty money.

2.4.4.3 Environmental Impacts

Between 1938 and 1957, fish run characteristics of Chinook salmon and steelhead were disturbed by dam construction and maintenance (Raymond 1988). Hirst (1991) addressed hindrance in rearing because of flow fluctuations, unbearable weather condition, improper habitant for breeding, and mortality due to passage through powerhouse turbines. According to the National Environmental Policy Act, Canada White Sturgeon

(*Acipenser transmontanus*) and the threatened Bull Trout (*Salvelinus confluentus*) are in danger in terms of existence (Mamun 2012). An additional function of flood control at Libby dam, known as "Variable Flow Flood Control", began in 2003 (initiated by the U.S. after CRT implementation). The outcomes of this initiative are negligible in comparison to Grand Coulee flood control. Moreover, it is assumed that it has increased bank erosion along the approximately 46 kilometers portion of the Kootenay River; Canada has requested compensation (Hyde 2010).

2.5 Changes in the CRT over Time

Over the time, many important segments have been added for proper functioning of the CRT which are given below:

-Supplemental operating (SOP) agreements (1993): SOP agreement has been signed for ensuring healthy habitation for fisheries and addressed environmental issues.

-Non-power uses agreement (1994): This agreement is primarily for fisheries wellbeing.

-Arrow flow shaping agreement (2007): This agreement was signed to benefit recreational facilities, environment, and economy.

-Fall storage agreement (2009): The fall storage agreement was signed to ensure more power generation using the additional storage of Arrow reservoir at the time when the electricity price is high.

-Summer storage agreement (2010): The summer storage agreement has been signed to include both additional power generation and non-power benefits.

2.6 CRT Scenarios under Climate Change

For future operation of the dams, it is important to consider if projected changes in climate threaten normal operations of dams under international treaties. For example, the Colorado River Compact (CRC) signed in

1922 faced critical times to meet the demand of the south-western states and Mexico, mainly because of the failure in estimating the water supply and demand in the Colorado River. It was estimated that the yearly flow was greater than 19,700 million cubic meter (16 million acre-feet (MAF)) per year at the time the CRC was signed. In reality, the actual average flow in the basin was between 16,600 million cubic meter (13.5 MAF) and 17, 200 million cubic meter (14 MAF) per year (Gleick 1988). To avoid these type of situations, longer streamflow time-series, and consideration of the impacts of climate change on both water supply and demand, should be considered during CRT renegotiation.

At the time of this writing, relevant agencies from both the U.S. and Canadian governments are reviewing possible treaty alternatives scenarios and their outcomes. In the U.S., the Bonneville Power administration (BPA) has been investigating several iterations of alternative treaty scenarios (personal communication-BPA). Scenarios for this study have been collected from their most updated version of the iteration (phase 2, Iteration 3) (Personal communication- BPA), described in more detail in Chapter 3.

Chapter 3: Methodology and Data

3.1 Model Description

3.1.1 Modeling of Unregulated Flow and Crop Water Demand

An integrated water resources modeling system was applied for this study (Figure 3.1). The modeling setup consist of two major segments: 1) a dynamic biophysical modeling system comprised of a macro-scale hydrologic model the Variable Infiltration Capacity model (VIC), a cropping system model (CropSyst), and 2) a water resources management module consisting of a reservoir system management model (ColSim) and a curtailment model to assess impacts on agriculture in response to scenarios of climate change, water management, treaty scenarios changes. The biophysical modeling system, VIC-CropSyst, is a coupling between two distinct models. The VIC model is a process-based macroscale hydrologic model (Liang et al. 1996) that solves the water and energy balances for every time-step and grid cell. VIC is used for calculating unregulated flow at each grid cell within a basin area. CropSyst (Stockle et al. 2014) is a multiple cropping system growth, phenology, and management model that is used for generating agricultural demand. VIC-CropSyst uses detailed soil, vegetation, crop parameters and climate data as inputs and has been set up at the 1/16th degree resolution over the CRB. VIC calibration was performed for the whole CRB using a multi-objective calibration algorithm (Barik et al., in prep). After simulating runoff and baseflow for individual cells using VIC-CropSyst, a routing model was applied to get flows at different reservoir locations. A bias correction scheme (Elsner et al. 2010, Vano et al. 2010) using the quantile mapping technique was performed at each of the locations to remove any systematic bias in the flow data. Surface irrigation water withdrawal from different diversion points were obtained by accumulating VIC-CropSyst irrigation water requirement (plus irrigation inefficiencies) output for each crop at each grid cell.

3.1.2 Modeling of Regulated Flow

The Columbia Simulation Reservoir Model (ColSim) (Hamlet and Lettenmaier 1999), which mimics major reservoir and dam operations in the CRB, is applied for reservoir simulations. This model has been widely applied for various climate change studies related to water resources management implications in the CRB (Payne et al. 2004; Hamlet and Lettenmaier 1999; Lee et al. 2009). Realistic representation of the flow condition in the major operational facilities in the CRB was simulated by fulfilling conditions for hydropower generation, flood control, irrigation diversions, minimum flow requirements and recreational operations. ColSim uses the bias corrected flow from VIC-CropSyst as input and simulates regulated flow considering water resources management rules at major dam and reservoir locations in the CRB. To capture these management operations at finer time scales the model was modified to weekly time-step for this study which traditionally runs at a monthly time-step.

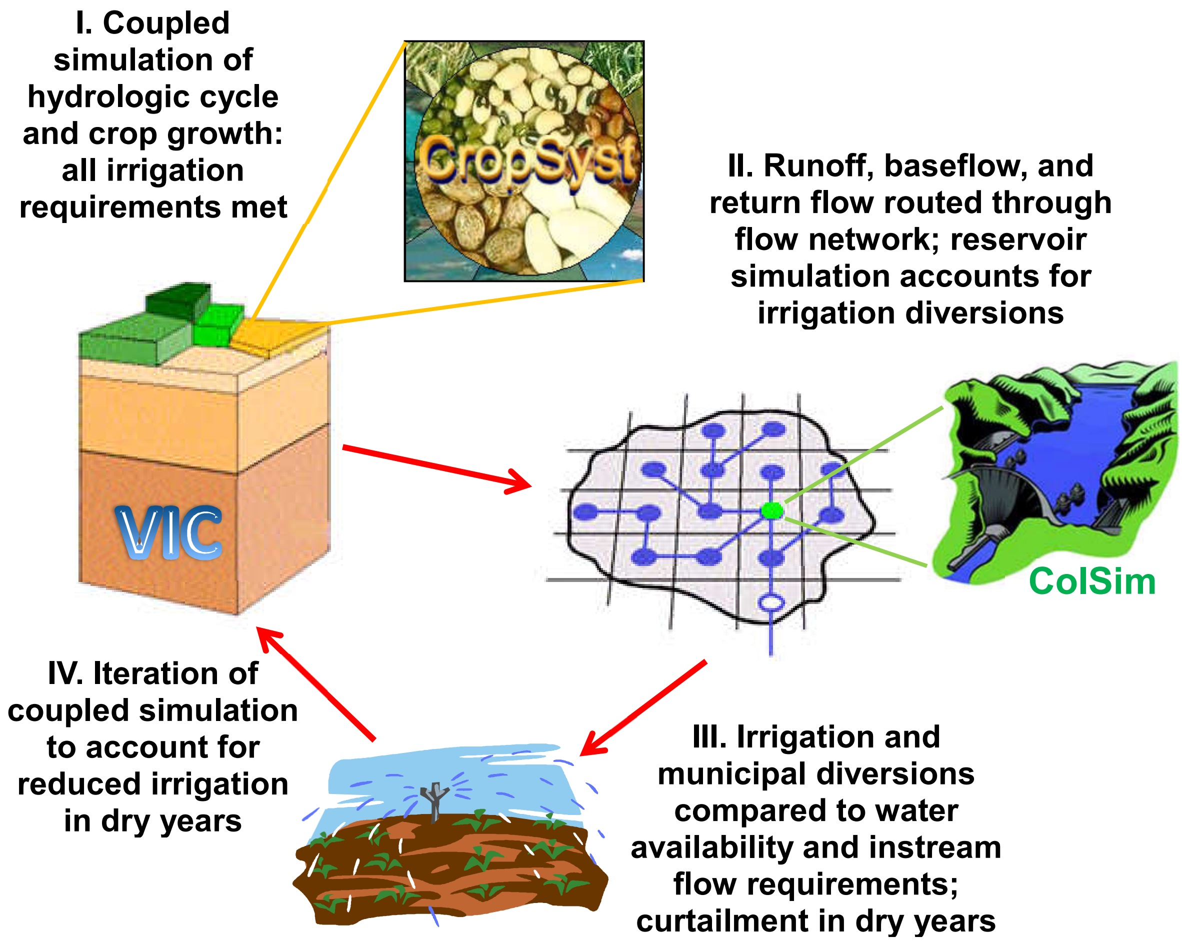


Figure 3.1: Schematic Diagram of biophysical modeling framework (Stöckle et al. 2014)

3.1.3 Modeling of Agricultural Water Rights Curtailment

Regulated flow and curtailment simulations are dependent on estimating of out-of-stream and instream demands. Surface water irrigation demand with associated conveyance loss and municipal demands are the primary out of stream demands that comprise the diversion amount. All agricultural demand was accumulated based on diversion points. (For example, 144 cells get water from the Priest Rapids dam. In this case, agricultural demand of these cells has been accumulated to get total demand of water from the Priest Rapids reservoir). Municipal demand and conveyance loss were considered in total demand calculation. The average conveyance loss percentage calculated for Washington was around 20% and this percentage is applied for any areas outside Washington that is considered for curtailment within Washington (Rajagopalan et al., in prep.). Public water supply in terms of gallons per capita per day (gpcd) for each county is obtained from the USGS estimation of 2010 water supply (Lane and Welch 2015) which was accumulated into total Water Resource Inventory Area (WRIA) municipal demand using WRIA population estimates. Future population is forecasted using an S-curve population projection method (Barik et al. in prep.). Growth in rural demand will likely be met by groundwater supplies, but it was assumed that domestic wells would be shallow enough to impact surface water flows. Total municipal water diverted form a diversion point was estimated from the WRIA municipal demand. Municipal demands from WRIAs were accumulated into total municipal demand from the diversion point demand assuming they proportionate to the percentage of WRIA areas within the diversion area (Barik et al. in prep.).

During a year with water supply shortage, the Department of Ecology in the State of Washington may curtail irrigators' water use to make water available to meet weekly instream flow targets. There are different types of curtailment applied to irrigation water use in Washington. Along the mainstem of the Columbia River, curtailment can be broadly divided into two classes: interruptible and non-interruptible. Water right holders who may not be recognized during a low water year to make more water available for in-stream uses is known as interruptible water rights. Water rights issued after 1980 in the Columbia River mainstem is specified as interruptible. When this type of water right holder is restricted from using water in the fields is known as interruptible curtailment. Non-interruptible water right holders have more permanent rights to water and may not be curtailed unless these is a severe shortage of water. This type of curtailment is known as prorated curtailment. Due to unavailability of more details information on non-interruptible water rights, only interruptible water right holders are curtailed in this study. Water rights information used for this study was available from Washington State Department of Ecology's water rights tracking system. More details on the procedure can be found in Rajagopalan et al. (in prep.). Curtailment in the mainstem is dependent on April through September total unregulated flow volume forecast at The Dalles Dam. The curtailment program is implemented only when this volume is predicted less than 74 cubic kilometers (60 MAF). In a year when the seasonal flow volume is less than 108.5 cubic kilometers (88 MAF), a reduction (known as “critical flow adjustment”) up to 25% to the established minimum weekly flow is applied. Due to modeling constrains this adjustment is not considered for mainstem curtailment. This brings a possibility of overestimation in mainstem curtailment results. Curtailment modeling in the mainstem was calculated over a period of 1981 to 2009 (29 years) instead of 1981 to 2011 for historic for a limitation in the model simulation. Similarly, 29 year periods from the future is considered while compared with the historic curtailment results.

Interruptible curtailment in the Columbia River mainstem was estimated based on simulated regulated flow from ColSim, agricultural demand, municipal demand, instream flow demand and portion of the agricultural demand that is coming from interruptible cells. VIC-CropSyst simulated naturalized flow (after deducting the amount of the total irrigation demand that is not generating from interruptible cells) is used as input in ColSim to get regulated flow. Next, municipal demand that is considered constant throughout time span of the study is subtracted from the regulated flow. If the regulated supply after considering municipal demand becomes lower than the instream flow requirement then curtailment is considered. If the difference between the regulated supply (after considering non-curtailed demand and municipal demand) becomes lower than the amount of interruptible demand, then the curtailment amount is equal to the difference of regulated supply (after demand withdrawal) and instream flow demand; otherwise, it is the same amount as the interruptible demand (Rajagopalan et al., in prep).

3.1.4 Modeling of Flood Risk

To determine the impacts of different climate and CRT scenarios on flood magnitude, flood frequency analysis at different locations in the CRB was performed. At first, yearly maximum flow at a weekly time step was ranked and fitted with the probability distributions. To determine the best fit probability distribution applicable to the basin four distributions were tested: generalized extreme value distribution (GEV), generalized Pareto distribution (GPA), generalized logistic distribution (GLO) and generalized normal distribution (GNO). All of these distributions have been used previously in determining extreme value (Kumar et al. 2005; Mantua et al. 2010).

All four distributions are characterized by three different parameters. Parameter estimation was conducted using the method of L-moments (Hosking and Wallis 2005). Four distribution parameter sets (each with three parameters) were derived by fitting four distribution functions for flows at eight reservoir locations for the period 1980-2011. If ξ is the location parameter, $\alpha\ is$ the scale parameter and K is the shape parameter, projected flow according to distribution has been derived using respective quantile equation in Table 3.1. The reservoir locations are Grand Coulee, Libby, Noxon Rapids, Priest Rapids, The Dalles, Wells, Rock Island and Hells Canyon. Selection of these locations are based on observed data availability from the USGS (2016).

Table 3.1: Parameter and Quantile Function of Different Distributions (Ahmad et al. 2011)

Distribution	Quantile Function	Parameter Estimation
GEV	$Q_m = \zeta + \frac{\alpha}{\kappa}\{1-(-\ln f)^{\kappa}\}$ If m = rank and n =number of annual maxima in the record, probability, $F_m = \frac{m}{n+1}$ and f = Non -exceedence probability = 1- F	$\alpha = \frac{\lambda_2 \kappa}{\Gamma(1+\kappa)\Gamma(1-2^{-\kappa})}$ $\zeta = \lambda_1 + \frac{\alpha(\Gamma(1+\kappa)-1)}{\kappa}$ $\kappa = 7.8590Z + 2.9554Z^2$ $Z = \frac{2}{3+\tau_3} - \frac{\ln 2}{\ln 3}$
GPA	$Q_m = \zeta + \frac{\alpha}{\kappa}\{1-(1-f)^{\kappa}\}$	$\alpha = \lambda_2[(\kappa+1)(\kappa+2)]$ $\zeta = \lambda_1 - \lambda_2(\kappa+2)$ $\kappa = \frac{1-3\tau_3}{1+\tau_3}$
GLO	$Q_m = \zeta + \frac{\alpha}{\kappa}\{1-(\frac{1-f}{f})^{\kappa}\}$	$\alpha = \frac{\lambda_2}{\Gamma(1+\kappa)\Gamma(1-k)}$ $\zeta = \lambda_1 + \frac{\lambda_2 - \alpha}{\kappa}$ $\kappa = -\tau_3$
GNO	$Q_m = \exp[\mu + \sigma\phi^{-1}(f)]$ Where μ is mean, standard deviation is σ and ϕ^{1} is the inverse of the standard normal distribution function	$\zeta = \mu = \lambda_1$ $\alpha = \sigma = \lambda_2\sqrt{\pi}$ $\kappa = \tau_3$

The best fit distribution for the flow of the CRB has been selected based on comparison of results of four goodness of fit tests namely: root mean square error (RMSE) (Barik et al. 2015), mean absolute deviation index (MADI) (Willmott et al. 2005), Nash-Sutcliffe Coefficient NSE) (Nash and Sutcliffe 1970) and Percent Bias (PB) (Sorooshian et al. 1993). A performance score was given to each distribution for flows at each reservoir locations. For example, for observed flow at Hells Canyon reservoir, RMSE is the lowest for GLO and highest for GPA. In this case GLO achieves a score of 4 and GPA achieves a 1. We find that the GEV distribution is best suited overall and so is selected for flood magnitude calculations (Table 3.2). The GEV distribution has been used to obtain estimates of quantile (Q_{m}) for a range of flood return periods for both USGS observed flow and ColSim-simulated flow at each of the reservoir locations.

Table 3.2: Scores for Four Distributions for Selecting the Best

Distribution	**GEV**	**GPA**	**GLO**	**GNO**
Score	83	80	80	77

3.1.5 Modeling of Hydropower Generation

ColSim simulates hydropower generation and associated revenue by considering the flow condition at dam locations with hydropower facility (Payne et al. 2004). Releases for hydropower generation in ColSim are controlled by the Energy Content Curve (ECC). ECC is the operating rule that is followed to control the release of water from the reservoirs at 95% confidence level of reservoir refill (BPA 2016). This ECC is constructed based on spring runoff volume forecast and critical period analysis for all the major dams (Hamlet and Lettenmaier 1999). A typical load shape based on hydropower market is applied to meet the system-wide energy target. Only dams with hydropower facility that are operated under Pacific Northwest Coordination Agreement (BPA et al. 1997) are included in ColSim for hydropower generation estimation. Production of the hydropower is divided into two categories; they are firm or non-firm energy. Firm energy is the critical hydropower production that is required to be generated under the least performing condition of the plant. Energy produced above the firm energy in response to the market demand is known as non-firm energy. Non-firm energy is only generated under conditions when reservoir draft goes above the ECC (Payne et al. 2004). For this study, the ECC are interpolated into weekly time-steps so that weekly outputs can be developed.

Hydropower generation in ColSim follows the equation 3.1 (Schwarzenegger 2008).

H=e.Q.h. ………………………… Eq. 3.1

Where, H is the hydropower produced, Qis the flow released, h is the net head (difference of elevation between estimated reservoir elevation and tail water elevation), e is the overall plant efficiency (usually assumed 80%), and is the unit weight of water.

3.2 Data Description

3.2.1 Data Sources

3.2.1.1 Land Cover

The land cover parameter sets contain information to simulate important components of the hydrologic cycle. The parameter set provides information for 119 land covers and crop types altogether. The land cover classification and parameters are obtained from the dataset developed by Maurer et al. (2002) and later improved to 1/16th resolution by Elsner et al. (2010) for VIC simulations. However, this land cover classification does not provide detailed crop types. To provide more detailed classification of crops two data layers have been used: i) the United States Department of Agriculture (USDA) (NASS 2013) Cropland Data Layer (CDL) and ii) the Washington State Department of Agriculture (WSDA) cropland distribution. These GIS crop layers provide the proportion of each crop in a VIC grid cell. Only the crops that contain at least 1% area of the total area of the grid cell are considered in the parameter file. Because of the unavailability of detailed crop information from the Canadian part of the CRB, the Elsner et al. (2010) classification was used unchanged in that portion. The WSDA dataset is the principal source of crop distribution information for the Washington part of the CRB, because it comes with more detailed survey-based information such as information on irrigation. The USDA CDL provides the crop distribution outside of Washington. This satellite based high resolution (30 m) crop data layer information is redistributed to the 1/16th degree scale. Unlike WSDA, this dataset does not come with any irrigation information. Thus, a very simple irrigation rule applied where only the high value crops are irrigated for the part of the CRB outside of Washington State (Rajagopalan et al. in prep.).

3.2.1.2 Soils

Soil classification, distribution and properties are primarily derived from the STATSGO2 soil database (Soil Survey Staff 2016). Surveyed soil layers from STATSGO2 are redistributed to 1/16th degree resolution and 17 soil moisture layers to have the format required for VIC-CropSyst runs. For the Canadian part of the CRB, the 1/16th degree soil dataset developed by Elsner et al. (2010) has been used for this study. This dataset is derived from Maurer et al. (2002) which is originally based on the Land Data Assimilation System (LDAS; Mitchell et al. 1999) dataset.

3.2.1.3 Water Rights Data

This study is primarily focusing on water curtailment in the watersheds of Washington State. For the curtailment analysis, water rights information is obtained from the Washington Department of Ecology's water rights tracking system. This has been used to model the curtailment process. This dataset provides information such as water right priority date, place of use, point of withdrawal or diversion, and type of use. Due to, data and other constrains only interruptible water right holders in the database are curtailed during a shortage.

3.2.1.4 Instream flow Rules

Instream flow rule in a stream is critical for curtailment decisions. Interruptible water right holders are usually interrupted when there is not enough water in the stream to maintain the instream flow targets. Instream flow targets are based on Washington Administrative Codes (WAC) or Surface Water Source Limitations (SWSL).

3.2.2 Climate Data

As inputs of the model, climate data for the U.S. part of the CRB are re-gridded from a 4 km resolution gridded meteorological data set (Abatzoglou 2013) to 1/16th degree resolution for VIC-CropSyst simulations. Gridded General Circulation Model (GCM) outputs from seven models participating in the CMIP5 downscaled using Multivariate Adapted Constructed Analogs (MACA) (Abatzoglou and Brown 2012) are used in this study. Livneh et al. (2013)'s 1/16th degree gridded meteorological data downscaled using MACA have been used for the Canadian part due to unavailability of the data from the above mentioned dataset. Climate scenarios selected for the analysis are discussed in the section below (3.4.2).

3.2.3 Flow Data

3.2.3.1 Observed Flow

Observed flow used for simulated flow evaluation has been obtained from United States Geological Survey's (USGS, 2016) stream gauge records. For reservoir signature purposes (discussed in section 3.3.1), wherever available, both pre-reservoir and post –reservoir data were obtained. As an example, since The Dalles Dam started operations in 1957 (BPA et al. 2011), data collected before the year 1957 is considered pre-reservoir and data collected after the year 1957 as post-reservoir. Details of all the USGS stations with data periods used in this study are summarized in Table 3.3. At some locations, the gauging station has been established after the reservoir was built. These locations do not have gauge data for the pre-reservoir period. In this situation, to get the pre-reservoir period flow, a nearby gauging station has been chosen at upper stream or lower stream (whichever is the closest to the dam locationto get the data for the pre-reservoir period. Wells, Ice harbor and Libby are such three reservoirs which used pre-reservoir data from a gauge that not at the dam location.

Table 3.3: Gauging Station and Flow Data Information

Reservoir	Streamflow Gauging Station	Gauging Station ID	Period of Record	Pre-reservoir Period	Post-reservoir Period
Libby	The Kootenai River at Libby	12303000	1929-1970	1929-1970	-----------
	The Kootenai River below Libby Dam	12301933	1971-2005	-----------	1980-2011
Wells	The Columbia River at Bridgeport, WA	12438000	1952-1966	1952-1966	----------
	The Columbia River Below Wells Dam, WA	12450700	1980-2011	-----------	1980-2011
Grand Coulee	The Columbia River at Grand Coulee	12436500	1930-2011	1930-1940	1980-2011
Priest Rapids	The Columbia River at Priest Rapids Dam	12472800	1928-201	1928-1960	1980-2011
Noxon Rapids	Clark Fork at Thompson Falls MT	12391000	1952-1959	1951-1959	----------
	Clark Fork below Noxon Rapids Dam near Noxon MT	12391400	1980-2011	----------	1980-2011
Ice Harbor	The Snake River at Clarkston	13343500	1928-1960	1928-1960	-----------
	The Snake River at Ice Harbor	13353000	1980-2011	-----------	1980-2011
Oxbow	Snake River Above Dam at Oxbow, OR	13290000	1929-1960	1929-1960	-----------
	Pine Creek near Oxbow, OR	13290190	1980-2011	-----------	1980-2011
The Dalles	The Columbia River at The Dalles	14105700	1928-2011	1928-1956	1980-2011

3.2.3.2 Naturalized Flow

Naturalized streamflow is obtained after all the effects of reservoir operations have been removed from observed flows. We need naturalized stream flows for calibration, evaluation and bias correction processes. Wherever available, naturalized flow has been collected from Bonneville Power Administration developed modified streamflow dataset (BPA 2011). For other locations we used naturalized flow provided from the University of Washington's Climate Impacts Group UW CIG (Elsner 2010). This flow is used as observed pre-reservoir flow for the locations where there were no pre-reservoir data.

3.3 Model Evaluation Methodology

3.3.1 Streamflow Evaluation

To properly quantify the impacts of climate change and CRT regulations on water availability for agriculture, both unregulated and regulated flow simulations should first be evaluated. To evaluate unregulated flow, we compare VIC-simulated hydrographs against BPA (2011) naturalized flow data. Prior to evaluation, VIC is first calibrated using a multi-objective automatic calibration tool called MOCOM-UA for sensitive soil parameters to reduce error in simulation (Hamlet et al. 2013; Barik et al. in prep.). The years of 1980-1994 have been selected for the calibration period while the years of 1995-2006 for the evaluation period at majority of the locations. Streamflow evaluation has been done both for the unregulated flow and regulated flow.

ColSim model performance has been evaluated by comparing observed reservoir signature with simulated reservoir signature at eight dam locations (Table 3.4). The selected of these dams are based on the availability of data for both pre and post reservoir periods. The change in flow hydrograph due to reservoir operation is defined as reservoir signature (following Adam et al. 2007). The observed reservoir signature constructed by taking the difference between post-reservoir USGS flow and pre-dam reservoir USGS flow at different gauging stations (USGS 2016) (the gauge selection procedure is described in section 3.2.3.1).

Simulated reservoir signatures were obtained as the difference between regulated flows from ColSim (as post-reservoir flow) using VIC-CropSyst unregulated flow and BPA 2011 unregulated flow (as pre-reservoir flow). Along with magnitude of reservoir signatures, difference between pre-reservoir and post-reservoir streamflow were also calculated as a percentage of pre-reservoir flow.

Table 3.4: Different Reservoir selected for regulated flow evaluation and dam locations

Reservoir Name	**River/Tributary**
Libby	Kootenai River
Wells	Upper Columbia River Basin
Grand Coulee	Upper Columbia River Basin
Priest Rapids	Upper Columbia River Basin between the Yakima Firing Range and the Hanford Nuclear Reservation)
Reservoir Name	**River/Tributary**
Noxon Rapids	Clark Fork River
Ice Harbor	Lower Snake River
Oxbow	Middle Snake River Between Idaho and Oregon
The Dalles	Middle Columbia River, Oregon

3.3.2 Flood Risk Evaluation

As described above, a goodness-of-fit test has been conducted between quantile values for observed and simulated as well as between simulated maximum flow and simulated quantile values to evaluate the performance of the regression equation. Hydrological performance of the model for predicting flood magnitude has been tested by three goodness-of-fit tests (Table 3.5)

Table 3.5: Goodness of fit tests for flood magnitude evaluation

Name	**Source**
Nash-Sutcliffe Coefficient NSE)	Nash and Sutcliffe 1970
Percent Bias (PB)	Sorooshian et al. 1993
Kling-Gupta Efficiency (KGE)	Gupta et al. 2009
Relative Index of Agreement (RI)	Willmott 1981

3.3.3 Hydropower Generation

A reliability test was conducted to measure the model performance to meet certain hydropower according to Hamlet and Lettenmaier (1999) using both modified flow (BPA 2011) and VIC-CropSyst generated unregulated flow as input to ColSim. Hydropower evaluation was performed using reliability. Reliability is a measurement of how well a water resources target was fulfilled for a certain time period (Hamlet and Lettenmaier 1999). This is a probability of achieving a target, usually presented as a percentage. The reliability of ColSim simulated regulated flow when run with VIC-CropSyst simulated flow to meet the hydropower generation target was compared with the reliability with the ColSim output simulated using the naturalized flow to evaluate the hydropower generation. The same evaluation measurement is applied in case of instream flow target evaluation.

3.3.4 Agricultural Curtailment and Instream Flow Target Evaluation

Historical unmet instream flow demand is compared against unmet instream flow demand estimated from simulated data. Subtracting minimum instream flow requirements (at locations where there are instream flow rules) from USGS gauge flows gives estimates of observed unmet instream flow demands. Unmet simulated instream flow demand was estimated form ColSim-simulated regulated flow after the agricultural and municipal demands were subtracted from the supply and after interruptible curtailments were modeled. This comparison indirectly provides an evaluation of simulation of agricultural curtailment. Higher differences between observed and simulated instream flows result in less confidence in the agricultural curtailment results since error in curtailment estimation contributes to this difference. Instream flow target fulfillment success rate is also evaluated using the reliability test described in section 3.3.3.

3.4 Model Scenarios

3.4.1 CRT Scenarios

Two alternative treaty scenarios are considered that focus on planned storage for flood risk and flow augmentation for ecosystem and water supply. These alternatives are targeted to provide extra planned storage in Arrow Lakes (Keenleyside Dam) to keep the flood risk level the same as current conditions before executing Effective Use and Called Upon operations. Along with the Arrow storage, additional storage is proposed for the Mica Dam in the second scenario. In parallel, under these scenarios, the provision for storing more water during the winter for release in the spring and summer for ecosystem uses and water supply are included. The proposed conditions of these scenarios are described below.

3.4.1.1 Alternative Treaty Scenario 1

Under this alternative treaty scenario, additional storage provided by Keenleyside Dam is proposed in addition to the existing 1200 cubic meter (1 MAF) Supplemental Operating Agreement (SOA) for in-stream and out-of-stream uses. To acquire this storage from April to September, water would be stored during the December-March period. This storage increases for the driest 20% of water years. The years with seasonal flow volume (April to September flow volume at The Dalles) lower than the 20th percentile of historical time-series of seasonal flow volumes are considered as dry years.

The layout for the proposed additional storages and associated storing period for Keenleyside Dam is given below:

1, 200 million cubic meter (1.0 MAF) (SOA): Already in place

600 million cubic meter (0.5 MAF): December – March

600 million cubic meter (0.5 MAF) (dry year): January – March

Thus, during a non-dry year, 600 million cubic meter (0.5 MAF) storage is requested in addition to the existing 1,200 million cubic meter (1.0 MAF) SOA storage. This additional storage request increases to 1,200 million cubic meter (1 MAF) during dry years leading to 2400 million cubic meter (2.0 MAF) in total storage. If the additional storages in the operation cannot be provisioned during the winter, then the additional water is released from Arrow in spring and summer.

The release schedule is laid out separately for a dry and non-dry years under this alternative treaty scenario. Current 1,200 million cubic meter SOA storage is released between April to September to support Priest Rapids and McNary minimum flow objectives. The proposed additional 600 million cubic meter storage is released according to the April - September Water Supply release schedule (Table 3. 6).

Table 3.6: Release schedule for a non-dry year.

Month	Release (%)
April	7
May	13
June	20
July	26
August	23
September	10

During dry years, an additional 1,200 million cubic meter of storage is released between April 16 to May 31 to support PRD and MCN minimum flow objectives. In case not all of the additional storage is released by May 31, the remainder is emptied by June.

3.4.1.2 Alternative Treaty Scenario 2:

Under this alternative scenario, in addition to the existing 1,200 million cubic meter SOA storage, an additional 4,100 (3.4 MAF) dedicated storage in Canada is proposed for in-stream and out-of-stream uses. To acquire this storage from April to September, water would be stored during the period of November-March. Of this additional 3.4 MAF, 0.9 MAF is treaty storage at Keenleyside and 2.5 MAF is non-treaty storage at Mica.

The layout for the proposed additional storages and their storing period for Keenleyside and Mica Dams are given below:

1,200 million cubic meter (1.0 MAF) (SOA): Already in place (Keenleyside dam)

1,100 million cubic meter (0.9 MAF) (Water supply for out-of-stream demands): November-March (Keenleyside Dam)

700 million cubic meter (0.6 MAF) (Water supply for instream demands): November-March (Mica Dam)

2,300 million cubic meter (1.9 MAF) (Flow augmentation for ecosystem): November-March (Mica Dam)

Similar to the alternative scenario 1, the release schedule is laid out separately for dry and non-dry years. The release of 1, 200 million cubic meter SOA storage remains the same as alternative scenario 1. However, the rest of the additional 4,100 million cubic meter storage is released according to the following schedule during a non-dry year:

1,100 million cubic meter treaty storage for out-of-stream demands is released according to the April - September Water Supply release schedule in Table 1

700 million cubic meter non-treaty storage for instream demands is released between April-September to support PRD and MCN minimum flow objectives

2,300 million cubic meter non-treaty storage for flow augmentation is released between July 1 to September 15 to support minimum flow objectives at PRD and MCN

In dry years, an additional 4,100 million cubic meter (3.4 MAF) storage in total is released between April 16 to May 31 to support PRD and MCN minimum flow objectives. In case not all of the additional storage is released by May 31, the remainder is emptied by June. If the additional storages in the operation cannot be provisioned during the winter, then the additional water is released from Arrow in spring and summer.

Finally, the above two alternative treaty scenarios are applied separately under 13,000 cubic meter per second (m^3/s) (450 kilo cubic feet per second –kcfs) and 17,000 m^3/s (600 kcfs) flood flow conditions at The Dalles. However, we did not simulate significant impacts when using one flood flow conditions. Therefore, in the results section wherever it is not mentioned results for the 13,000 m^3/s flood flow condition are used.

All of the storage changes considered in the alternate scenarios are incorporated in the model by changing the evacuation schedule. For an example, to accommodate 600 million cubic meter (0.5 MAF) in December-March, less water has been released throughout theses month such in a way that in total 6,000 million cubic meter (0.5 MAF) less water would be evacuated throughout these four months. Similarly, during April through September the evaluation curve has been changed in a way that additional stored water can be evacuated following the alternate release schedules in the treaty. Figure 3.2 has an illustration of how an evacuation curve has been changed due to incorporating storage and release changes from alternative treaty scenario CRT-I. Detail description of implementing CRT scenarios provided in Appendix – A.

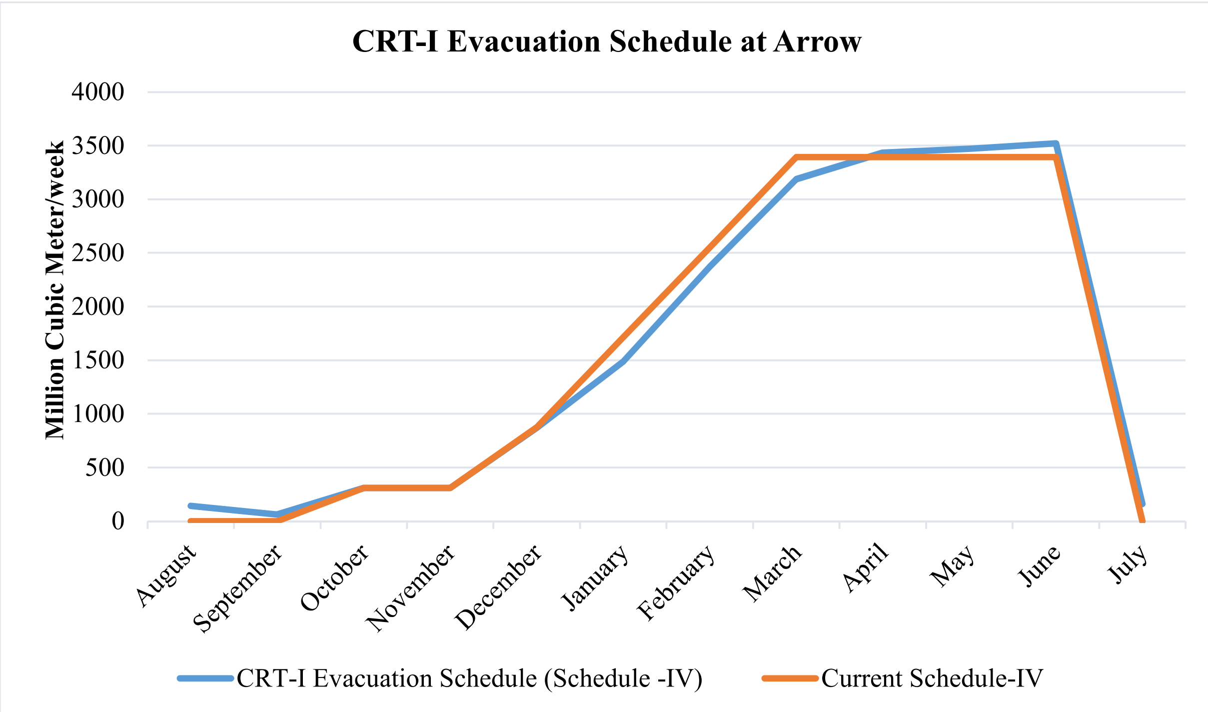


Figure 3.2: Change in an evacuation curve (IV) to incorporate alternate storage and release from treaty alternative CRT-I

3.4.2 Climate Change Scenarios

Five scenarios for each of the IPCC's Representative Concentration Pathway 4.5 (RCP4.5) and 8.5 (RCP8.5) were considered. These scenarios are selected based on streamflow sensitivity to precipitation and temperature (Vano et al. 2015) and their magnitude in a way that they capture the entire spread of temperature and precipitation change projection for the area for the 2030s. The selected GCMs for the scenarios are GFDL-ESM2M, IPSL-CM5A-LR, GFDL-ESM2G, bcc-csm1-1, CanESM2 for RCP4.5; and GFDL-ESM2M, BNU-ESM, bcc-csm1-1-m, GFDL-ESM2G, CanESM2 for RCP8.5. Data periods that have been considered for the analysis are between 1981-2011 for historic and 2020-2079 for the future. Two separate periods in the future are selected considering the implication of treaty impacts for both near and long terms. While projection for 2030s (2020-2049) gives us near future impacts of the treaty changes on the water resources the 2060s (2050-2079) will be suitable for long-term planning and effectiveness of this international treaty.

Chapter 4: Results and Discussion

4.1 Evaluation of Modeling Results

4.1.1 Streamflow Evaluation

Calibration and evaluation results for VIC-CropSyst simulated flow at multiple locations along the mainstem of the Columbia River and the Snake River are summarized in Table 4.1. While compared with the naturalized flow all of the locations except the Libby dam show reasonable error margin both for the calibration (NSE 0.75-0.91) and evaluation (NSE 0.61-0.91) periods (Table 4.1). Most of the watershed area upstream of Libby dam is in Canada. Lack of high resolution landcover and soil information in the Canada part may be contributing to the error.

Table 4.1: Calibration and evaluation of naturalized streamflow at various locations along the Columbia River and the Snake River mainstems (Barik et al. in prep.)

Location Name	**Calibration**			**Evaluation**		
	NSE	**% BIAS**	**R**	**NSE**	**% BIAS**	**R**
PEND OREILLE RIVER AT ALBENI FALLS DAM	0.75	20.8	0.96	0.78	24.4	0.95
KOOTENAY RIVER AT CORRA LINN DAM	0.74	33.7	0.96	0.61	39.4	0.95
COLUMBIA RIVER AT THE DALLES	0.81	21.1	0.97	0.78	26.8	0.97
COLUMBIA RIVER AT GRAND COULEE DAM	0.88	18.9	0.98	0.83	24.1	0.97
SNAKE RIVER AT ICE HARBOR DAM	0.9	15.4	0.98	0.89	17.2	0.97
KOOTENAI RIVER AT LIBBY DAM	0.2	57.3	0.97	0.26	73.5	0.95

Location Name	Calibration			Evaluation		
	NSE	% BIAS	R	NSE	% BIAS	R
SNAKE RIVER AT MILNER	0.77	21.5	0.94			
COLUMBIA RIVER AT PRIEST RAPIDS DAM	0.86	20.6	0.98	0.81	25.5	0.97
COLUMBIA RIVER AT REVELSTOKE DAM	0.91	9.61	0.97	0.85	24.1	0.97
COLUMBIA RIVER AT ROCKY REACH DAM	0.87	20.2	0.98	0.82	25.2	0.98
PEND DOREILLE RIVER AT WANETA DAM	0.78	31.5	0.93	0.67	32.9	0.77
COLUMBIA RIVER AT WELLS DAM	0.87	20.4	0.98	0.81	25.3	0.97
COLUMBIA RIVER AT ROCK ISLAND DAM	0.87	19.8	0.98	0.82	24.6	0.98

Regulated flow is evaluated by comparing between observed and simulated reservoir signatures (Figures 4.1-4.2). Reservoirs have significant influence on monthly streamflow, in that they store water during the winter and spring release it during the summer. Therefore, it is expected that flow differences will be negative during March-April and become positive starting in the summer, which is the case observed in the plots. Taking the magnitude of difference between the pre and post reservoir flows show that reservoir effects are close between the observed and simulated scenarios, except at Oxbow and Priest Rapids Dams (Figure 4.2). However, when the difference is presented as the percentage of pre-reservoir flow, the highest discrepancies are observed for Ice Harbor, Noxon Rapids and Oxbow dams (Figure 4.1-4.2). Furthermore, the locations which show poor performance are due to differences between observed and simulated flows during both pre- and post-reservoir conditions (Figure 4.4-4.5). Model simulation uncertainties, unavailability of pre-reservoir flow data, and inaccurate gauge observations are some of reasons behind these differences. However, the percentage flow differences between observed and simulated do not differ much for reservoirs with higher storage capacities, e.g. Grand Coulee, Priest Rapids, The Dalles and Wells (Figures 4.1-4.2).

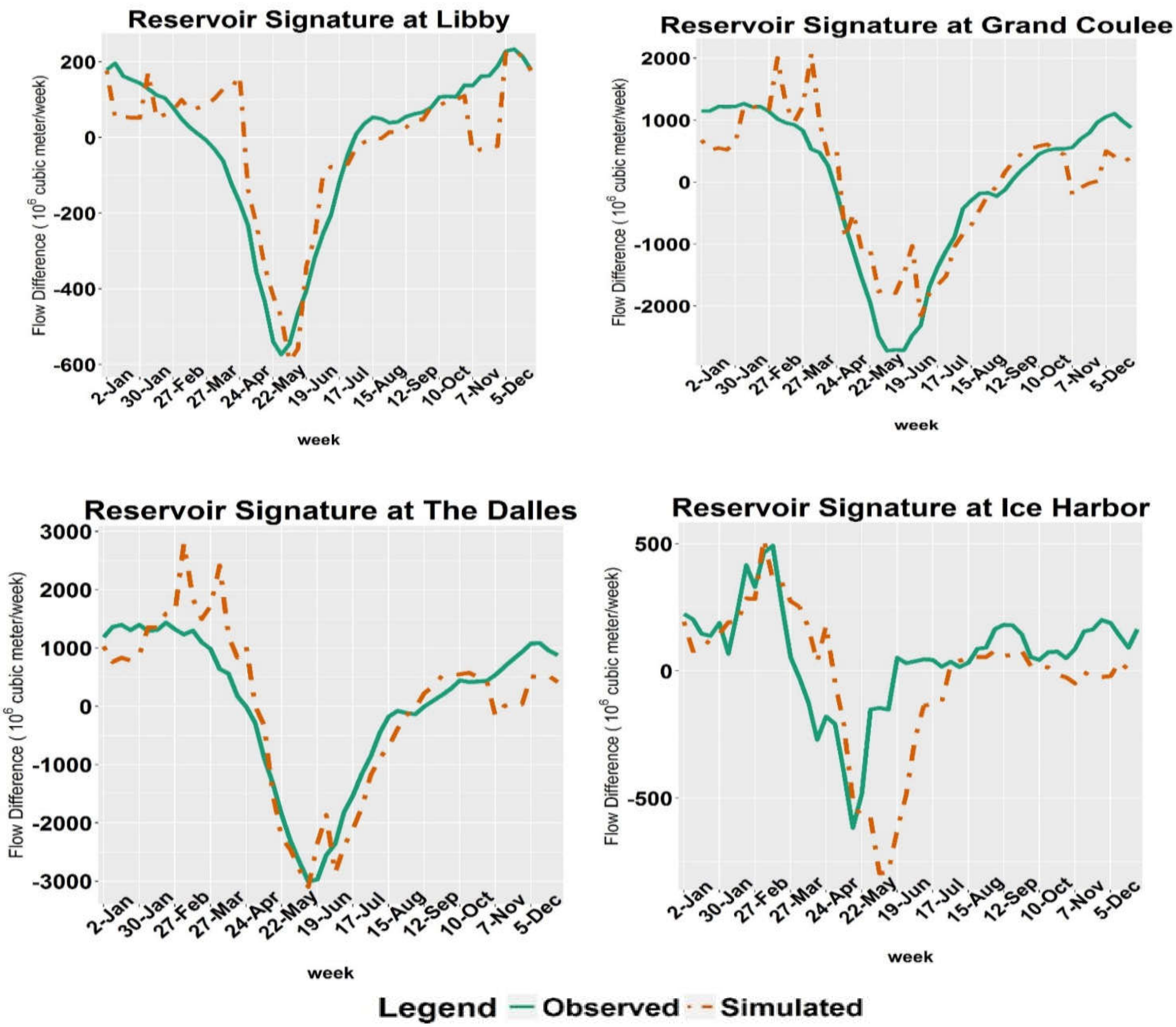


Figure 4.1: Comparison of observed and simulated weekly reservoir signatures at each of the evaluation gauging stations. The dam locations correspond to those in Table 3.4. Observed reservoir signature (green lines)

and simulated reservoir signature (dotted red lines) streamflow at reservoir outlet.

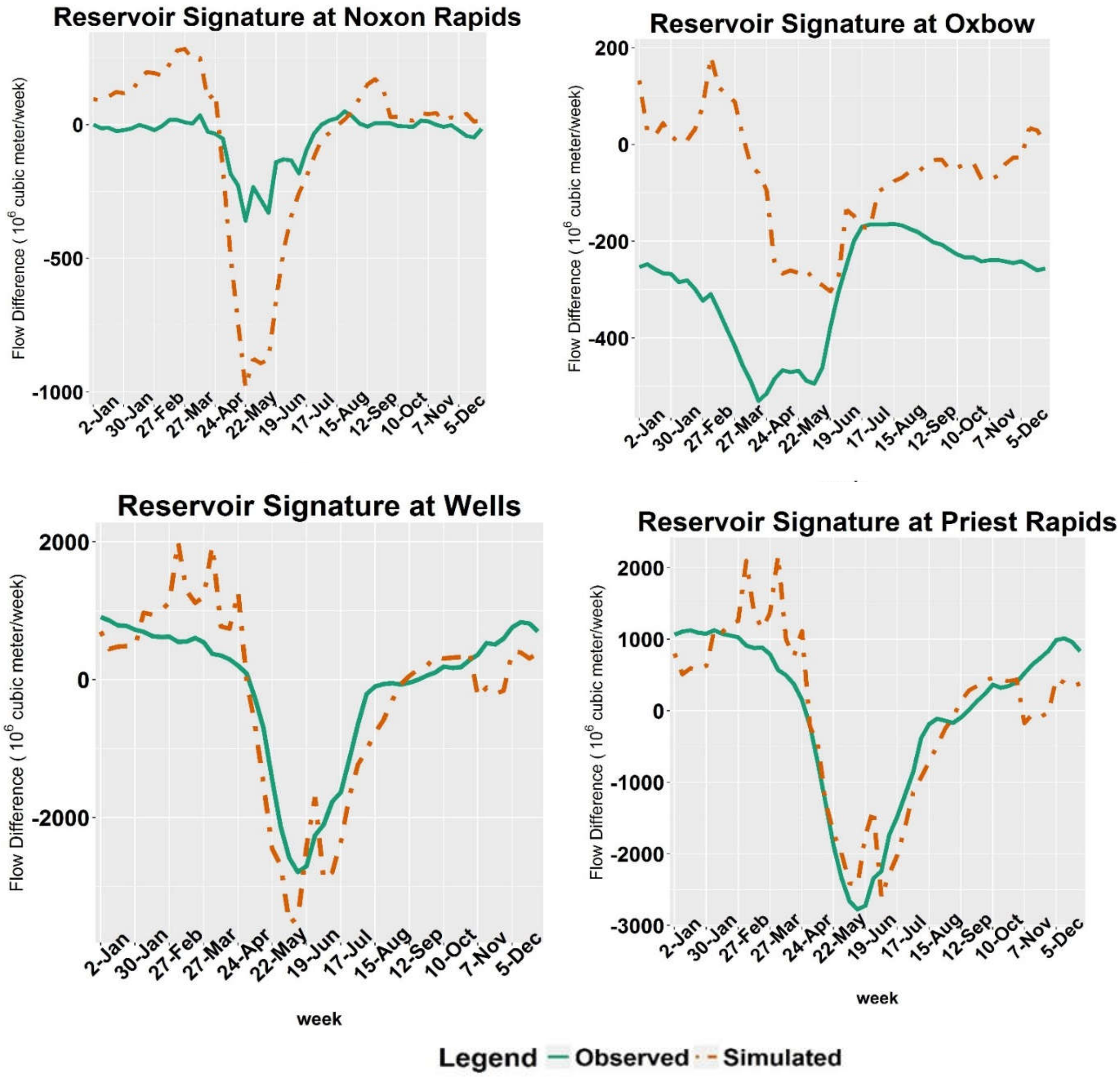


Figure 4.2: Comparison of observed and simulated weekly reservoir signatures at each of the evaluation gauging stations. The dam locations correspond to those in Table 3.4. Observed reservoir signature (green lines) and simulated reservoir signature (dotted red lines) streamflow at reservoir outlet.

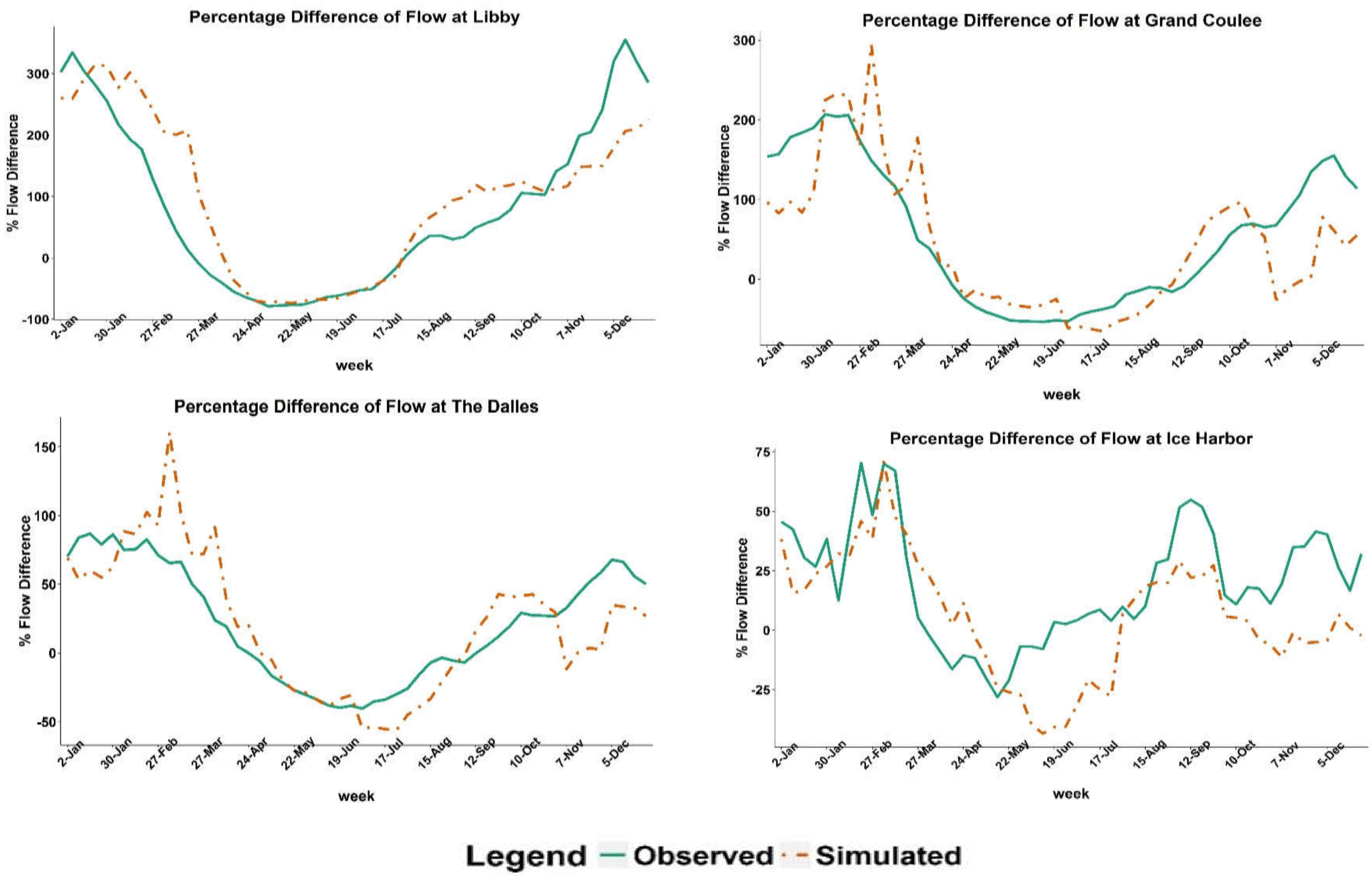


Figure 4.3: Percent difference (with respect to observed prereservoir mean weekly flow) between postreservoir and prereservoir mean weekly streamflow. Observed reservoir signature (green lines) and simulated reservoir signature (dotted red lines) streamflow at reservoir outlet.

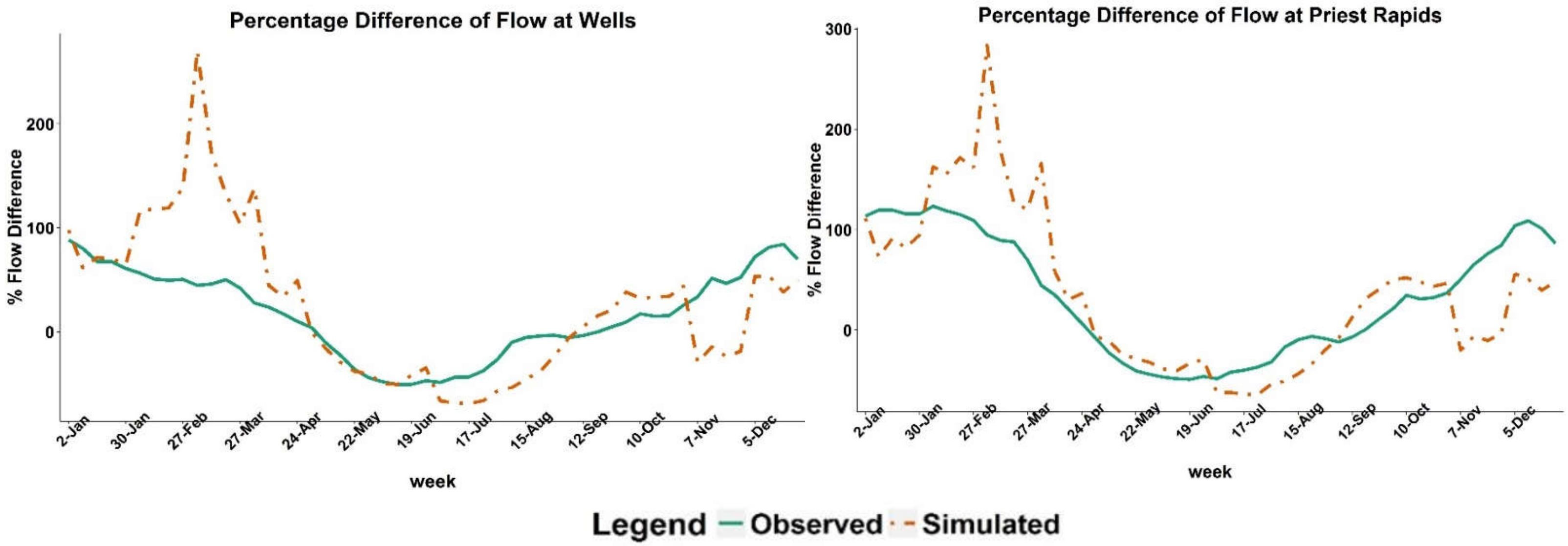


Figure 4.4: Percent difference (with respect to observed prereservoir mean weekly flow) between postreservoir and prereservoir mean weekly streamflow. Observed reservoir signature (green lines) and simulated reservoir signature (dotted red lines) streamflow at dam locations.

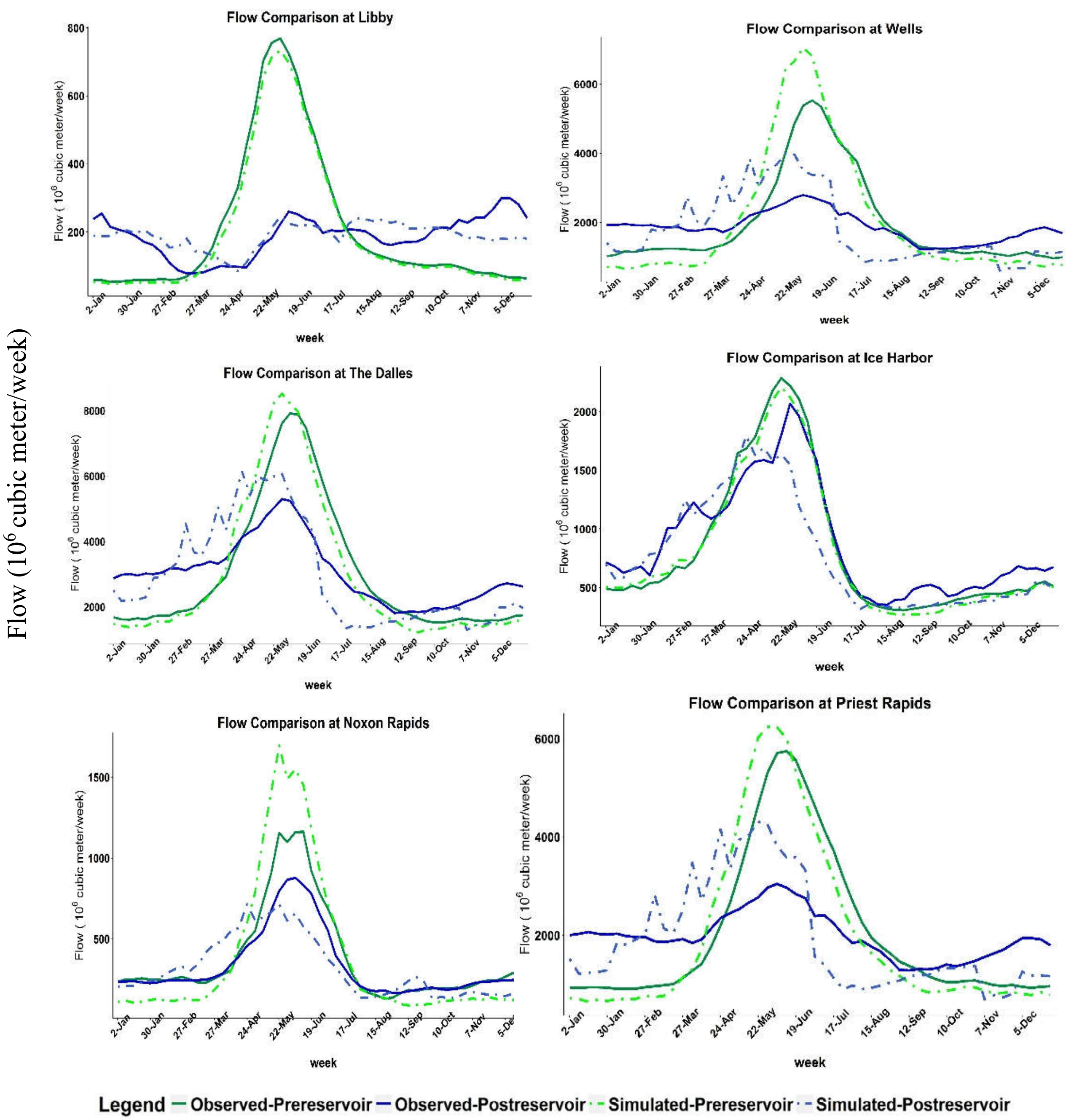


Figure 4.5: Prereservoir and post reservoir streamflow comparison. Solid lines indicate observed streamflow and dotted indicate simulated streamflow. Green lines indicate pre-reservoir condition and blue lines indicate post-reservoir condition.

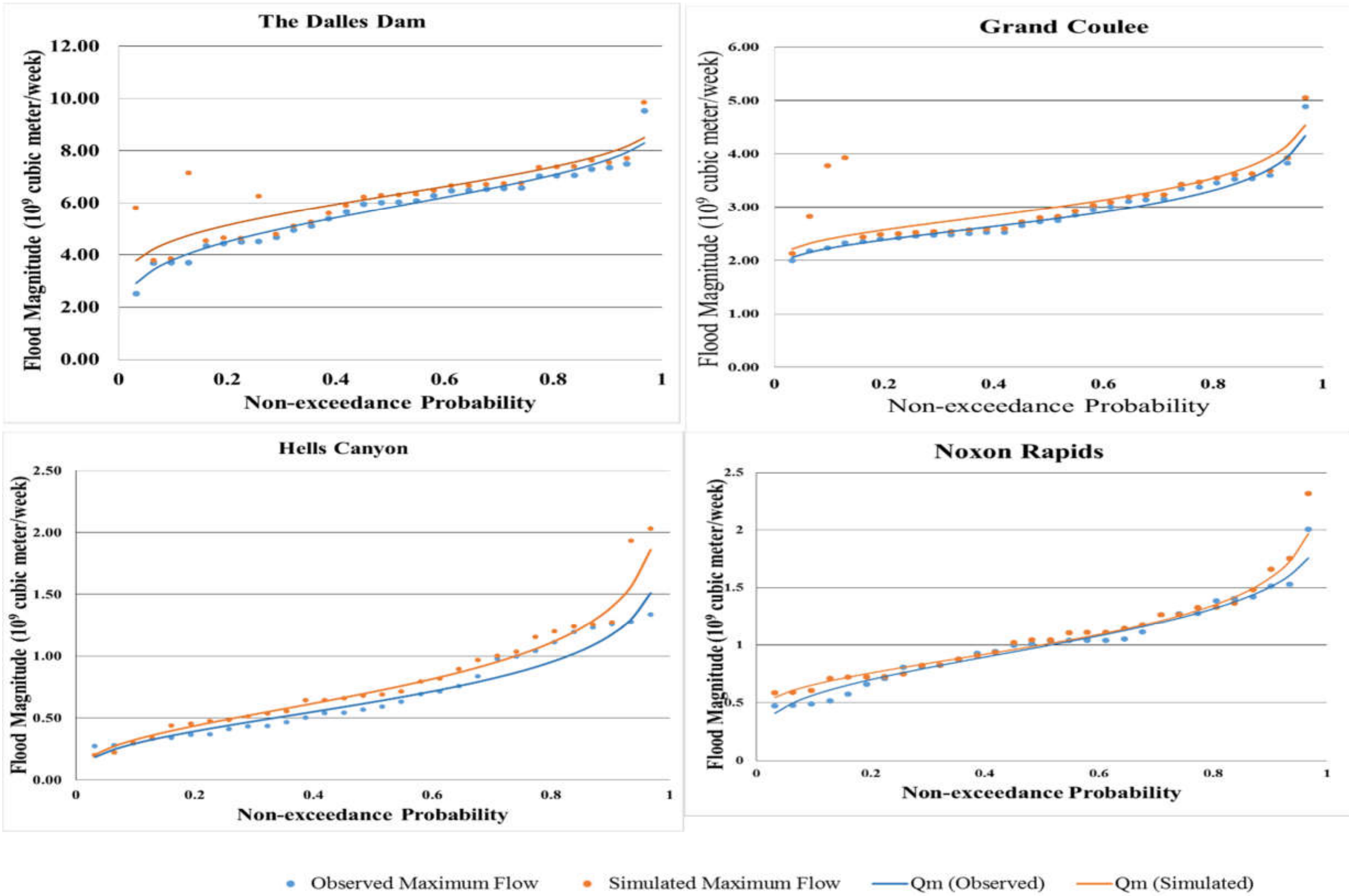


Figure 4.6: Flood magnitude for different non-exceedance probability values for observed and simulated quantiles Appendix-A for more flood magnitude evaluation figures.

4.1.2 Flood Magnitude Evaluation

Plotting of flood magnitudes against the non-exceedance probability using the observed and simulated flow quantiles shows that performance of the flood magnitude prediction may vary depending on the quality of the regression equation (Figure 4.6). Out of the four dams presented in Figure 4.6, flood magnitude estimated at The Dalles location is more reliable as compared to the other three.

A comparison between simulated and observed yearly maximum weekly flows shows NSE values vary from -0.23 (Wells) to 0.96 (Libby) (Table 4.1). RI values show a good agreement between them. The probability distribution has been fitted with both simulated and observed values. While simulated quantile value (Flood magnitude) has been compared with observed quantile values, NSE values differ from 0.56 (Wells) to 0.96 (Libby and Noxon Rapids) (Table 4.1). On the other hand, PB values vary from 15.4% (Hells Canyon) to 3.9 (Libby). KGE, a modified form of NSE, is the lowest for Flood magnitude at Wells and highest at Rock Island. Additionally, RI values (0.93 to 0.99) represent a good agreement between observed and simulated quantile values (Table 4.1).

To quantify how well the quantile values represent the actual simulated yearly maximum weekly flow, goodness–of–fit tests have been conducted. In this case, NSE values vary from -0.18 (Libby) and 0.96 (Hells Canyon). PB values vary from - 2.5 (Hells Canyon) to 0.20 (The Dalles).

Table 4.2: Goodness-of-fit tests between different quantile values. $Q_{sq,\ oq,}$ is the difference between simulated quantile value and observed quantile values; $Q_{sm,\ om,}$ is the difference between simulated maximum value and observed maximum value; and $Q_{sq,\ sm}$ is the difference between simulated quantile value and simulated maximum values

Reservoir Name	**NSE -∞ to 1) [1 means ideal model]**			**PB -100% to 100%) [0% means ideal model]**			**KGE -∞ to 1) [1 means ideal model]**			**RI 1 to 0) [1 means ideal model]**		
	$Q_{sq,\ oq}$	$Q_{sm,\ om}$	$Q_{sq,\ sm}$	$Q_{sq,\ oq}$	$Q_{sm,\ om}$	$Q_{sq,\ sm}$	$Q_{sq,\ oq}$	$Q_{sm,\ om}$	$Q_{sq,\ sm}$	$Q_{sq,\ oq}$	$Q_{sm,\ om}$	$Q_{sq,\ sm}$
The Dalles	0.86	0.57	0.68	8.3	8.4	0.2	0.85	0.78	0.81	0.93	0.6	0.91
Grand Coulee	0.85	0.49	0.54	7.2	7.1	-0.7	0.92	0.79	0.73	0.96	0.81	0.91
Libby	0.96	0.96	-0.18	3.9	4	-0.9	0.95	0.94	0.3	0.99	0.99	0.36
Priest Rapids	0.81	0.57	0.73	8	8.3	-1.1	0.77	0.75	0.81	0.97	0.91	0.96
Noxon Rapids	0.96	0.92	0.96	4.9	6	-1.4	0.95	0.91	0.89	0.98	0.97	0.99
Wells	0.56	-0.23	0.44	11.7	12.7	-1.9	0.64	0.51	0.66	0.95	0.73	0.93
Hells Canyon	0.83	0.67	0.96	15.4	16.2	-2.5	0.72	0.66	0.89	0.98	0.96	0.99
Rock Island	0.94	0.95	0.93	5	5	-0.7	0.95	0.95	0.88	0.98	0.98	0.99

4.1.3 Evaluation for Hydropower Target Reliability

Comparisons between hydropower reliabilities using modified flows from 1980 to 2007 and the simulated reliabilities using historical simulated flows from VIC-CropSyst for the same period have been conducted for both firm and non-firm energy targets (Table 4.3). The mean reliability of non-firm energy is 71% for observed modified flow and 73% for simulated VIC flow. On the other hand, mean reliability of firm energy using observed modified flow is 76% and using simulated flow is 77%.

Table 4.3: Hydropower reliability for both firm and non-firm energy target for observed and simulated stream flows

Name	Observed (1980-2007) (%)	Simulated (1980-2007) (%)
Firm Energy Target	76	77
Non-firm Energy Target	71	73

4.1.4 Evaluation for Instream flow Target Reliability in Mainstem

Annual instream flow target reliabilities for both and observed flows have been compared for the 1980-2007 period (Table 4.4) at four different dam locations. The two sets of reliabilities are similar at each of the locations (differences between 0%-2%), except at the Lower Granite in Snake River (difference is 6%).

Table 4.4: Reliability of instream flow target, describing the mean reliability of instream flow target between the reliabilities simulated using observed modified flows from 1980 to 2007 and the reliabilities simulated using historic simulated flows from VIC-CropSyst for the same period.

Flow Target Control Point	Observed %)	Simulated %)
Columbia Falls	100	100
Lower Granite	65	71
McNary	81	81
Vernita Bar [near Priest Rapids]	95	93

4.1.5 Agricultural Curtailment and Instream Flow Target Evaluation

Comparison between historical (1980-2011) observed unmet instream flow demand and simulated unmet instream flow demands has been conducted in five watersheds in the CRB. Result of inaccuracies in supply estimates, demand estimates, and not considering non-interruptible curtailments is reflected in the difference (Table 4.5). It is noted, this evaluation is performed annually, and however, error generated from the curtailment occurs only during the irrigation season (March-October). It has been found from the historical data that curtailment program has been run two during the 1981-2009 period. Our modeled curtailment for the same period also showed the same frequency.

Table 4.5: Comparison of model simulated unmet instream flow demands, and observed unmet instream flow demands (provided by the Washington Department of Ecology) in low flow years (Barik et al. in prep.)

Location	Low flow year	Simulated (acre-feet) (1)	Observed (acre-feet) (2)	Difference (2) -(1)	Potential Interruptible demand (acre-feet)	Error as a fraction of potential interruptible demand (acre-feet)
Okanogan River, near Mallot	2001	104,590	124,171	19,581	13,076	1.5
Methow River, near Pateros	2001	136,108	147,579	11,471	4,626	2.5
Colville River, near Kettle Falls	1989	0	174	174	7398	0.0
Little Spokane River	1992	0	15,069	15,069	1675	9.0
Wenatchee River, near Monitor	1993	52,955	80,812	27,857	11,290	2.5

4.2 Impacts on Agriculture:

4.2.1 Impacts of Climate Change on Agriculture

Climate change has a significant impact on the hydrologic cycle and crop growth processes, impacting water supply and crop water demand. Therefore, unmet demand as well as curtailment of agricultural water supply will be affected in the CRB. Figures 4.7-4.8 show the impact of climate change on water supply (top panels), out-of-stream water demand (middle panel), and curtailment of interruptible agricultural water rights (bottom panel) at Priest rapids (similar plots for other reservoir locations are provided at Appendix-B) along the Columbia Mainstem. The results in the CRB, show there is a shift in the supply towards earlier in the season with higher flows occurring from January through April and comparatively lower flows during the summer months. This condition intensifies in 2060s compared to 2030s. Climate change is also causing out-of-stream demand to shift earlier in the season. In general, 2060s shows higher shift and lower irrigation demand compared to 2030s. This is because warming is causing many of the crops to mature earlier; this reduces the length of irrigation season and causes much of the growth to occur earlier in the season when there is greater rainfall. Although, there is a projection of overall reduction in demands in the future compared to the historic simulation, curtailment shows increases during the early irrigation season. Along the mainstem, a faster earlier shift in demand as compared to supply and increased demand early in the irrigation season are the explanation for this. However, different response in curtailment may be observed in regional watersheds (Barik et al. in prep.).

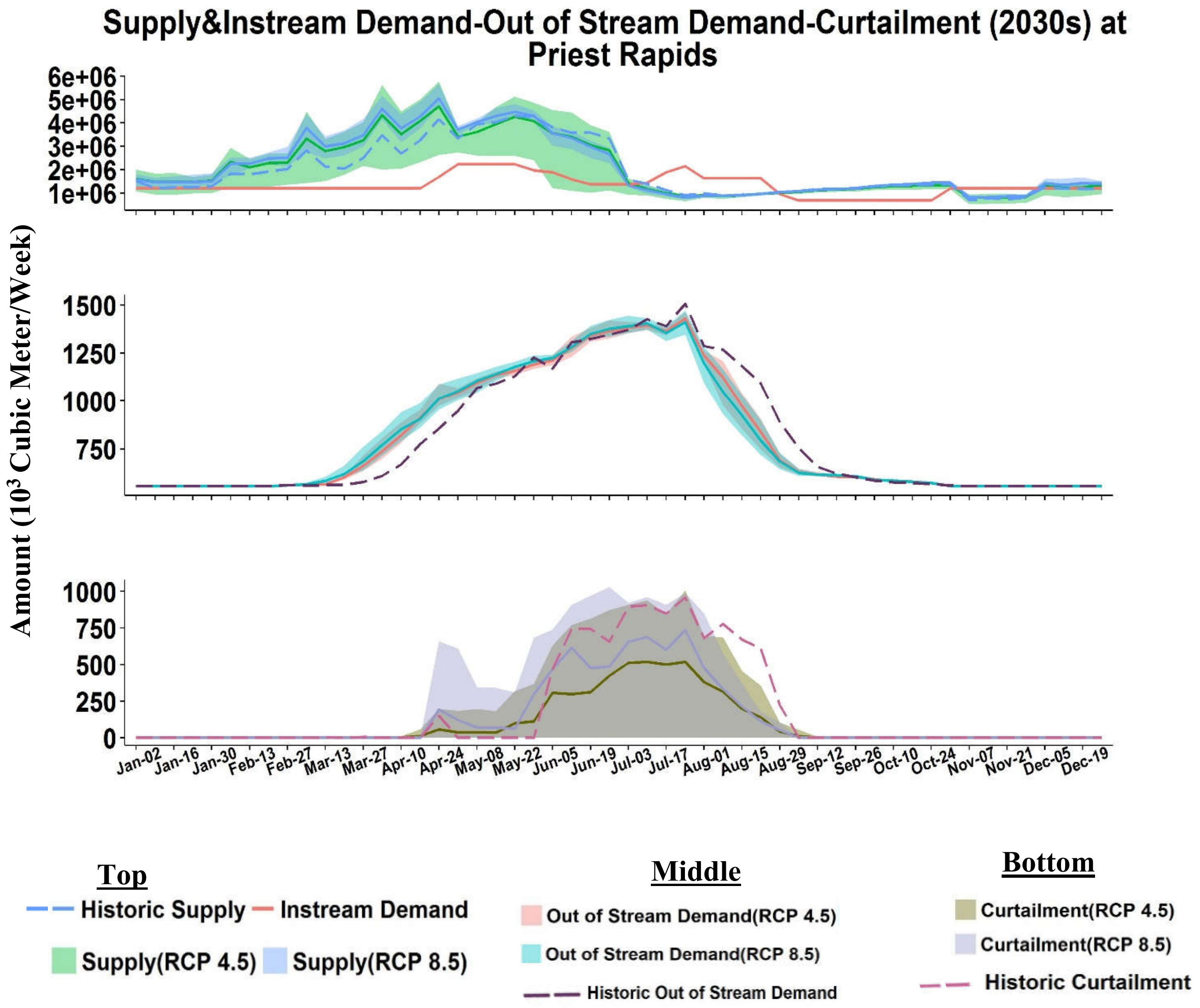


Figure 4.7: Supply and Instream Demand (top), Out of Stream Demand (middle) and Agricultural Curtailment at McNary Reservoir. In top panel, shaded areas show supply in 2030s under RCP 4.5 scenario (light green) and RCP 8.5 (light blue) and current CRT scenarios with considering uncertainty range. Middle panel shows out of stream demand (agriculture and municipal demand) under RCP 4.5 scenario (light red) and RCP 8.5 (cyan) and bottom panel shows curtailment amount in agriculture under RCP 4.5 scenario (light red) and RCP 8.5 (cyan).

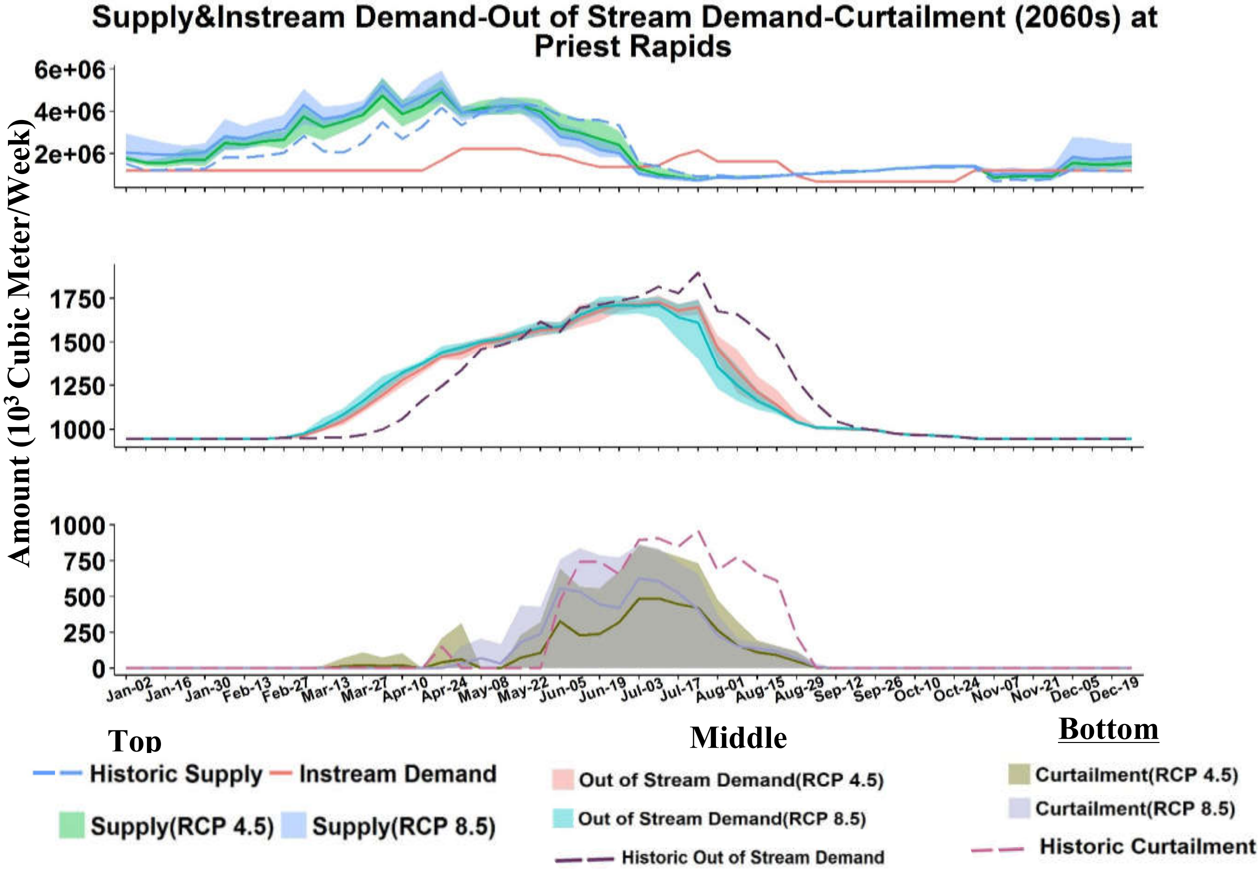
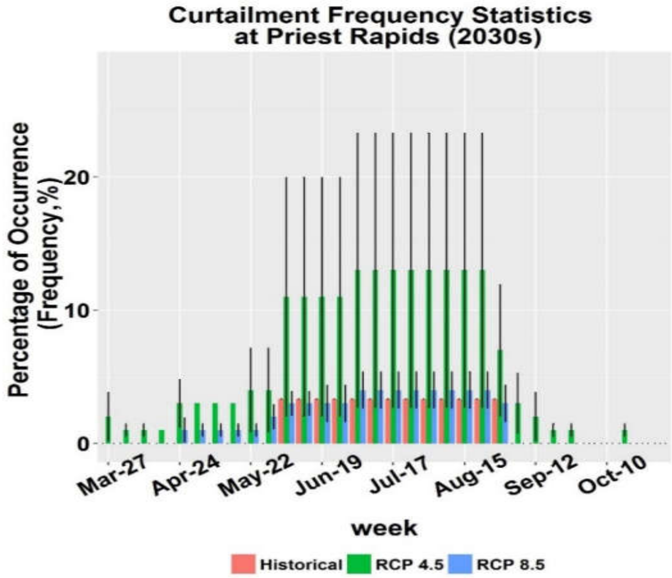


Figure 4.8: Supply and Instream Demand (top), Out of Stream Demand (middle) and Agricultural Curtailment at McNary Reservoir. In top panel, shaded areas show supply in 2060s under RCP 4.5 scenario (light green) and RCP 8.5 (light blue) and current CRT scenarios with considering uncertainty range. Middle panel shows out of stream demand (agriculture and municipal demand) under RCP 4.5 scenario (light red) and RCP 8.5 (cyan) and bottom panel shows curtailment amount in agriculture under RCP 4.5 scenario (light red) and RCP 8.5 (cyan).

Relative comparison between the percentage of occurrence of curtailment in future (2030s - figure 4.9a and 2060s – figure 4.9b) under both RCP 4.5 and 8.5 and histrocial percentage of occurrence of curtailment has been given in Figure 4.9. It has been predicted that curtailment occurrence might happer earlier in the irrigation season (Mid March to October). As the uncetainty range is higher in the 2030s as compared to the 2060s, uncentainty in the occurrence of curtailment is also larger in the 2030s.

a.



b.

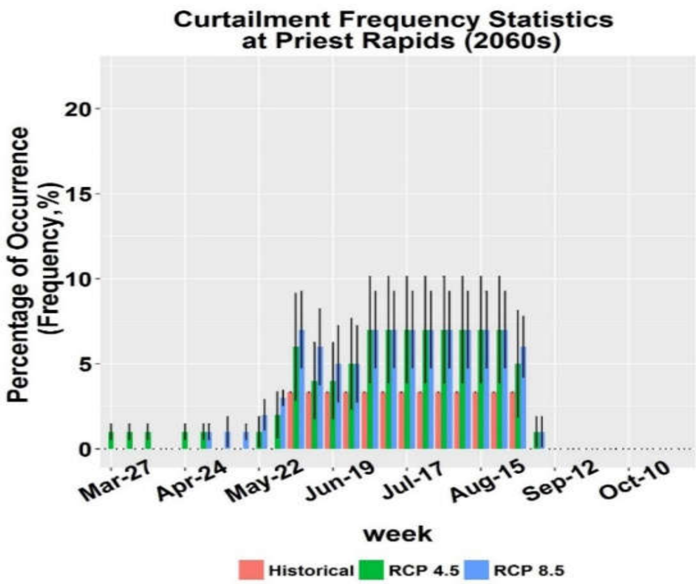


Figure 4.9: Percentage of frequency of curtailment happening each week of the year. Red bar, green bar and blue bar indicates historical, RCP 4.5 and RCP 8.5 respectively. (Appendix- C for similar plots at different reservoir location).

4.1.2 Combined impacts of alternative CRT and climate change scenarios on agriculture

Figure 4.10-4.13 and Appendix – D show curtailment frequency under both CRT and climate change scenarios. Differences in frequency between two future scenarios (climate change with modified CRT and climate change under current CRT) and two historic scenarios (historic under modified CRT and historic under current CRT) are also included in the same plots. In 2030s, under both RCP scenarios, the modified CRT scenarios result in reduced curtailment frequency (Figure 4.10-4.14). However, the conditions associated with CRT-II (in comparison to CRT-I) are more effective in reducing curtailment frequency and magnitude (Figure 4.13-4.14) under RCP 8.5 in 2060s. On the other hand, (Figure 4.11-4.12) in 2030s under RCP 4.5 for CRT – II scenario curtailment frequency has reduced as well as increase in late March. As there is less water released during December – March, it might trigger more curtailment in this time.

Higher spread in supply with lower range in flow in 2030s than 2060 resulted in higher frequency on average for 2030.

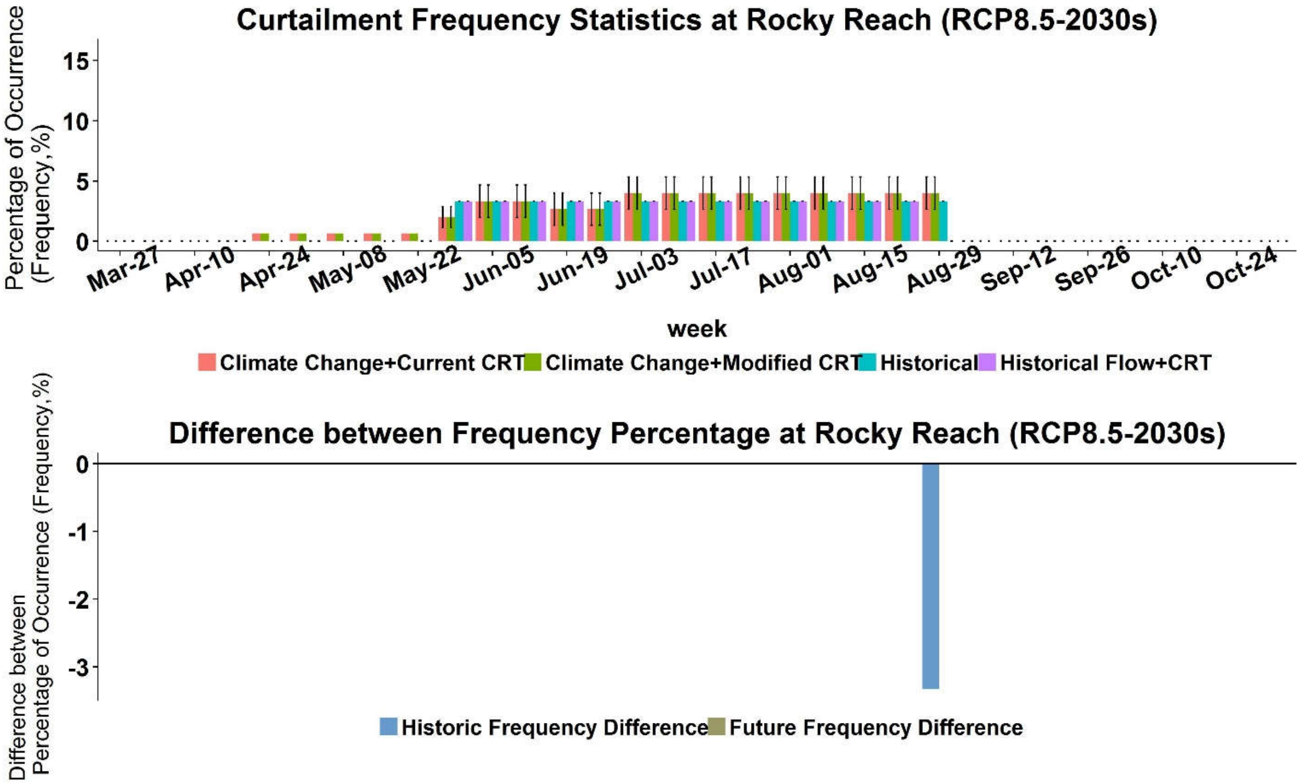


Figure 4.10: Percentage of frequency of curtailment happening each week of the year under CRT-I scenarios at Rocky Reach dam location. In top panel, red bad and green bars, respectively, indicate percentage of frequency under RCP8.5 future climate (2030s) under current CRT and percentage of frequency under climate under CRT-I scenario. Cyan and purple bars respectively, indicate curtailment in historical and CRT-I under historical scenario. Bottom panel shows changes in percentage of frequency of curtailment because of CRT-I for both historical and future climate scenarios.

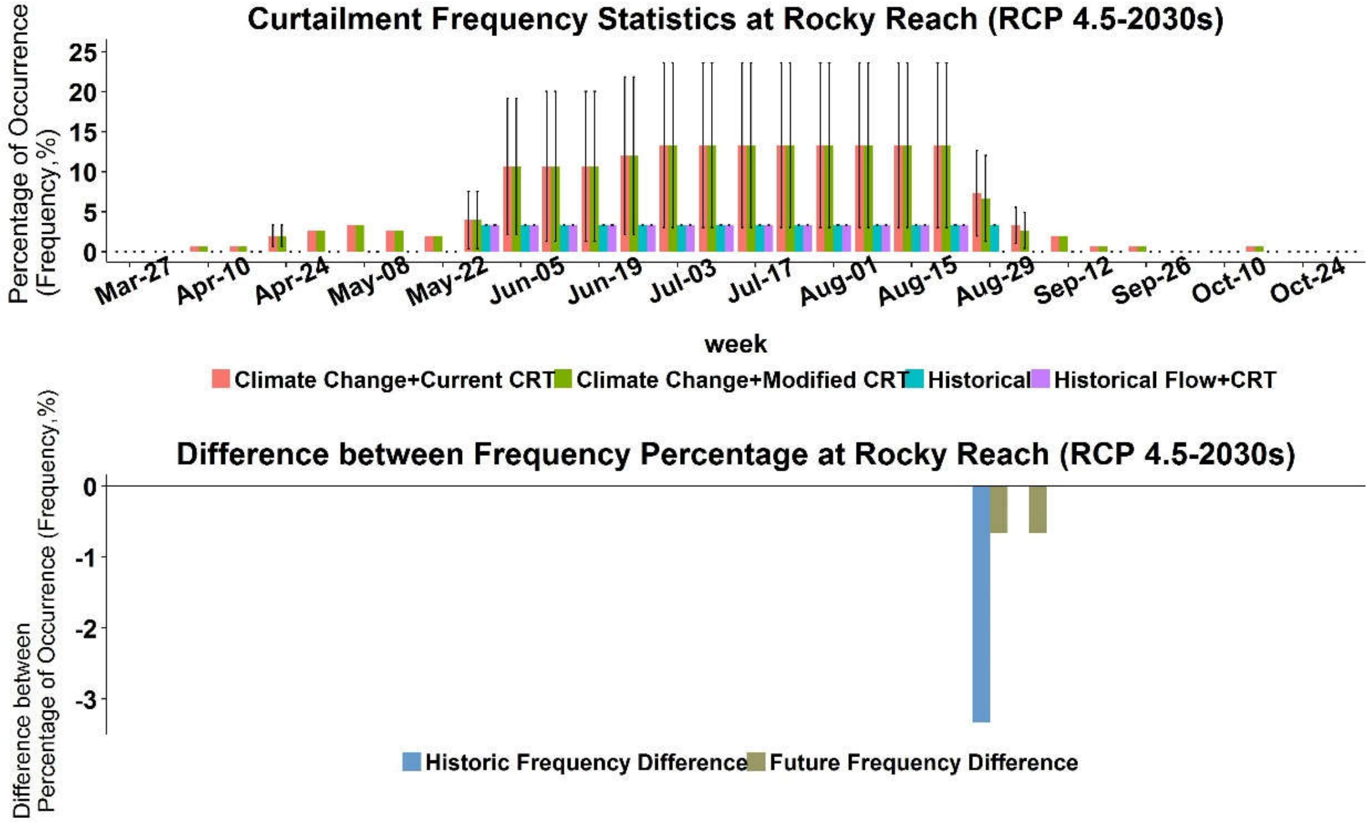


Figure 4.11: Percentage of frequency of curtailment happening each week of the year under CRT-I scenarios at Rocky Reach dam location. In top panel, red bar and green bars respectively, indicate percentage of frequency under RCP 4.5 future climate (2030s) under current CRT and percentage of frequency under climate under CRT-I scenario.

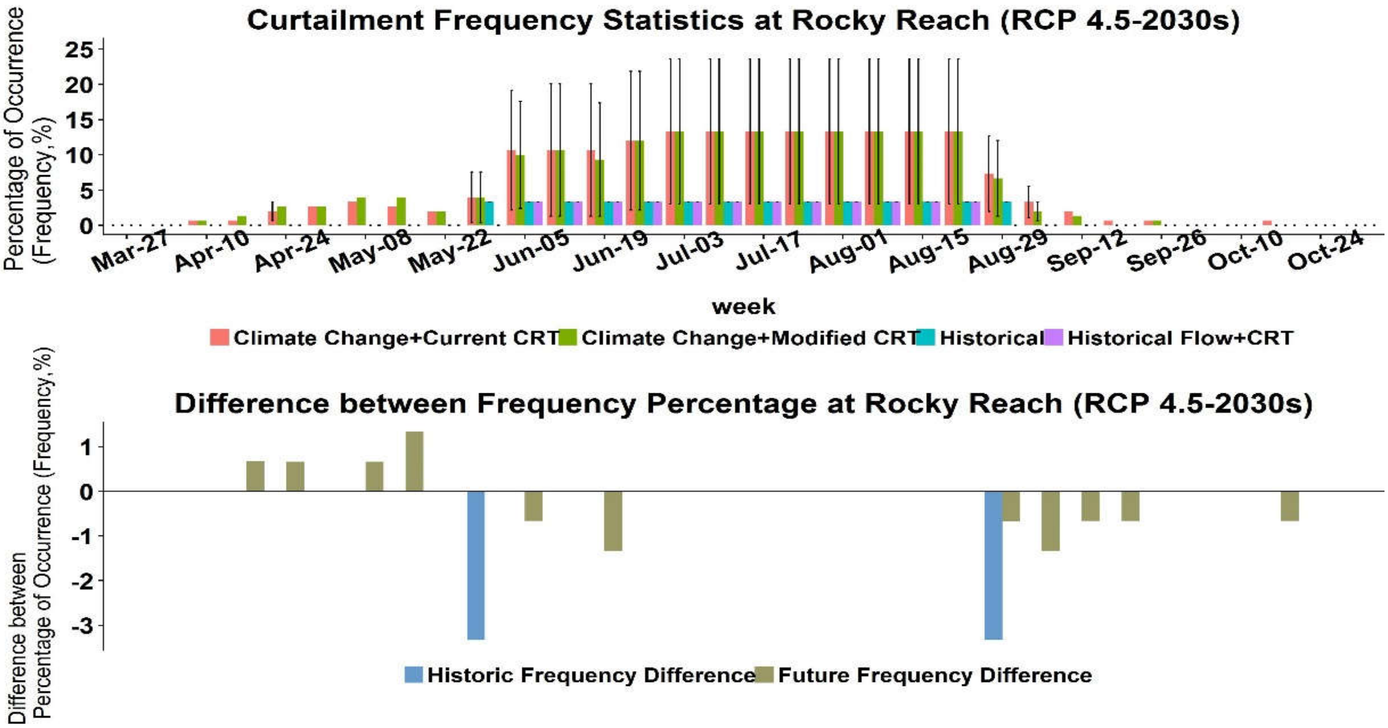


Figure 4.12: Percentage of frequency of curtailment happening each week of the year under CRT-II scenarios at Rocky Reach dam location. In top panel, red bad and green bars respectively, indicate percentage of frequency under RCP 4.5 future climate (2030s) under current CRT and percentage of frequency under climate under CRT-II scenario.

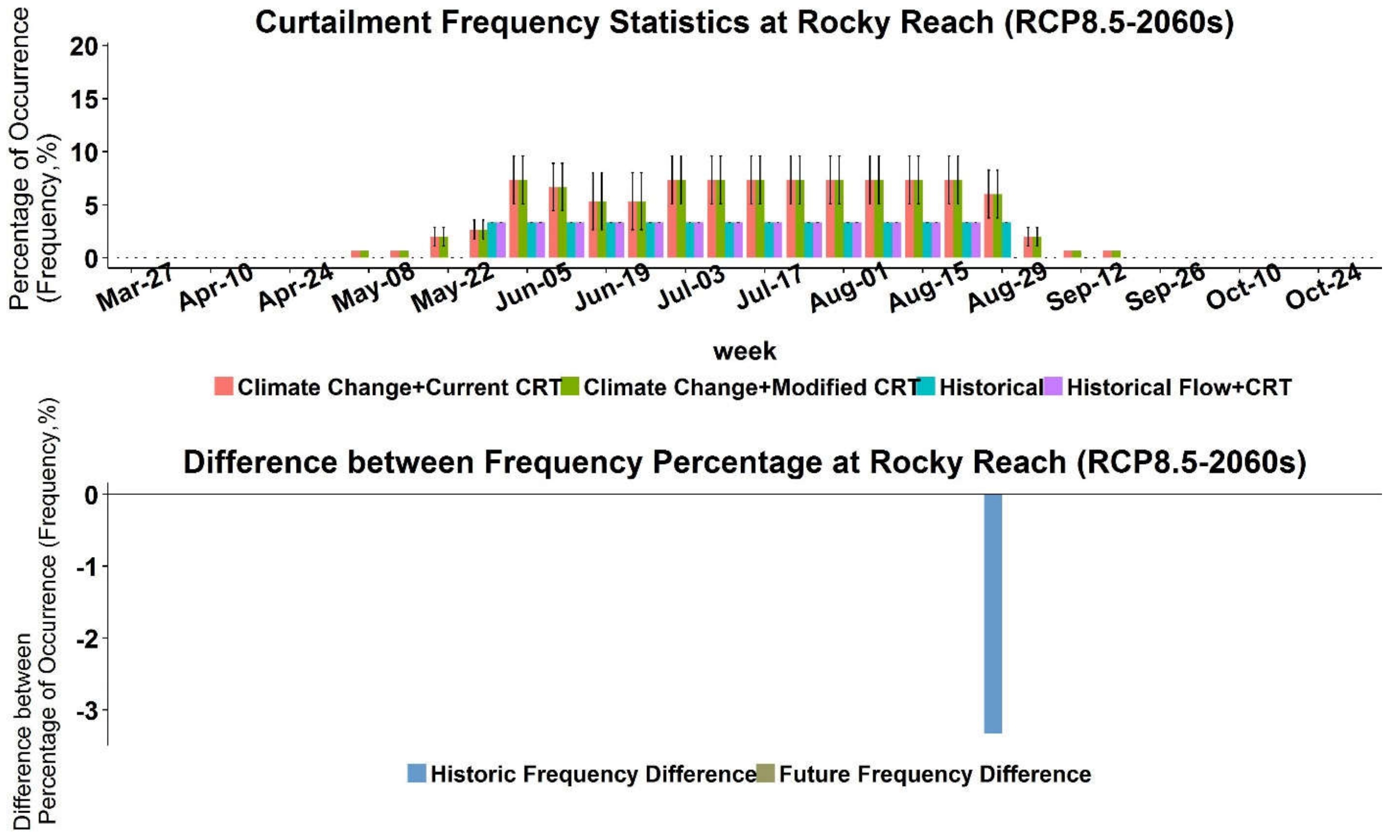


Figure 4.13: Percentage of frequency of curtailment happening each week of the year under CRT-I scenarios at Rocky Reach dam location. Future climate scenario for 2060s has been considered. In top panel, red bad and green bar indicate percentage of frequency under RCP 8.5 future climate (2060s) under current CRT and percentage of frequency under climate under CRT-I scenario. Cyan and purple bars respectively, indicate curtailment in historical and CRT-I under historical scenario. Bottom panel shows changes in percentage of frequency of curtailment because of CRT-I for both historical and future climate scenarios.

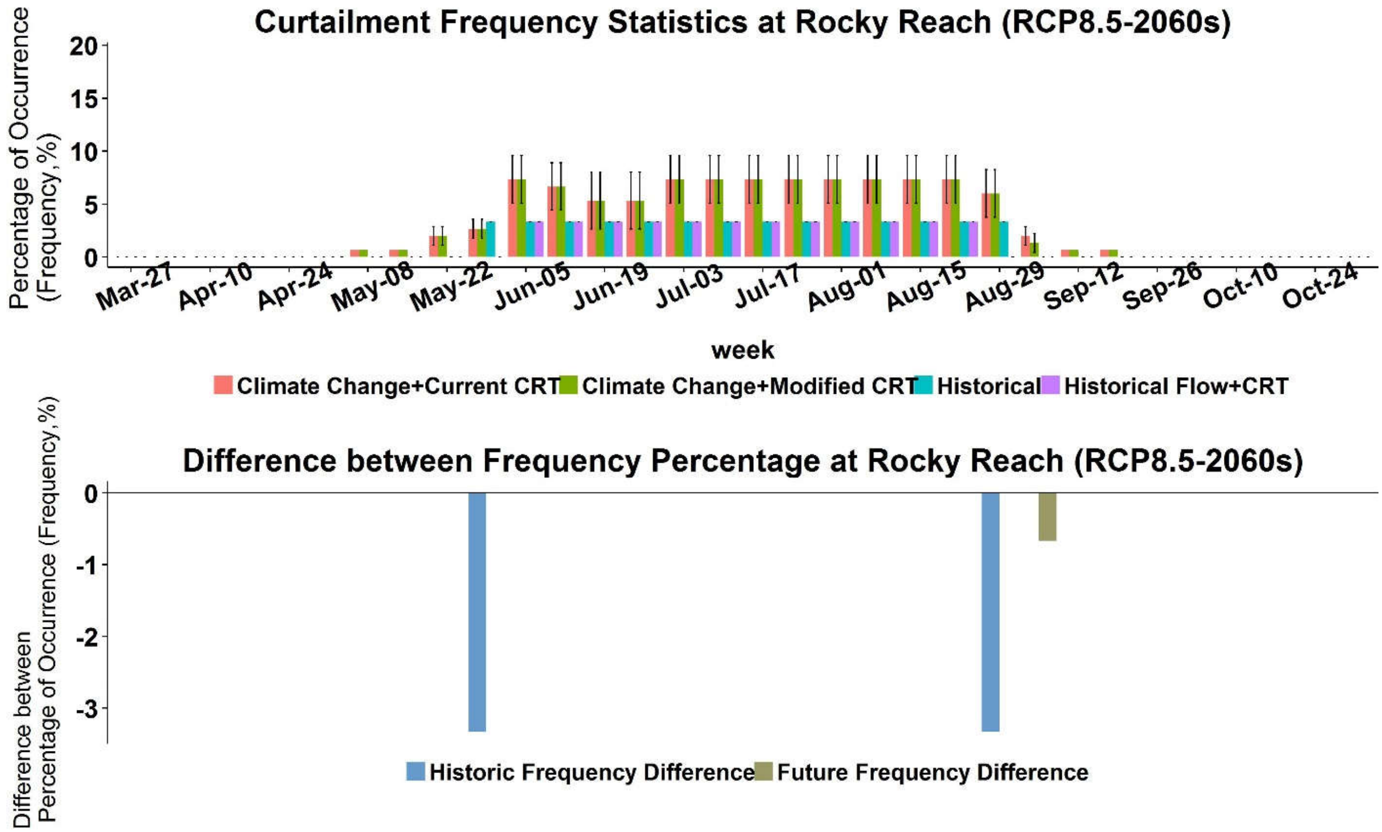


Figure 4.14: Percentage of frequency of curtailment happening each week of the year under CRT-II scenarios at Rocky Reach dam location. Future climate scenario for 2060s has been considered. In top panel, red bad and green bar indicate percentage of frequency under RCP 4.5 future climate (2060s) under current CRT and percentage of frequency under climate under CRT-IT scenario. Cyan and purple bars respectively, indicate curtailment in historical and CRT-II under historical scenario. Bottom panel shows changes in percentage of frequency of curtailment because of CRT-II for both historical and future climate scenarios.

Variation in the unmet demand magnitude (unmet demand = Supply – All demand) at Rocky Reach throughout the irrigation season is presented in Figures 4.15-4.16. As our model only examines curtailment of grid cells with interruptible water rights, it is also import to look at the unmet demand that cannot be fulfilled. Differences in unmet demand magnitude between two future scenarios (climate change with modified CRT and climate change under current CRT) and two historic scenarios (historic under modified CRT and historic under current CRT) are also included in these figures as the bottom panels. Percent change in unmet demand is also separately included in tables 4.6-4.8 respectively for McNary, Priest Rapids and Wanapum Dams. Total unmet demand is estimated by deducting instream and out-of-stream demands from the supply without any curtailment consideration, i.e., it can be thought of as the total supply deficit. Curtailment magnitude at McNary is reduced under the modified CRT (CRT-I and CRT-II) scenarios during the peak and beginning of the irrigation season (Figures 4.14-4.21) for both historic and future conditions. Tables 4.6-4.8 show the percent change in curtailment magnitude after considering the modified CRT scenarios at three dam locations (McNary, Priest Rapids and Wanapum). Results indicate that, in most of the cases, curtailment magnitude is reduced after considering modified CRT scenarios (Table 4.6-4.8). However, CRT-II is more successful in reducing curtailment magnitude than the CRT-I both for the historic and future period.

CRT –I Impacts: (2030s)

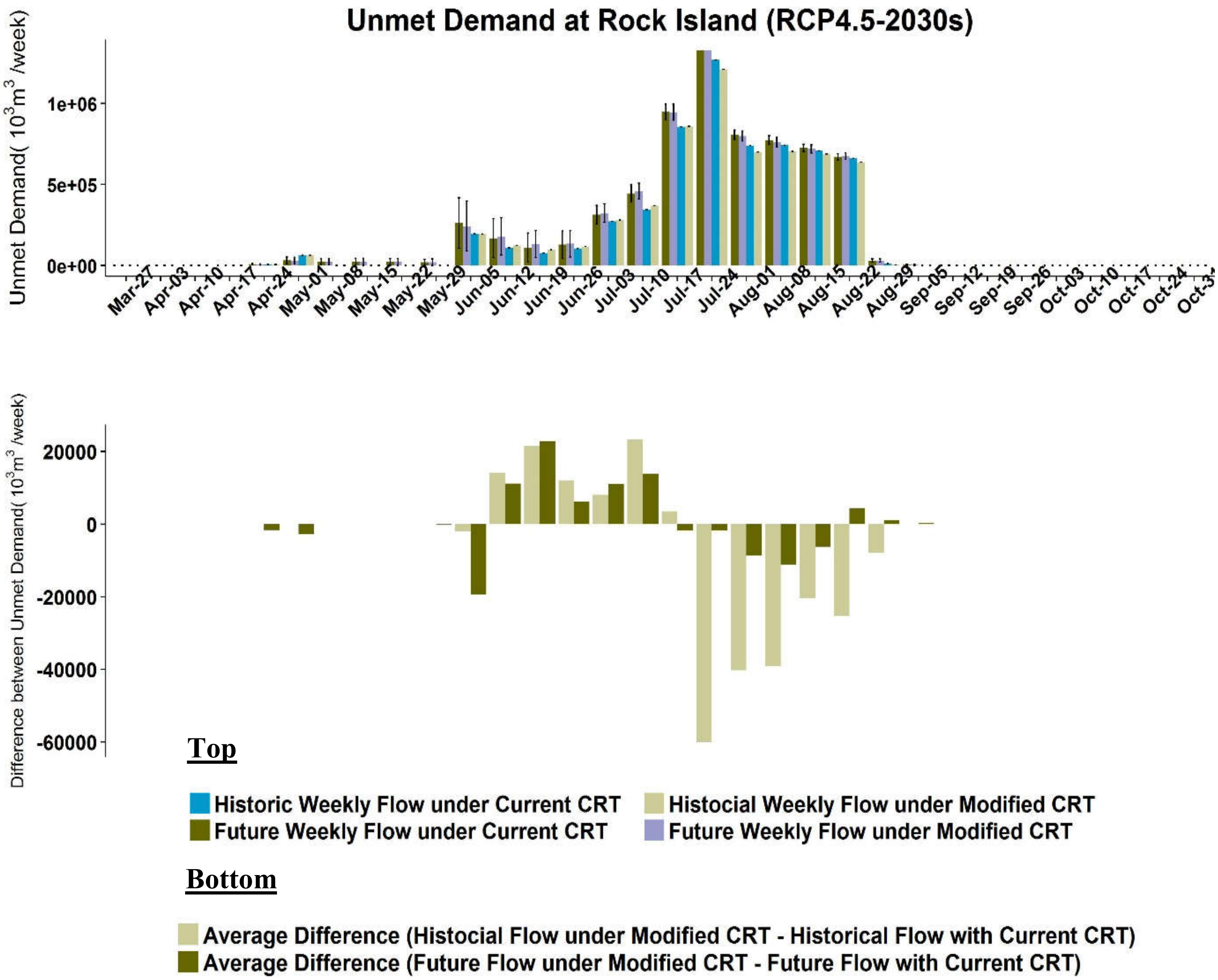


Figure 4.15: Unmet Demand at Rock Island dam (RCP 4.5) [CRT –I Impact] for 2030s. The top panel shows the unmet demand at Wanapum dam and bottom panel shows the differences between unmet demand because of CRT-I scenario.

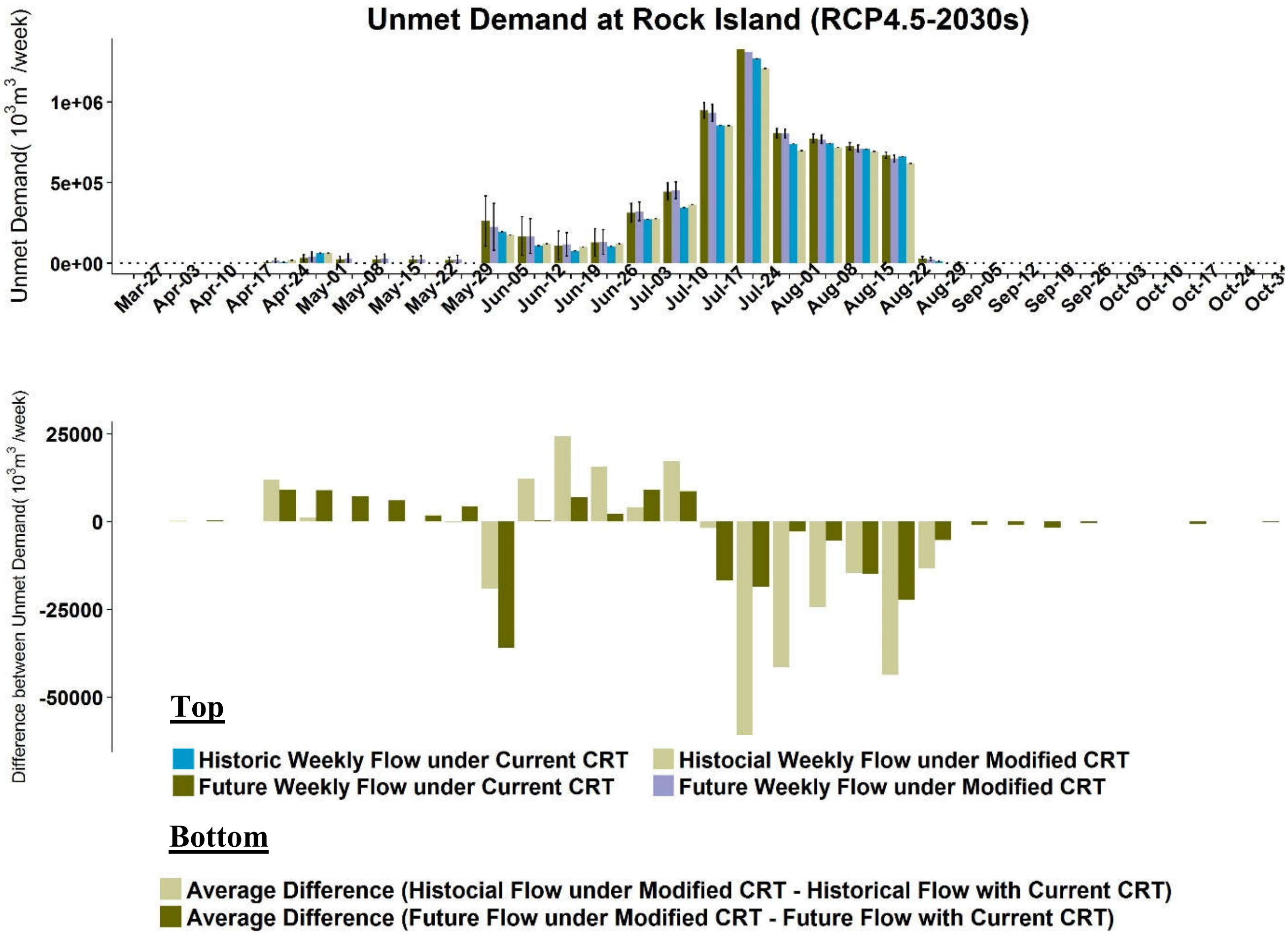


Figure 4.16: Unmet Demand at Rock Island dam (RCP 4.5) [CRT –II Impact] for 2030s. The top panel shows the unmet demand at Wanapum dam and bottom panel shows the differences between unmet demand because of CRT-II scenario.

Table 4.6: Yearly Average Unmet Demand for McNary Reservoir. Negative in the last column means curtailment is reduced after modified CRT is considered, negative values mean that curtailment is increased

CRT Scenarios	**Year**	**Climate Scenarios**	**Percent change after considering alternative CRT scenarios (%)**
CRT-I	1981-2010	Historic	-2.49
	2035	RCP 4.5	**0 .13**
		RCP 8.5	**0.57**
	2065	RCP 4.5	**0.01**
		RCP 8.5	**0.42**
CRT-II	1981-2010	Historic	-3.97
	2035	RCP 4.5	-1.31
		RCP 8.5	-0.78
	2065	RCP 4.5	-1.66
		RCP 8.5	-0.84

Table 4.7: Yearly Average Unmet Demand for Priest Reservoir. Negative in the last column means curtailment is reduced after modified CRT is considered; negative values mean that curtailment is increased

CRT Scenarios	**Year**	**Climate Scenarios**	**Percent change after considering alternative CRT scenarios (%)**
CRT-I	1981-2010	Historic	-1.84
	2035	RCP 4.5	-0.58
		RCP 8.5	0.10
	2065	RCP 4.5	-0.43
		RCP 8.5	0.003
CRT-II	1981-2010	Historic	-0.42
	2035	RCP 4.5	-0.97
		RCP 8.5	-0.23
	2065	RCP 4.5	-1.10
		RCP 8.5	-0.89

Table 4.8: Yearly Average Unmet Demand for Wanapum Reservoir. Negative in the last column means curtailment is reduced after modified CRT is considered; negative values mean that curtailment is increased

CRT Scenarios	Year	Climate Scenarios	Percent change after considering alternative CRT scenarios (%)
CRT-I	1981-2010	Historic	-2.53
	2035	RCP 4.5	0.26
		RCP 8.5	1.02
	2065	RCP 4.5	0.09
		RCP 8.5	0.37
CRT-II	1981-2010	Historic	-3.21
	2035	RCP 4.5	-1.14
		RCP 8.5	-0.35
	2065	RCP 4.5	-1.61
		RCP 8.5	-1.16

4.3 Impacts of alternative CRT and climate change scenarios on flood magnitude

The 10, 20, 30, 40, 50 and 100-year flood magnitudes were calculated for historic and future climate change scenarios, as well as for modified CRT scenarios. Climate change is projected to significantly increase flood magnitude (e.g. at Mica, Arrow, Duncan and Revelstoke), except for a few reservoir locations in the upper Columbia. For example, at Mica flood magnitudes increase for the 20, 30, 40, 50 and 100 year return periods for both RCP 4.5 and 8.5 with a higher impact later in the 2030s (Figure 4.22).

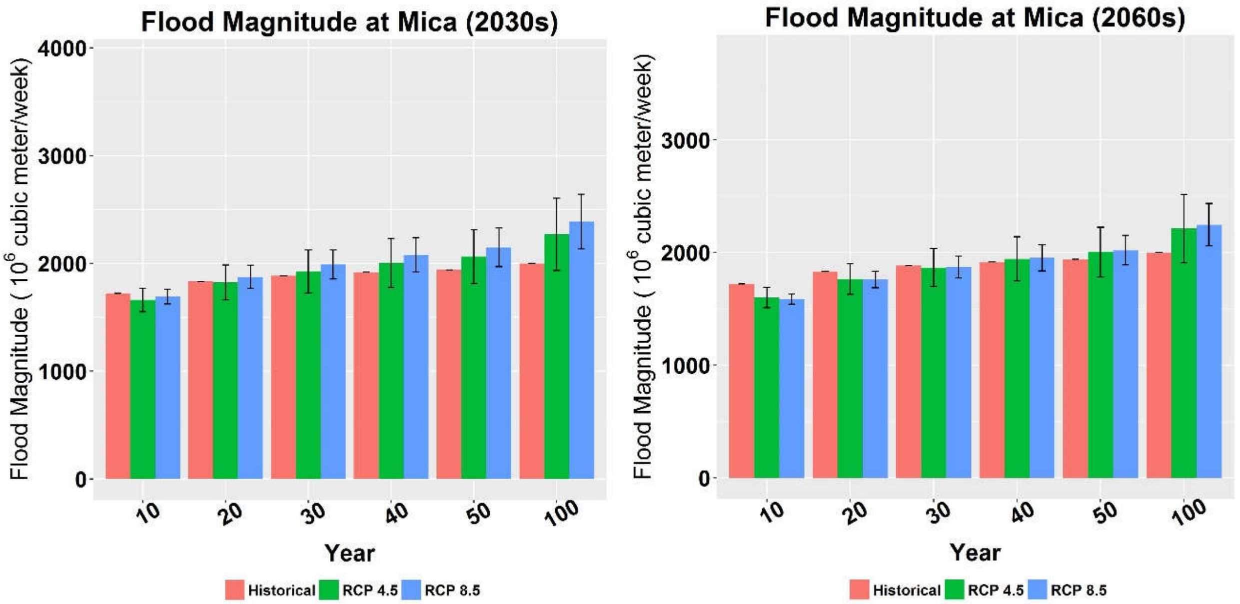


Figure 4.17: Flood Magnitudes at Mica under climate change scenarios. Red bar, green and blue bar indicate historical flood magnitude, flood magnitude under RCP 4.5 climate scenario and flood magnitude under RCP 4.5 climate scenario.

Interestingly, flood magnitudes increase (with respect to historical) only for the 40, 50 and 100 year return period for 2060s (Figure 4.22). Extreme flood events would be more likely in altered climate for both RCP 4.5 and RCP 8.5 climate scenarios in future. In this case, CRT-I and CRT-II both mitigate, to some extent, the effects that climate change has on increasing flood risk. To better understand the increase in future weekly flood magnitude as compared to historic, flood ratios have been calculated and grouped into four classes: i) climate change+current CRT, ii) climate change + modified CRT, iii) historical+current CRT, and iv) historical+modified CRT. We use the following equations to calculate the following flood ratios, were “F” is used for quantifying the impacts of climate change on flood magnitude, and “H” is used for quantifying the impact of treaty alternatives on flood magnitude.

A flood ratio less than one indicates a decrease in flood ratio and a ratio greater than one indicates an increase in flood ratios.

Future Flood Ratio, F = $\frac{Future\ Flood\ Magnitude\ under\ Climate\ Change}{Historical\ Flood\ Magnitude}$

Historical Flood Ratio, H = $\frac{Flood\ magnitude\ for\ historical\ streamflow\ under\ modified\ CRT}{Historical\ flood\ magnitude\ under\ current\ CRT}$

Climate change is observed to increase flood ratio at the majority of dam locations except for Keenleyside, Duncan, Mica and Revelstoke (Table 4.9-4.11). Under both climate change and modified CRT scenarios a mixed result is observed such that flood ratio is reduced at Mica for both CRT scenarios (Figure 4.23), and flood ratio is mostly increased for CRT-I but decreased for CRT-II at Albeni Falls (Figure 4.24-4.25). CRT-II is predicted to be more beneficial than the CRT-I to reduce flood risk (Table 4.9-4.11). CRT-II results greater reductions in flood magnitude at upper Columbia dam locations. McNary, Wanapum, Wells, Grand Coulee, Hells Canyon reservoir locations increase in flood magnitude under both climate change scenarios for 2030s and 2060s; however, CRT-I and CRT-II reduce these flood ratios (Table 4.9-4.11). CRT-I reduces the flood ratio at Priest Rapids Dam, but CRT-II increases the flood ratio by 0.4% to 1.2% in 2060s for both RCP 4.5 and 8.5.

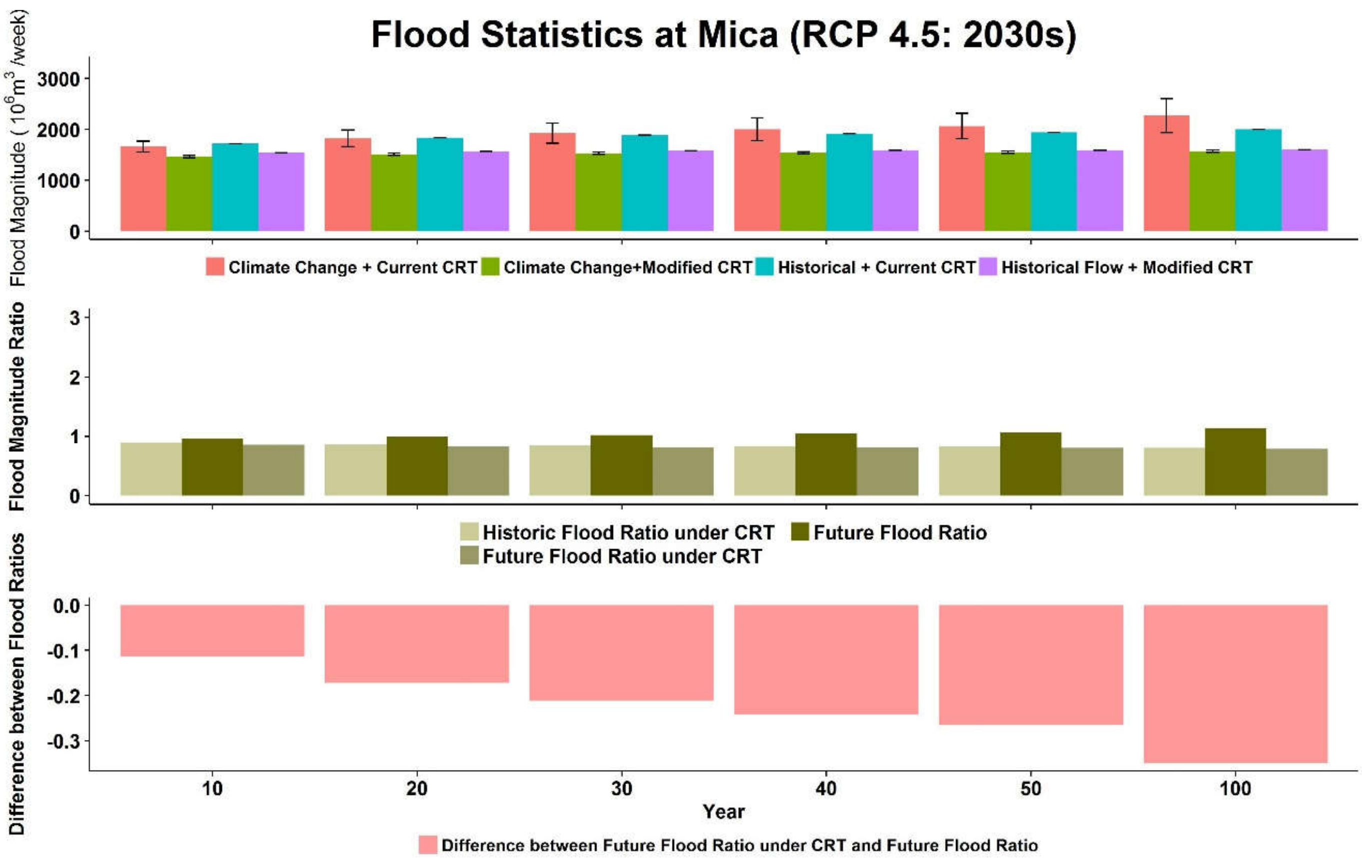


Figure 4.18: Flood statistics at Mica for 2030s under CRT-I scenario. In the top panel the red bar, green bar, cyan bar and purple bar show flood magnitude in 2030s under RCP 4.5 climate scenario, flood magnitude in 2030s under RCP 4.5 climate and CRT-I scenario, historical flood magnitude under current CRT condition and historical flood magnitude under CRT-I scenario.

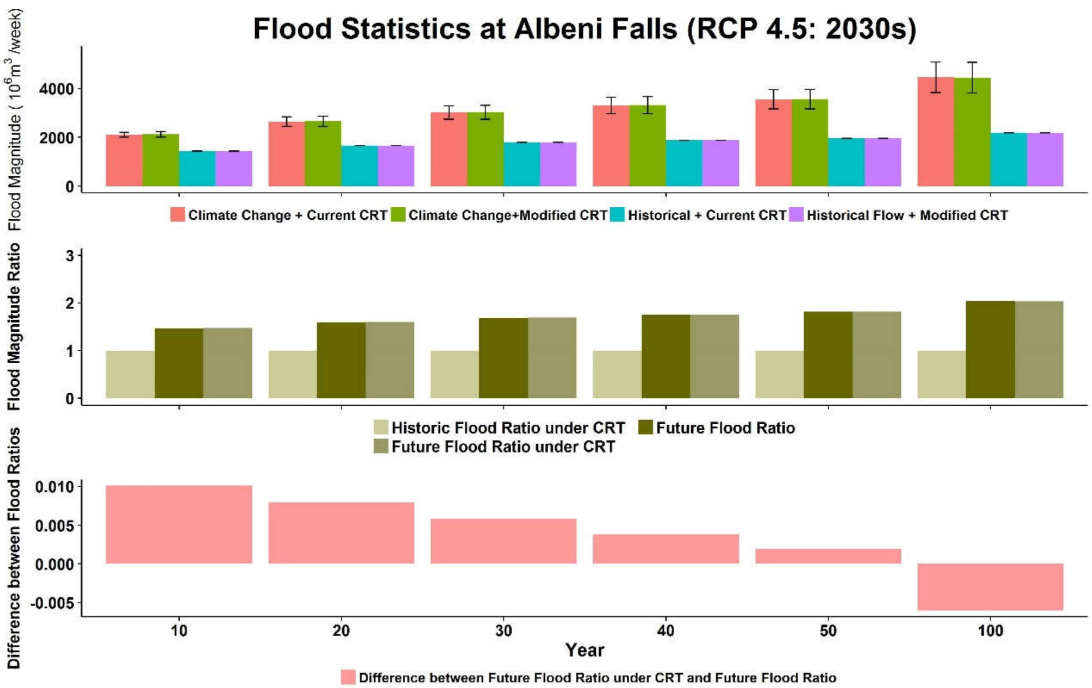


Figure 4.19: Flood Statistics at Albeni Falls under CRT-I scenario

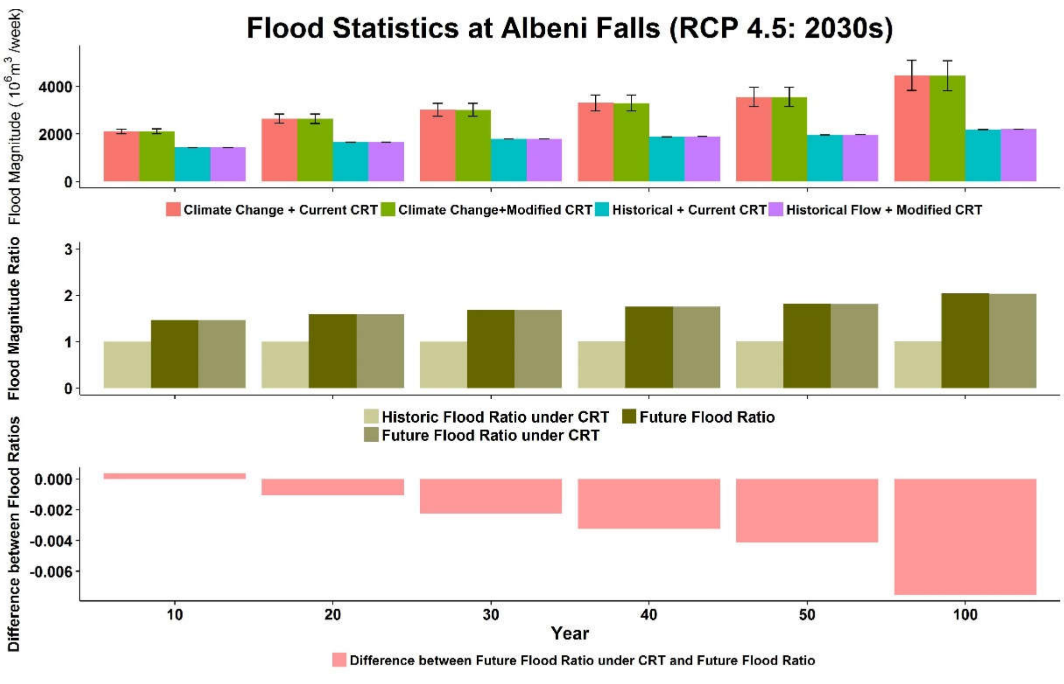


Figure 4.20: Flood Statistics at Albeni Falls under CRT-II scenario

At some reservoir locations (John Day, The Dalles) situated at the lower Columbia it is predicted to have some impact on flood magnitude for changing flood target at The Dalles from 13,000 m^3/s to 17,000 m^3/s under some climate change and CRT scenarios.

a.

b.

Figure 4.21: Flood Statistics for RCP 8.5-2030s at John Day. Panel (a) shows flood statistics at The Dalles flood target at 13,000 m3/s and Panel (a) shows flood statistics at The Dalles flood target at 17,000 m3/s.

Table 4.9: 20-Year Flood Magnitude Ratios at Different Reservoir Locations

Name	RCP_4.5 (2030s)	RCP_8.5 (2030s)	RCP_4.5 (2060s)	RCP_8.5 (2060s)	RCP_4.5 2030s CRT_1	RCP_8.5 2030s CRT_1	RCP_4.5 2060s CRT_1	RCP_8.5 2060s CRT_1	RCP_4.5 2030s CRT_2	RCP_8.5 2030s CRT_2	RCP_4.5 2060s CRT_2	RCP_8.5 2060s CRT_2
Albeni Falls	1.59	1.59	1.64	1.91	1.60	1.59	1.64	1.91	1.59	1.59	1.63	1.91
Arrow	0.89	1.04	1.03	1.02	0.85	1.03	1.01	1.01	0.83	1.01	1.00	1.01
Bonneville	1.07	1.22	1.06	1.22	1.05	1.21	1.06	1.21	1.05	1.21	1.07	1.21
Boundary	1.33	1.28	1.17	1.42	1.34	1.28	1.17	1.42	1.33	1.28	1.17	1.41
Brownlee	1.52	1.52	1.45	1.66	1.52	1.52	1.44	1.66	1.52	1.52	1.44	1.66
Cabinet Gorge	1.60	1.60	1.65	1.92	1.61	1.60	1.66	1.92	1.60	1.59	1.64	1.92
Chief Joseph	1.07	1.17	1.09	1.14	1.03	1.14	1.07	1.12	1.01	1.14	1.09	1.14
Corra Linn	1.07	1.12	1.01	1.13	1.07	1.12	1.01	1.14	1.07	1.12	1.01	1.12
The Dalles	1.07	1.23	1.07	1.22	1.05	1.22	1.06	1.21	1.05	1.22	1.07	1.21
Duncan	0.94	0.93	0.93	0.91	0.94	0.93	0.94	0.91	0.94	0.92	0.93	0.91
Dworshak	1.16	1.20	0.99	1.10	1.15	1.21	0.99	1.10	1.14	1.18	0.98	1.10
Kerr	1.42	1.45	1.33	1.58	1.43	1.44	1.33	1.58	1.42	1.43	1.32	1.55
Hungry Horse	1.11	1.08	1.09	1.09	1.12	1.07	1.10	1.08	1.10	1.04	1.10	1.05
Grand Coulee	1.07	1.17	1.09	1.14	1.03	1.14	1.07	1.12	1.01	1.14	1.09	1.14
Hells Canyon	1.52	1.53	1.45	1.67	1.52	1.53	1.45	1.67	1.52	1.53	1.45	1.67
Ice Harbor	1.63	1.64	1.46	1.72	1.63	1.65	1.46	1.72	1.63	1.64	1.46	1.72
John Day	1.07	1.23	1.07	1.22	1.05	1.22	1.07	1.21	1.05	1.22	1.08	1.22
Little Goose	1.63	1.65	1.46	1.73	1.63	1.65	1.46	1.73	1.63	1.65	1.46	1.73
Lower Granite	1.63	1.65	1.46	1.73	1.63	1.65	1.46	1.73	1.63	1.65	1.46	1.73
Libby	1.14	1.14	1.14	1.26	1.14	1.15	1.17	1.27	1.11	1.14	1.12	1.24
Lower Monumental	1.63	1.64	1.46	1.72	1.63	1.65	1.46	1.72	1.63	1.64	1.46	1.72
McNary	1.07	1.22	1.06	1.20	1.05	1.21	1.05	1.19	1.05	1.21	1.06	1.20
Mica	1.00	1.02	0.96	0.96	0.82	0.83	0.85	0.85	0.84	0.86	0.87	0.86
Noxon Rapids	1.44	1.28	1.18	1.48	1.48	1.27	1.17	1.48	1.44	1.27	1.17	1.47
Oxbow	1.52	1.52	1.45	1.66	1.52	1.52	1.44	1.66	1.52	1.52	1.44	1.66
Priest Rapids	1.06	1.16	1.08	1.14	1.03	1.14	1.06	1.13	1.01	1.15	1.09	1.15
Revelstoke	0.97	1.02	0.99	0.96	0.91	0.93	0.93	0.91	0.94	0.97	0.96	0.93
Rock Island	1.06	1.16	1.08	1.14	1.03	1.14	1.06	1.13	1.01	1.15	1.09	1.15
Rocky Reach	1.06	1.16	1.08	1.14	1.03	1.14	1.07	1.13	1.01	1.15	1.09	1.15
Wanapum	1.06	1.16	1.08	1.14	1.03	1.14	1.06	1.13	1.01	1.15	1.09	1.15
Wells	1.08	1.16	1.08	1.14	1.03	1.14	1.07	1.12	1.02	1.14	1.09	1.14

Table 4.10: 50-Year Flood Magnitude Ratios at Different Reservoir Locations

Name	RCP_4.5 (2030s)	RCP_8.5 (2030s)	RCP_4.5 (2060s)	RCP_8.5 (2060s)	RCP_4.5 2030s CRT_1	RCP_8.5 2030s CRT_1	RCP_4.5 2060s CRT_1	RCP_8.5 2060s CRT_1	RCP_4.5 2030s CRT_2	RCP_8.5 2030s CRT_2	RCP_4.5 2060s CRT_2	RCP_8.5 2060s CRT_2
Albeni Falls	1.82	1.73	1.63	1.99	1.82	1.73	1.63	1.99	1.81	1.72	1.62	1.98
Arrow	0.96	1.12	1.14	1.09	0.92	1.10	1.12	1.07	0.87	1.07	1.10	1.06
Bonneville	1.07	1.25	1.03	1.21	1.04	1.24	1.02	1.19	1.04	1.24	1.03	1.20
Boundary	1.40	1.32	1.18	1.45	1.40	1.32	1.18	1.45	1.40	1.32	1.18	1.44
Brownlee	1.63	1.51	1.41	1.58	1.63	1.51	1.41	1.58	1.63	1.51	1.41	1.58
Cabinet Gorge	1.83	1.74	1.67	2.00	1.83	1.74	1.67	2.00	1.82	1.73	1.66	1.99
Chief Joseph	1.15	1.21	1.10	1.16	1.07	1.17	1.08	1.14	1.04	1.17	1.10	1.16
Corra Linn	1.08	1.17	1.02	1.16	1.08	1.16	1.02	1.17	1.07	1.17	1.01	1.15
The Dalles	1.07	1.25	1.03	1.22	1.05	1.25	1.03	1.20	1.04	1.24	1.04	1.21
Duncan	0.91	0.89	0.90	0.87	0.91	0.89	0.90	0.87	0.92	0.89	0.90	0.87
Dworshak	1.15	1.22	0.93	1.05	1.14	1.23	0.92	1.05	1.13	1.21	0.91	1.06
Kerr	1.49	1.55	1.34	1.61	1.51	1.53	1.33	1.61	1.50	1.52	1.31	1.59
Hungry Horse	1.07	1.05	1.04	1.02	1.07	1.03	1.04	1.01	1.04	1.01	1.05	0.99
Grand Coulee	1.15	1.21	1.10	1.16	1.07	1.17	1.08	1.14	1.04	1.17	1.10	1.16
Hells Canyon	1.63	1.52	1.41	1.59	1.63	1.52	1.41	1.58	1.63	1.52	1.41	1.58
Ice Harbor	1.77	1.74	1.51	1.70	1.77	1.75	1.51	1.70	1.77	1.75	1.51	1.70
John Day	1.08	1.26	1.04	1.22	1.05	1.25	1.03	1.20	1.04	1.25	1.04	1.21
Little Goose	1.77	1.75	1.51	1.71	1.77	1.75	1.51	1.70	1.77	1.75	1.51	1.71
Lower Granite	1.77	1.75	1.51	1.71	1.77	1.75	1.51	1.70	1.77	1.75	1.51	1.71
Libby	1.23	1.23	1.25	1.35	1.22	1.26	1.28	1.37	1.22	1.29	1.29	1.37
Lower Monumental	1.77	1.74	1.51	1.70	1.77	1.75	1.51	1.70	1.77	1.75	1.51	1.70
McNary	1.09	1.25	1.03	1.20	1.06	1.24	1.03	1.19	1.06	1.24	1.04	1.20
Mica	1.06	1.11	1.03	1.04	0.80	0.80	0.85	0.85	0.80	0.83	0.87	0.85
Noxon Rapids	1.45	1.25	1.10	1.43	1.52	1.24	1.09	1.43	1.45	1.25	1.09	1.42
Oxbow	1.63	1.51	1.41	1.58	1.63	1.51	1.41	1.58	1.63	1.51	1.41	1.58
Priest Rapids	1.13	1.20	1.09	1.17	1.07	1.18	1.07	1.16	1.03	1.18	1.10	1.18
Revelstoke	1.00	1.07	1.04	1.00	0.92	0.94	0.95	0.93	0.94	0.98	0.97	0.94
Rock Island	1.13	1.20	1.09	1.17	1.07	1.18	1.07	1.16	1.03	1.18	1.10	1.18
Rocky Reach	1.12	1.21	1.10	1.17	1.06	1.18	1.08	1.16	1.03	1.18	1.10	1.18
Wanapum	1.13	1.20	1.09	1.17	1.07	1.18	1.07	1.16	1.03	1.18	1.10	1.18
Wells	1.15	1.21	1.09	1.16	1.08	1.17	1.08	1.15	1.05	1.18	1.10	1.16

Table 4.11: 100-Year Flood Magnitude Ratios at Different Reservoir Locations

Name	RCP_4.5 (2030s)	RCP_8.5 (2030s)	RCP_4.5 (2060s)	RCP_8.5 (2060s)	RCP_4.5 2030s CRT_1	RCP_8.5 2030s CRT_1	RCP_4.5 2060s CRT_1	RCP_8.5 2060s CRT_1	RCP_4.5 2030s CRT_2	RCP_8.5 2030s CRT_2	RCP_4.5 2060s CRT_2	RCP_8.5 2060s CRT_2
Albeni Falls	2.04	1.85	1.63	2.05	2.03	1.85	1.62	2.05	2.03	1.84	1.61	2.05
Arrow	1.03	1.20	1.24	1.15	0.98	1.18	1.23	1.13	0.92	1.14	1.21	1.12
Bonneville	1.07	1.27	1.00	1.21	1.04	1.27	1.00	1.18	1.04	1.26	1.01	1.20
Boundary	1.45	1.36	1.19	1.47	1.46	1.36	1.19	1.47	1.45	1.36	1.19	1.46
Brownlee	1.74	1.51	1.39	1.53	1.74	1.51	1.38	1.52	1.74	1.51	1.38	1.52
Cabinet Gorge	2.04	1.87	1.68	2.07	2.05	1.87	1.68	2.07	2.04	1.85	1.66	2.07
Chief Joseph	1.21	1.25	1.10	1.18	1.11	1.20	1.08	1.16	1.06	1.20	1.11	1.18
Corra Linn	1.08	1.21	1.03	1.18	1.09	1.20	1.02	1.19	1.08	1.21	1.02	1.16
The Dalles	1.08	1.28	1.01	1.21	1.05	1.28	1.00	1.19	1.04	1.27	1.01	1.20
Duncan	0.90	0.87	0.88	0.84	0.90	0.87	0.89	0.84	0.91	0.88	0.88	0.85
Dworshak	1.15	1.24	0.88	1.01	1.13	1.25	0.88	1.01	1.12	1.23	0.87	1.02
Kerr	1.56	1.63	1.34	1.64	1.59	1.60	1.33	1.64	1.58	1.59	1.31	1.61
Hungry Horse	1.05	1.04	1.00	0.98	1.04	1.00	1.00	0.97	1.01	0.98	1.02	0.94
Grand Coulee	1.21	1.25	1.10	1.18	1.11	1.20	1.08	1.16	1.06	1.20	1.11	1.18
Hells Canyon	1.75	1.52	1.39	1.53	1.75	1.52	1.39	1.53	1.75	1.52	1.39	1.53
Ice Harbor	1.89	1.83	1.55	1.68	1.89	1.84	1.55	1.68	1.89	1.84	1.55	1.68
John Day	1.09	1.29	1.02	1.22	1.05	1.29	1.01	1.20	1.04	1.27	1.02	1.21
Little Goose	1.89	1.84	1.55	1.69	1.89	1.84	1.55	1.68	1.89	1.84	1.55	1.68
Lower Granite	1.89	1.84	1.55	1.69	1.89	1.84	1.55	1.68	1.89	1.84	1.55	1.68
Libby	1.31	1.30	1.34	1.43	1.29	1.34	1.37	1.44	1.32	1.43	1.45	1.49
Lower Monumental	1.89	1.83	1.55	1.68	1.89	1.84	1.55	1.68	1.89	1.84	1.55	1.68
McNary	1.11	1.28	1.01	1.20	1.08	1.28	1.01	1.18	1.07	1.27	1.02	1.20
Mica	1.13	1.19	1.11	1.12	0.78	0.78	0.86	0.87	0.79	0.81	0.88	0.85
Noxon Rapids	1.46	1.23	1.04	1.39	1.56	1.23	1.03	1.39	1.46	1.23	1.04	1.38
Oxbow	1.74	1.51	1.39	1.53	1.74	1.51	1.38	1.52	1.74	1.51	1.38	1.52
Priest Rapids	1.19	1.24	1.10	1.20	1.10	1.21	1.08	1.18	1.05	1.21	1.11	1.21
Revelstoke	1.02	1.10	1.09	1.04	0.93	0.94	0.97	0.94	0.94	0.98	0.98	0.95
Rock Island	1.19	1.24	1.10	1.20	1.10	1.21	1.08	1.18	1.05	1.21	1.11	1.21
Rocky Reach	1.18	1.24	1.11	1.20	1.09	1.21	1.08	1.18	1.04	1.20	1.11	1.21
Wanapum	1.19	1.24	1.10	1.20	1.10	1.21	1.08	1.18	1.05	1.21	1.11	1.21
Wells	1.22	1.25	1.10	1.18	1.12	1.20	1.08	1.17	1.07	1.21	1.11	1.18

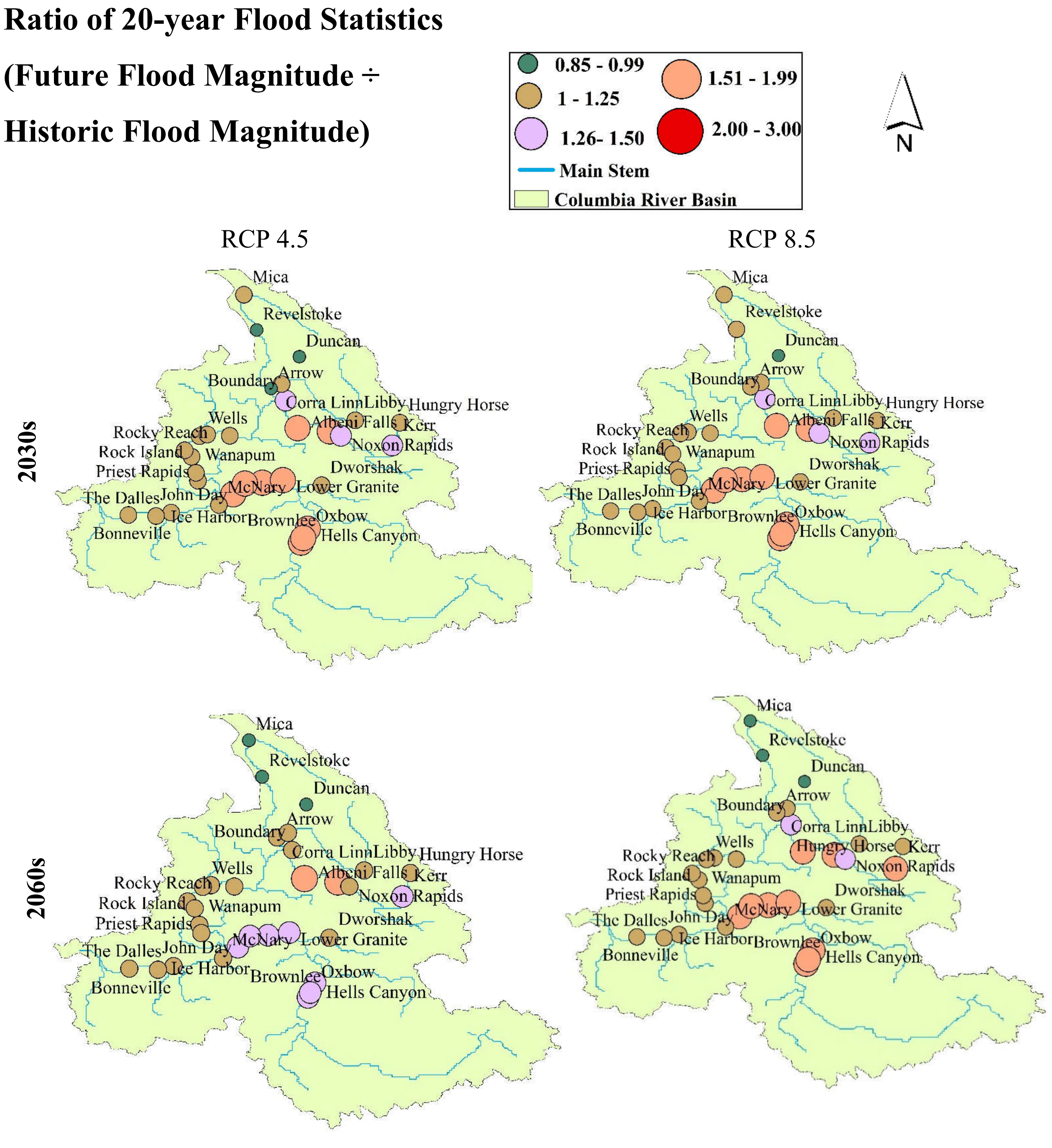


Figure 4.22: Ratio of the 20-year flood ratios in Columbia River Basin. [Top panels show simulated changes for the 2030s, bottom panels for the 2060s. Left columns for RCP 4.5 and right columns for RCP 8.5].

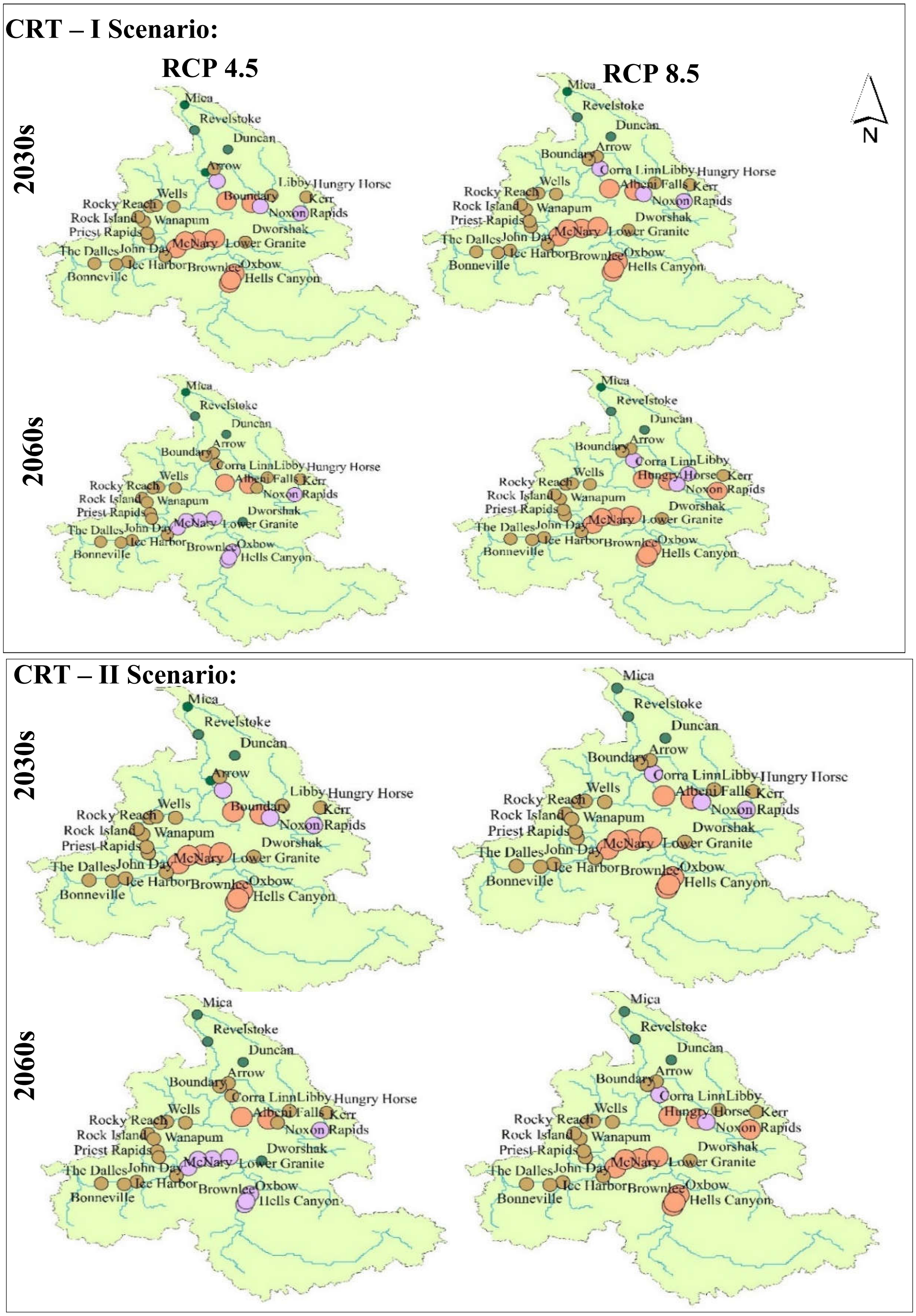


Figure 4.23: Ratio of the 20-year flood ratios in Columbia River Basin. Each box is for each CRT scenario. Top

panels of each box show simulated changes for the 2030s, bottom panels for the 2060s. Left columns for RCP 4.5 and right columns for RCP 8.5.

4.7 Impacts on Hydropower Target Reliability

CRT-I and CRT-II scenarios show a mixed response for firm and non-firm hydropower target reliability. Under current CRT, both RCP 4.5 and 8.5 scenarios project for 2030s and 2060s that there will be a decrease in non-firm hydropower reliability and increase in firm hydropower reliability.

While alternative treaty scenarios are considered, there is an increase in average yearly non-firm energy production under CRT-II scenario than CRT-I in future (Table 4.12), since the CRT-II scenario makes more water available during the low flow months compared to CRT-I. When we compared firm hydropower reliability in monthly scale for alternative CRT-I, there is an increase in reliability observed for firm hydropower generation during both historical and future periods (Figure 4.24). CRT-II condition reduces firm hydropower production both in 2030s and 2060s under RCP 4.5 scenarios (Appendix F: Figure F.1 and Figure F.2 respectively). Under RCP 8.5 scenario, reliability of firm hydropower production seems to reduce in 2030s, but increases in 2060s under alternative CRT-II scenario. (Appendix F: Figure F.3).

On the contrary, there is a decrease in non-firm reliabilities for all months under CRT-I condition (Figure 4. 25). The decrease is also prominent under RCP 8.5 climate scenario during both 2030s and 2060s (Appendix F: Figure F.4 and Figure F.5). As reflected in yearly change in non-firm energy target, CRT-II is beneficial for non-firm hydropower production for all months (Figure 4.26). During December-March (when less release occurs compared to current CRT), it seems to have less increase in non-firm energy reliability compared to that during April-September (when more release occurs compared to current CRT condition) (Figure 4.26). Reliability of meeting non-firm energy target increases with the increase in release. On the other hand, reliability of firm energy target decreases with increase in release (Figure 4.24).

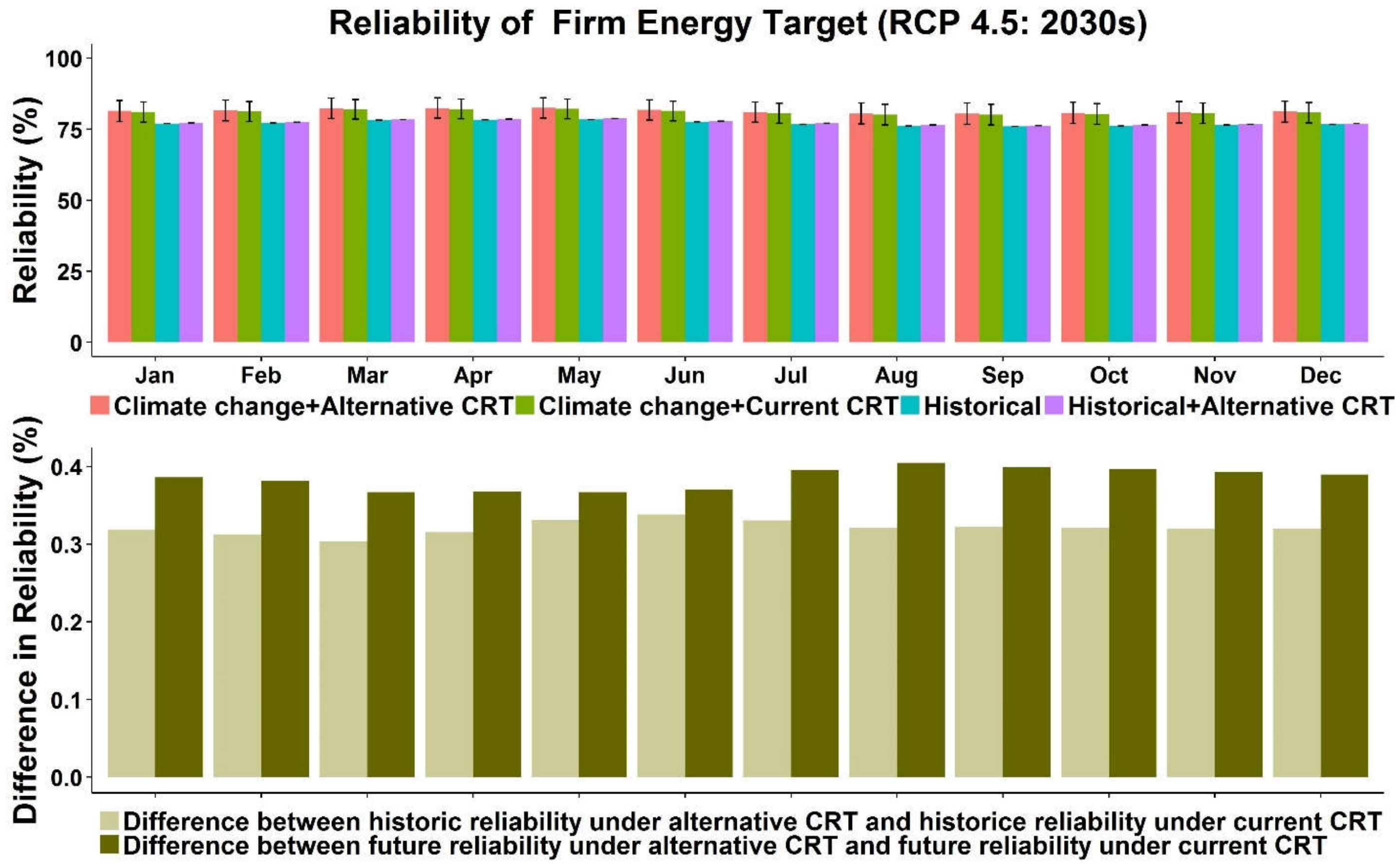


Figure 4.24: Reliability of Firm Energy Target. In top panel, red bar shows the reliability of meeting firm energy target under CRT-I in 2030s, green bar shows the reliability of meeting firm energy target under current CRT in 2030s, cyan bar shows historical reliability of firm energy target under current CRT and purple bar shows historical reliability under CRT-I. In the bottom panel, light olive bar shows the difference between historical firm energy reliabilities under CRT-I and under current CRT and dark olive bar indicates the difference between future firm energy reliabilities under CRT-I and under current CRT.

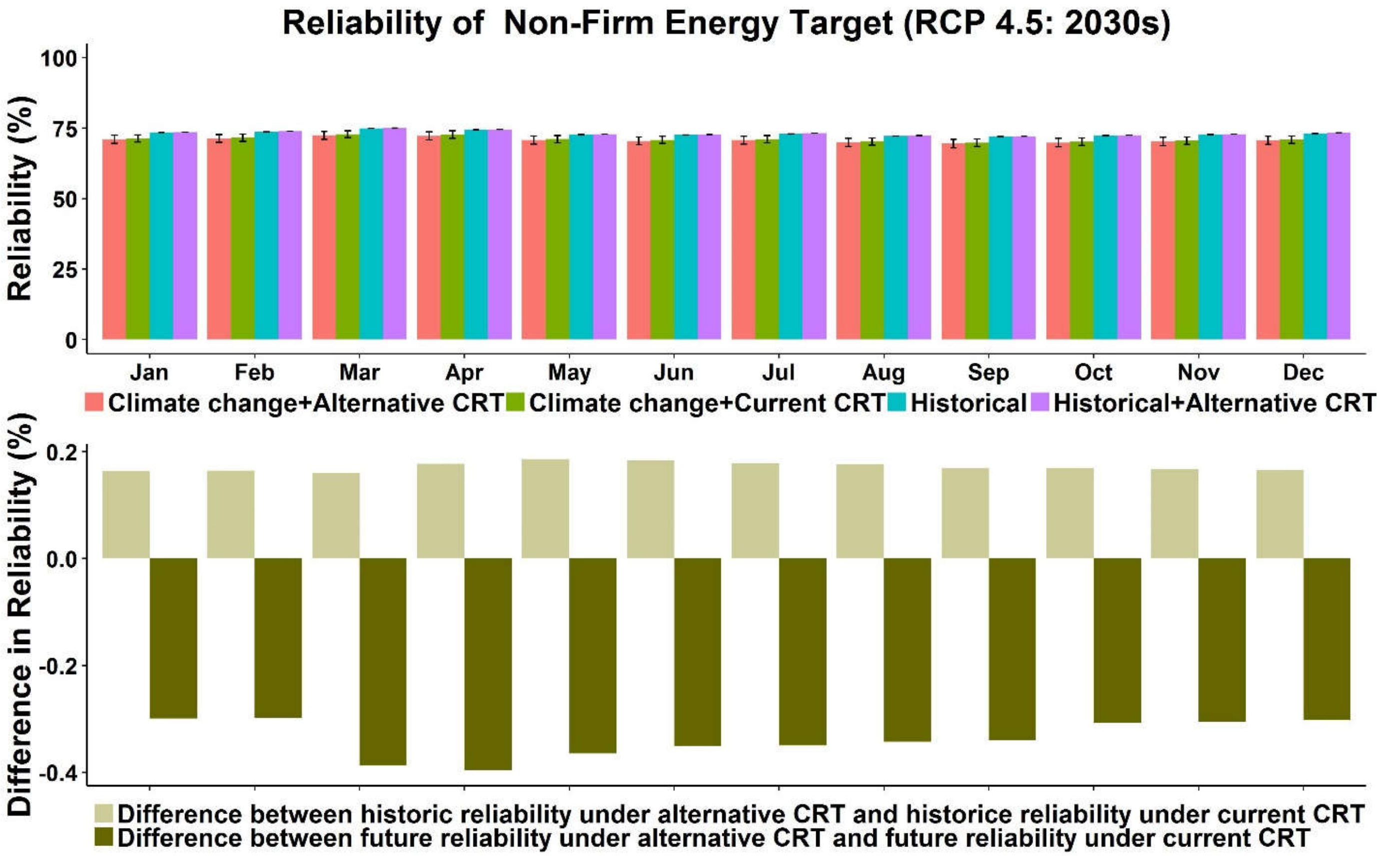


Figure 4.25: Reliability of Non-firm Energy Target. In top panel, red bar shows the reliability of meeting non-firm energy target under CRT-I in 2030s. Green bar shows the reliability of meeting non-firm energy target under current CRT in 2030s, cyan bar shows historical reliability of non-firm energy target under current CRT and purple bar shows historical reliability under CRT-I. In the bottom panel, light olive bar shows the difference between historical non-firm energy reliabilities under CRT-I and under current CRT and dark olive bar indicates the difference between future non-firm energy reliabilities under CRT-I and under current CRT.

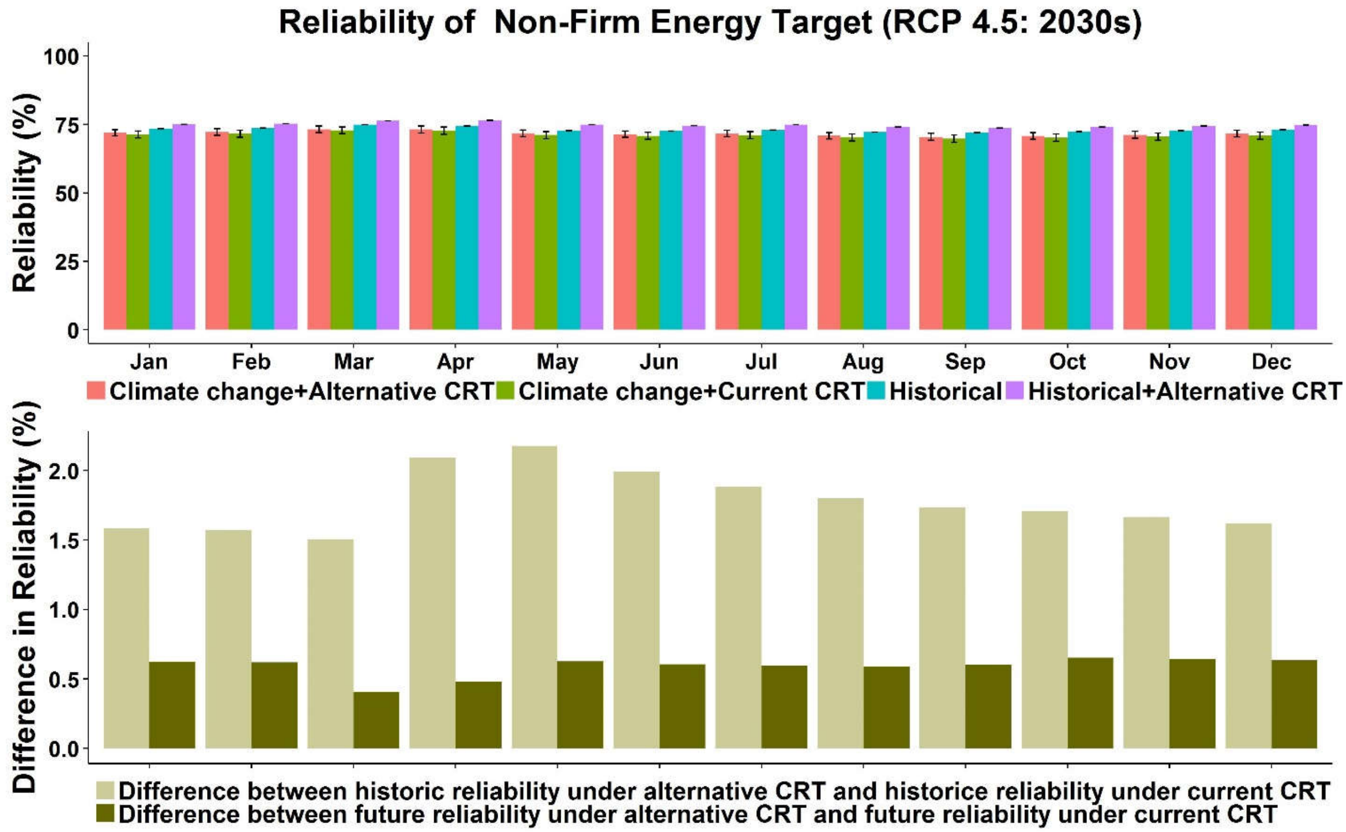


Figure 4.26: Reliability of Non-firm Energy Target. In top panel, red bar shows the reliability of meeting non-firm energy target under CRT-II in 2030s. Green bar shows the reliability of meeting non-firm energy target under current CRT in 2030s, cyan bar shows historical reliability of non-firm energy target under current CRT and purple bar shows historical reliability under CRT-II. In the bottom panel, light olive bar shows the difference between historical non-firm energy reliabilities under CRT-II and under current CRT and dark olive bar indicates the difference between future non-firm energy reliabilities under CRT-III and under current CRT.

4.8 Impacts on Instream Target Reliability

Except at McNary, due to climate change, average annual reliabilities of meeting the instream flow target predicted to increase in future compared to annual historical reliabilities (Table 4.13). The annual reliability of meeting the instream flow target near McNary reservoir observed to decrease under future climate scenarios. In 2030s and 2060s, alternative CRT-I scenario observed to decrease the reliability of instream target more compared to current CRT conditions. On the other hand, target at Vernita Bar near Priest Rapids would be more annually fulfilled under CRT-I and CRT-II conditions. However, CRT-II would more beneficial compared to CRT-I while yearly performance is considered. Monthly results are consistent with yearly performance. At McNary, instream target is less fulfilled under CRT-I scenario in future climate compared to the historic (Figure 4.27). Unsuccessful in meeting instream flow target increases during March-May (Figure 4.27). On the other hand, the reliability of instream flow target has been predicted to increase for all months under CRT-II scenario both in 2030s and 2060s at Bonnevile, McNary and Vernita Bar locations (Appendix-G: Figure G.1 - G.6 under CRT-II and RCP 4.5 scenario).

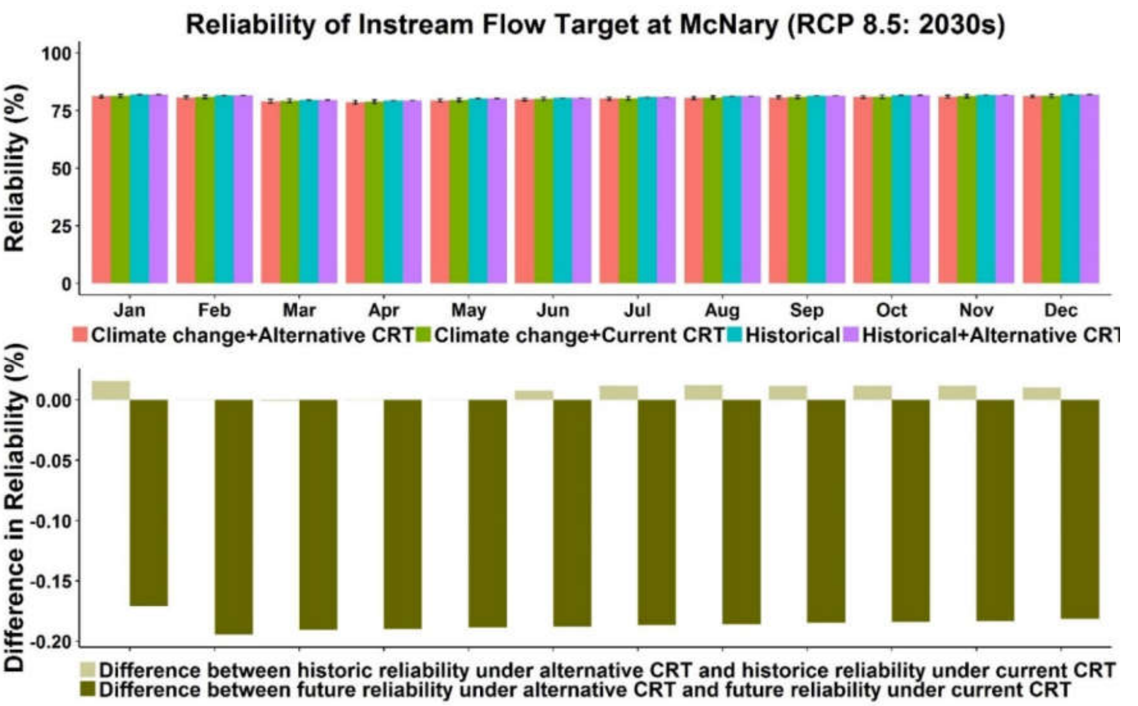


Figure 4.27: Reliability of instream Flow Target at McNary. In top panel, red bar shows the reliability of instream flow target under CRT-I in 2030s. Green bar shows the reliability of meeting instream target under

current CRT in 2030s, cyan bar shows historical reliability of instream flow target under current CRT and purple bar shows historical reliability under CRT-I. In the bottom panel, light olive bar shows the difference between historical instream flow reliabilities under CRT-I and under current CRT and dark olive bar indicates the difference between future instream flow reliabilities under CRT-I and under current CRT.

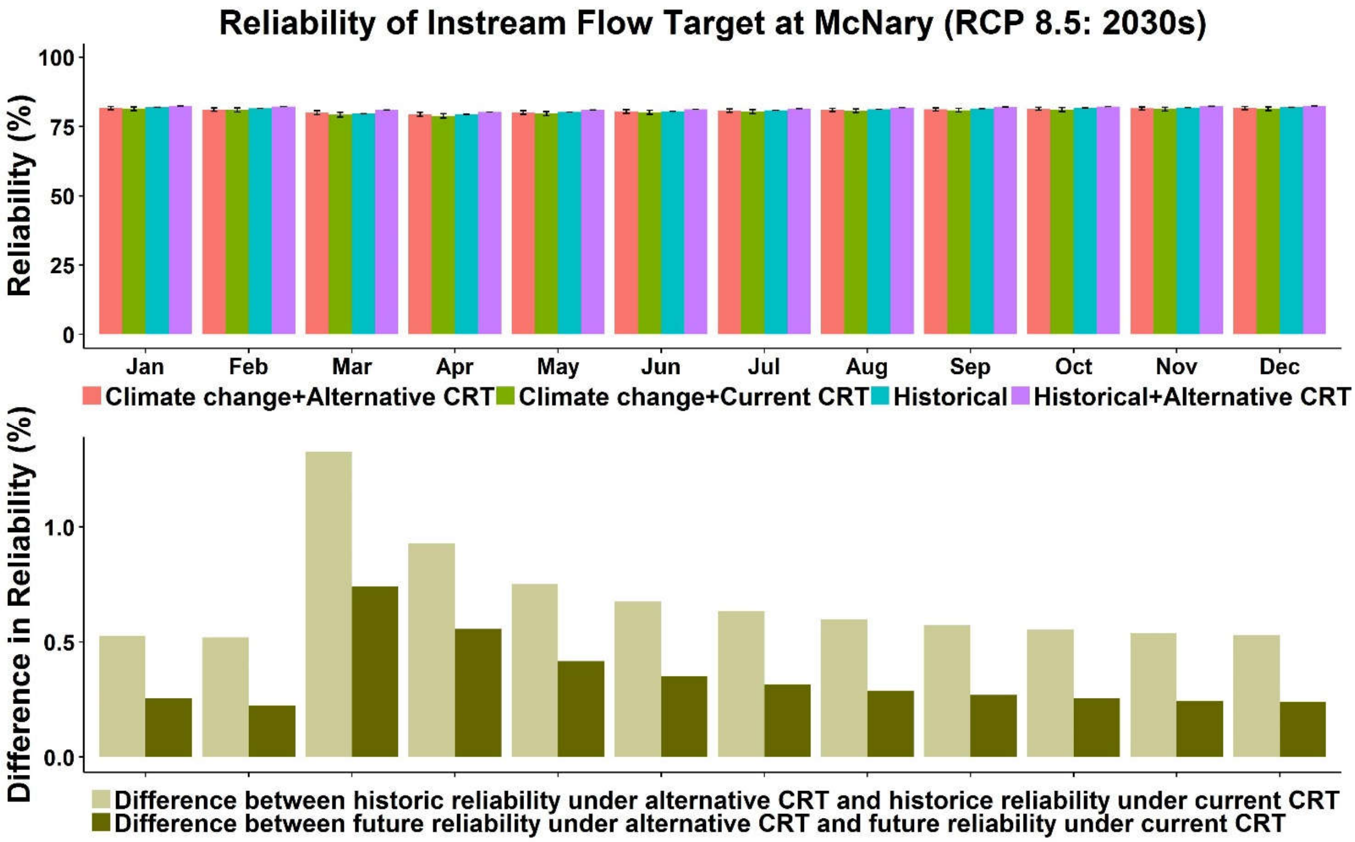


Figure 4.28: Reliability of instream Flow Target at McNary. In top panel, red bar shows the reliability of instream flow target under CRT-II in 2030s. Green bar shows the reliability of meeting instream target under current CRT in 2030s, cyan bar shows historical reliability of instream flow target under current CRT and purple bar shows historical reliability under CRT-II. In the bottom panel, light olive bar shows the difference between historical instream flow reliabilities under CRT-II and under current CRT and dark olive bar indicates the difference between future instream flow reliabilities under CRT-II and under current CRT.

Table 4.12: Reliability of Firm and Non-firm Hydropower in Columbia River

Name	Historic (1980-2007)	RCP_4.5 (2030s)	RCP_8.5 (2030s)	RCP_4.5 (2060s)	RCP_8.5 (2060s)	RCP_4.5 2030s CRT_1	RCP_8.5 2030s CRT_1	RCP_4.5 2060s CRT_1	RCP_8.5 2060s CRT_1	RCP_4.5 2030s CRT_2	RCP_8.5 2030s CRT_2	RCP_4.5 2060s CRT_2	RCP_8.5 2060s CRT_2
Firm Energy Target	77.2	81.3	81.9	82.2	82.6	81.7	82.0	82.7	83.0	81.0	81.6	82.2	82.7
Non-firm Energy Target	72.9	71.2	71.3	69.8	69.4	70.8	71.1	69.6	69.1	71.7	71.9	70.8	70.1

Table 4.13: Reliability of instream flow target in Columbia River

Name	Historic (1980-2007)	RCP_4.5 (2030s)	RCP_8.5 (2030s)	RCP_4.5 (2060s)	RCP_8.5 (2060s)	RCP_4.5 2030s CRT_1	RCP_8.5 2030s CRT_1	RCP_4.5 2060s CRT_1	RCP_8.5 2060s CRT_1	RCP_4.5 2030s CRT_2	RCP_8.5 2030s CRT_2	RCP_4.5 2060s CRT_2	RCP_8.5 2060s CRT_2
Columbia Falls	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Lower Granite	71.0	73.0	73.6	70.2	70.7	73.0	73.6	70.2	70.7	73.1	73.6	70.2	70.7
McNary	81.2	78.9	80.2	78.1	77.7	78.9	80.0	77.9	77.6	79.2	80.7	78.7	77.7
Vernita Bar	93.2	94.0	95.1	95.1	96.3	94.1	95.1	95.2	96.4	94.2	94.8	95.2	96.1
Bonneville	76.7	81.9	83.6	86.8	87.3	82.2	83.7	86.9	87.3	82.0	83.6	87.0	87.3

4.9 Impact of flood target at The Dalles

There is negligible or no impact on unmet instream flow demand and curtailment for considering alternative treaty scenarios under two separate flow targets (13,000 m^3/s and 17,000 m^3/s) at The Dalles (figures are not included). However, there is some increase on flood magnitude in the lower Columbia (John Day, The Dalles) due to increase in flood target from 13,000 m^3/s to 17,000 m^3/s.

4.10 Relative tradeoff of different CRT alternatives among different sectors

There are tradeoffs among these alternative treaty scenarios. Our results show, while CRT-I is favoring hydropower generation, CRT-II is good for out of stream demand such as irrigation. Under CRT-I scenario, reliability of producing firm hydropower production has observed to increase more during the winter when energy demand reaches its peak (EIA 2016). Though CRT-II has positive impacts on non-firm energy production, reliability of non-firm hydropower production increases more during the summer compared to that of winter under this scenario. Over generation during off peak season (summer) may lead the system to more spilling of water. Spilling of water is associated with production of undissolved gases which are detrimental to aquatic fauna and eco-system (Raymond 1988). Although CRT-I is beneficial for hydropower generation (since it is more successful in fulfilling the firm hydropower target) it creates negative impacts on fulfilling instream flow target at McNary during both historical and future periods. Though at Lower Granite, and Priest Rapids CRT-I scenario has positive impacts for historic period, it is less beneficial during 2030s and 2060s climate conditions (Appendix G: Figure G.7-G.10 – Reliability of Instream flow target at Vernita Bar near Priest Rapids). The flood magnitude was observed to decrease for 10, 20, 30, 40, 50 and 100 year flood especially at middle and lower Columbia under both alternative CRT-I and CRT-II scenarios. While CRT-II has not been resulted as good as CRT-I in terms of hydropower degeneration, it is beneficial for out of stream demand such as agriculture unmet demand (Table 4.6-4.8) and resulted in less agricultural curtailment (Figure 4.12).

4.11 Discussion

Because of the importance of water in the Columbia Basin, a wide range of research has focused on impacts of climate change on the water resources. Climate change is a major concern in the CRB due to the impacts this region has already experiencing from increasing temperature and changing precipitation patterns. Streamflow in the CRB is strongly influenced by snowmelt which is sensitive to temperature and precipitation changes. This snowmelt induced water is heavily controlled for multiple instream and out of stream uses. Any change in river flow characteristics is of immense importance for water resources management in this basin. While only climate change scenarios are considered, the trends along the mainstem are increased streamflow during the spring months and shift in peak flow earlier in the season. The climate change impact characteristics projected in this study are consistent with other studies focusing this basin (Hamlet et al. 2001, Hamlet 2003, Hamlet et al. 2013, Lee et al. 2009, 2011, Payne et al. 2004). The shift of supply earlier in the season moves the water away from the peak irrigation season. On demand side, due to temperature and carbon dioxide increase, irrigation season is projected to start earlier and last shorter. Increased atmospheric carbon dioxide concentrations result in the majority of the crops in the region to respond with less water demand. Furthermore, warming is causing many of the crops to reach maturation earlier (and earlier harvest), reducing the length of the irrigation season for these crops, and reducing the opportunity for water to these crops to be curtailed later in the irrigation season. As a result, we do not see any significant increase in curtailment demand even though water supply in the late summer is projected to decrease. On the other hand, it has been predicted that there would be a significant increase in flood magnitude both in 2030s and 2060s. The Columbia has been classified as the snowmelt dominated river historically (Mantua et al. 2010) where snowmelt contributes more in stream flow and river characteristics than rain. Because of climate change, it has been projected that there will be a transition from snowmelt dominance (Barnett et al. 2005, Mote et al. 2005).

Due to increase in temperature, earlier snowmelt will generate a possibility in shift in hydrograph and maximum stream flow will be available earlier in the season (Barnett et al. 2005). This is why additional water beyond reservoir capacity would be drained out which will result in increase in flood magnitude at most of the reservoir locations. On the contrary, results show a decrease in flood magnitude at reservoir locations situated at the upper Columbia with low mean annual temperature. Reduction in snow pack in this area may reduce the springtime flood possibility (Mantua et al. 2010).

Similarly, as hydropower generation depends on flow volume (Payne et al. 2004, Hamlet and Lettenmaier 1999), an early snowmelt increases the volume of water during the winter season when firm energy is in highest demand. This is why the model projects more reliability in firm energy production. In contrast, because of less water volume during the summer, a decrease in reliability of meeting non-firm energy target has been projected.

We project an increase in reliability in meeting instream flow targets at four out of five locations simulated by ColSim (Columbia Falls, Lower Granite, Vernita Bar [near Priest Rapids], and Bonneville). A decrease in reliability of instream has been observed only at McNary. From figure 4.28, it is visible that during month of June flow decreases due to substantial shift in hydrograph. It results in decreased reliability on McNary flow target.

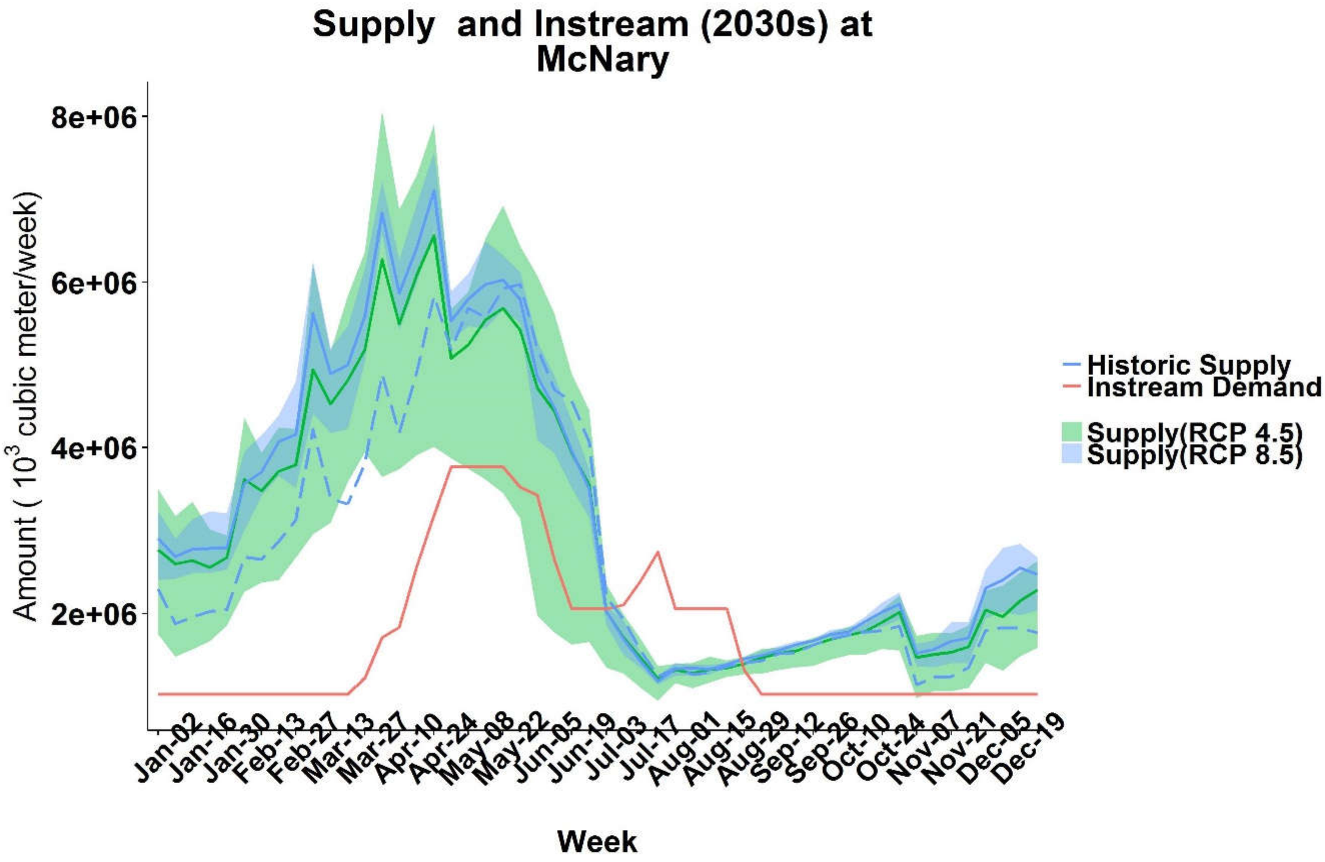


Figure 4.29: Streamflow and instream target comparison at McNary Dam for 2030s climate. Red line shows instream regulation, dotted blue line indicates historical stream flow, blue shed area shows streamflow in RCP 8.5 future climate and green shed area shows streamflow in RCP 4.5 future climate

When considering alternatives for the CRT, we ask two questions. i) How will alternative treaty scenarios interact with the climate change? ii) Which alternatives are going to be most beneficial for agricultural, hydropower and flood risk in the basin in mitigating the negative effects of the climate change? Alternative treaty scenarios considered for this study are mainly developed with the target of increasing the flow during low flow season by storing more water during winter to make it beneficial for fisheries, ecosystem and out-of-stream uses in the future. Both of the CRT-I and CRT-II scenarios have the provision of additional storage during the winter months to be used during summer months. While climate change increases curtailment earlier in the irrigation season, the alternative treaty scenarios offset this impact. However, alternative treaty scenario CRT-II is more beneficial to the agriculture of this basin due than CRT-I because of a higher storage provision. Availability of more storage during the wet season in the treaty dams and more release during the dry season reduces the frequency and magnitude of curtailment events. Thus, treaty scenarios considered in this study, if implemented, will be advantageous to irrigated agriculture of the region. The major reservoirs of the Columbia River operate in such a way that they evacuate during the fall and early winter (Payne et al. 2004). Adding more storage under the alternative treaty scenarios causes the reservoirs to evacuate more, allowing for additional storage in the spring. This change in reservoir dynamics in treaty dams along with the climate scenarios alters the downstream flood risk. Reductions in firm energy due to increased storage comply with the results obtained by Payne et al. (2004).

Chapter 6: Conclusion

Within a biophysical modeling system, VIC-CropSyst, a reservoir system simulation model, ColSim along with an irrigation water curtailment model were used to predict the impacts of climate change and alternative treaty scenarios on the water resources of the CRB. In summary, the results showed, implementing the alternative treaty scenarios with additional storages benefits the irrigated agriculture of the CRB in the future. However, in terms of floods it brings mixed impacts with increasing the risk in some of the locations while reducing in others. Similarly, mixed response has been observed for hydropower and instream target. Overall, out of the two alternative treaty scenarios, the one with the higher storage availability (CRT-II) is more favorable for the flood control and agriculture in this basin. Though it has been observed some negative impacts on the hydropower firm-energy which is being compensated by increasing non-firm energy production. These scenarios are applied considering that there will be no adaptation in crop management practice, use of drought resistance crop in response to climate change or change in total treaty storage. This gives the study a level ground for all the scenarios to quantify the impacts. In future, it will be interesting to extend these studies with more possible adaptation strategies in the basin.

Simulation results from any modeling framework include some degree of uncertainties. The bias observed in the simulated streamflow may be resulted from input meteorological data, hydrological parameters, land cover properties or modeling assumptions. Regional downscaling method used to downscale GCM output could be a potential source of uncertainty. The reservoir system in ColSim simulates only the major reservoirs in the Columbia River basin. It does not have all the reservoirs that are actually being operated and regulated in the system. This simplification in the reservoir system may have impact on the regulated flow. In addition, firm and non-firm target were considered unchanged over the entire period of study which might change in real life with the change in global change as well as population increase. The hydrologic model was calibrated against the naturalized from which are reconstructed data. Error in this dataset brings potential bias in the calibrated flow. All these uncertainties and error sources could affect VIC-CropSyst outputs and ultimately impacting the curtailment results. Unavailability of observed curtailment record makes it difficult to evaluate modeled curtailment results. An indirect effort was paid to evaluate the curtailment using gauge data. However, due to large uncertainty low confidence can be given to the curtailment results.

This study can be expanded in future work by providing more in-depth technical and analytical aspects. As this work is based on real life water related impact analysis, results are valuable for decision makers as well as end users. At first, future study can be conducted on updating the technical aspects of reservoir operation model by incorporating more water management components. Also, these results can be presented as end-user tailored interactive and easily visible decision making tools at the grass-root level. Secondly, a future analysis could be done on crop yield changing pattern because of curtailment. Also, similar methodology used in this research can be applied to other areas of the world. However, although some aspects of this modeling framework can be transitioned to other regions with minimal effort, it may not be easily applicable to any other areas because of unavailability of certain water rights and agriculture management information. In this case, a future study can be done on developing agricultural management database as well as other crop related database.

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Appendices

Appendix – A: CRT-I Scenario Implementation in ColSim

Each dam operates on a rule curve selected form a family of rule curves based on flow prediction for the following year at the Dalles. Each rule curve is associated with particular evacuation schedule determined by USACE, 2003. For each dam, the total amount of storage available for use is considered as full pool volume or maximum capacity. The pool volume set for each operation interval for the reservoir in the rule curve is known as rule volume. The rule volume can be defined as below:

Rule Volume = Full Pool Volume – Evacuation Amount. ……. Eq-A.1

Since the full pool volume cannot be changed, the evacuation schedule is adjusted to make provision for the alternate storage and release. As an example, Keenleyside dam (Arrow) has six different evacuation schedules. Out of those schedules, one is selected for a particular year based on the April to September flow volume forecasting at the Dalles (Table A.1). Now, the evacuation schedule is adjusted in a way that this volume can be stored during winter to release during summer according to the alternate treaty requirements. For CRT-I, 0.5 million acre-feet (MAF) additional storage was added for normal years which is increased to 1 for a dry year. The years with seasonal flow volume (April to September flow volume at The Dalles) lower than the 20th percentile of historical time-series of seasonal flow volumes are considered as dry years. According to historic time series flow lower than 72 MAF is considered as dry year thus schedule-I, II and III for are considered as dry year schedule and schedule-IV and V are for normal years (Table A.1). Thus, to implement CRT-I, schedule-I, II, and III evacuation curves were adjusted such a way that 1.0 MAF decrease in release during December-March equals to absolute value of increase in release during March-April. Similarly, 0.5 MAF water for normal year was designed to release during April-September, but decrease in release in total amount of

0.5 MAF would happen during December-March. Distribution of more storages among these four months (December-March) are equally allocated and distribution of more release among six months (April-September) was performed following Table 3.6.

For an example, schedule-I was modified for 1 MAF increase in storage (i.e. decrease in release) during December-March and released between April to June for the Keenleyside dam in Table A.2. For each new evacuation schedule, we get newly constructed rule curve using Eq-A.1. For weekly conversion, monthly rule curves are linearly interpolated. In figure A.1, orange line is the current rule curve and grey line is the rule curve under alternative CRT-I scenario.

Table A.1: Evacuation schedules for Keenlyside dam

Evacuation Schedule	**The Dalles April to September flow volume**
Schedule -I	<64.0e6 acre-feet
Schedule -II	<65.0e6 acre-feet
Schedule - III	<70.0e6 acre-feet
Schedule -IV	<75.0e6 acre-feet
Schedule -V	>=110.0e6 acre-feet
Schedule - VI	Based on need. Special condition. Not implemented in ColSim.

Table A.2: Change in evacuation schedule-I to make provision for CRT-I dry year condition

Month	**Schedule-I (Present Condition)** **A**	**Change in Monthly Release** **B**	**Schedule –I (Alternative CRT-I Scenario) (A+B)**
August	0	115000	115000
September	0	50000	50000
October	250,000	0	250,000
November	160,000	0	160,000
December	620,000	-250,000	370,000
January	620,000	-250,000	370,000
February	620,000	-250,000	370,000
March	620,000	-250,000	370,000
April	710,000	285,000	995,000
May	710,000	315,000	1,025,000
June	710,000	105,000	815,000
July	0	130,000	130,000

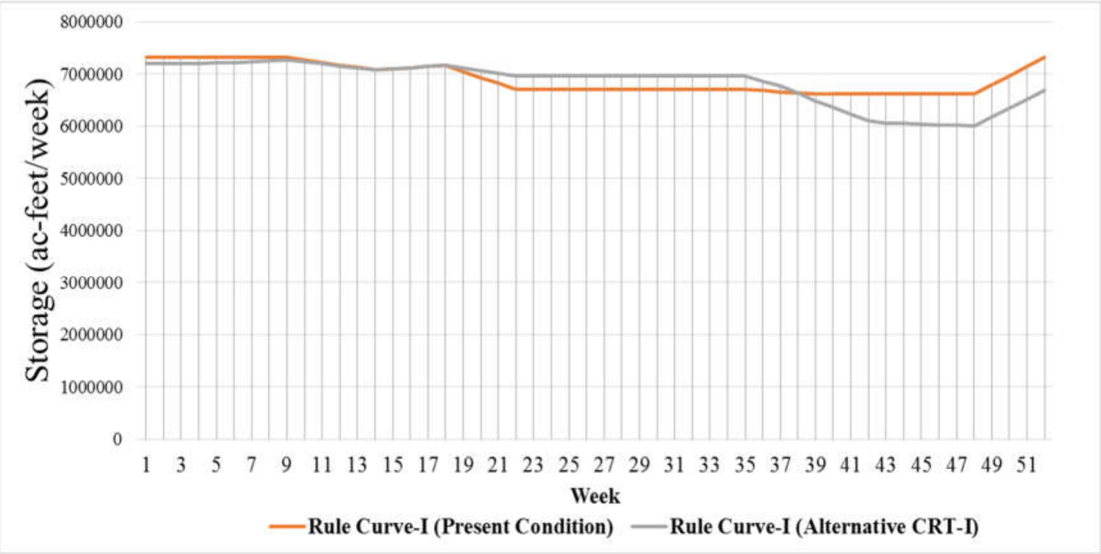


Figure A.1: Rule Curve for Evacuation Schedule-I for dry condition of CRT-I

In ColSim, there is a specific converter (component of system dynamics modeling) assigned for each rule curve. Values in each converter were changed according to alternative CRT-I volume for rule curve (Figure A.2).

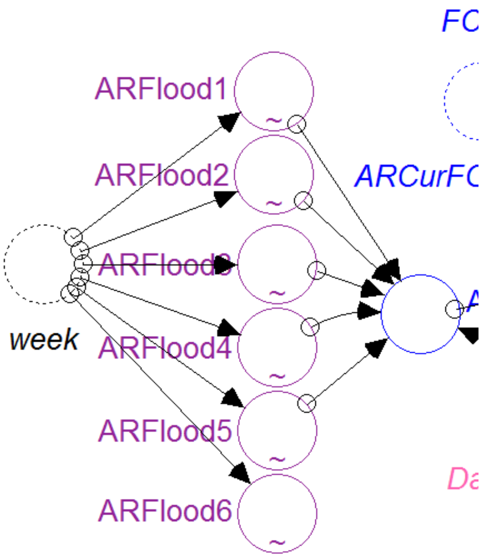


Figure A.2: ColSim converter for rule curve change

Appendix – B: Flood Magnitude Evaluation

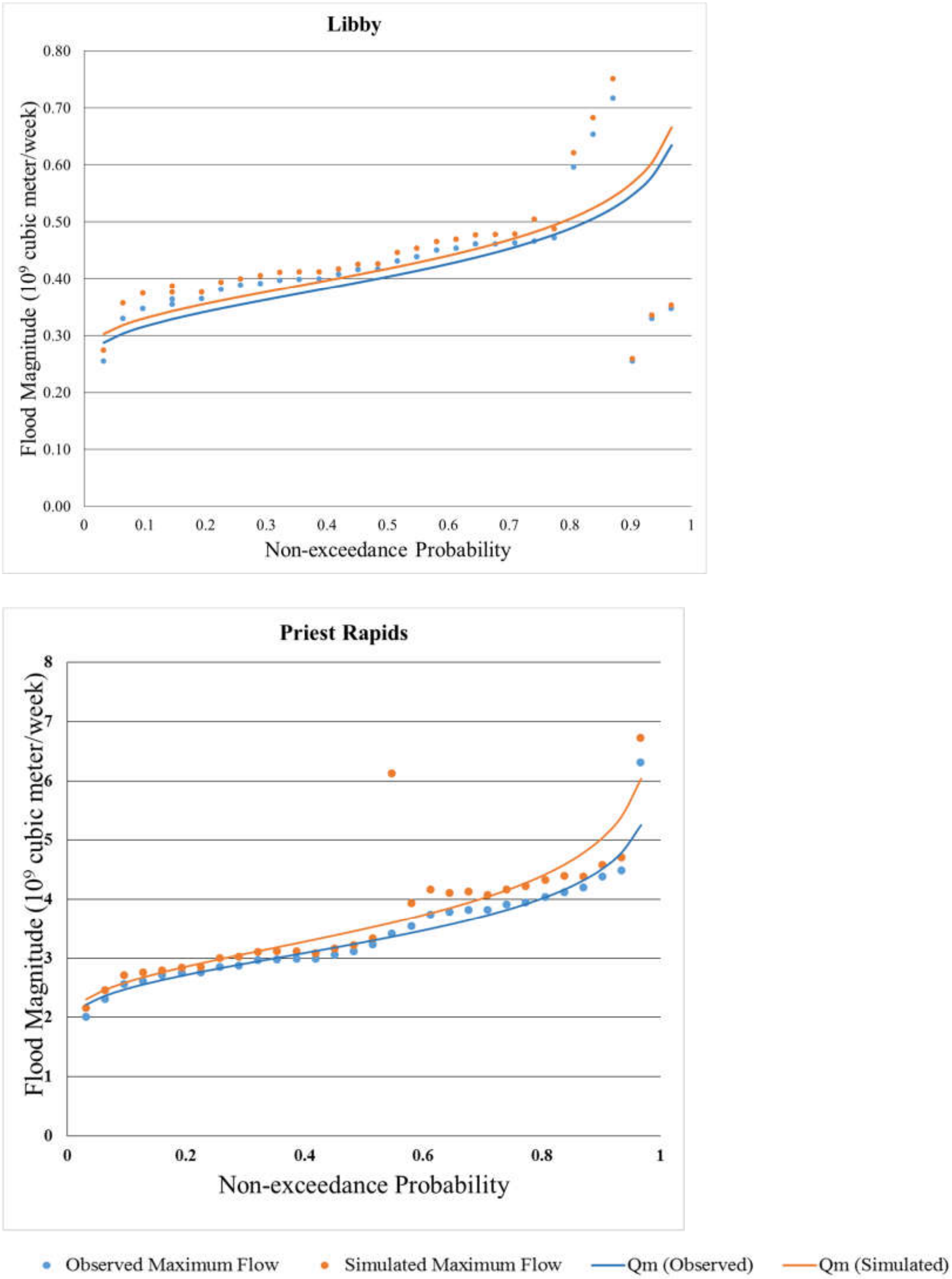


Figure B.1: Flood magnitude for different non-exceedance probability values for observed and simulated quantiles (corresponding to Figure 4.6)

Appendix – C: Supply, Instream, Out of Stream and Curtailment Plots (Corresponding to figure 4.7)

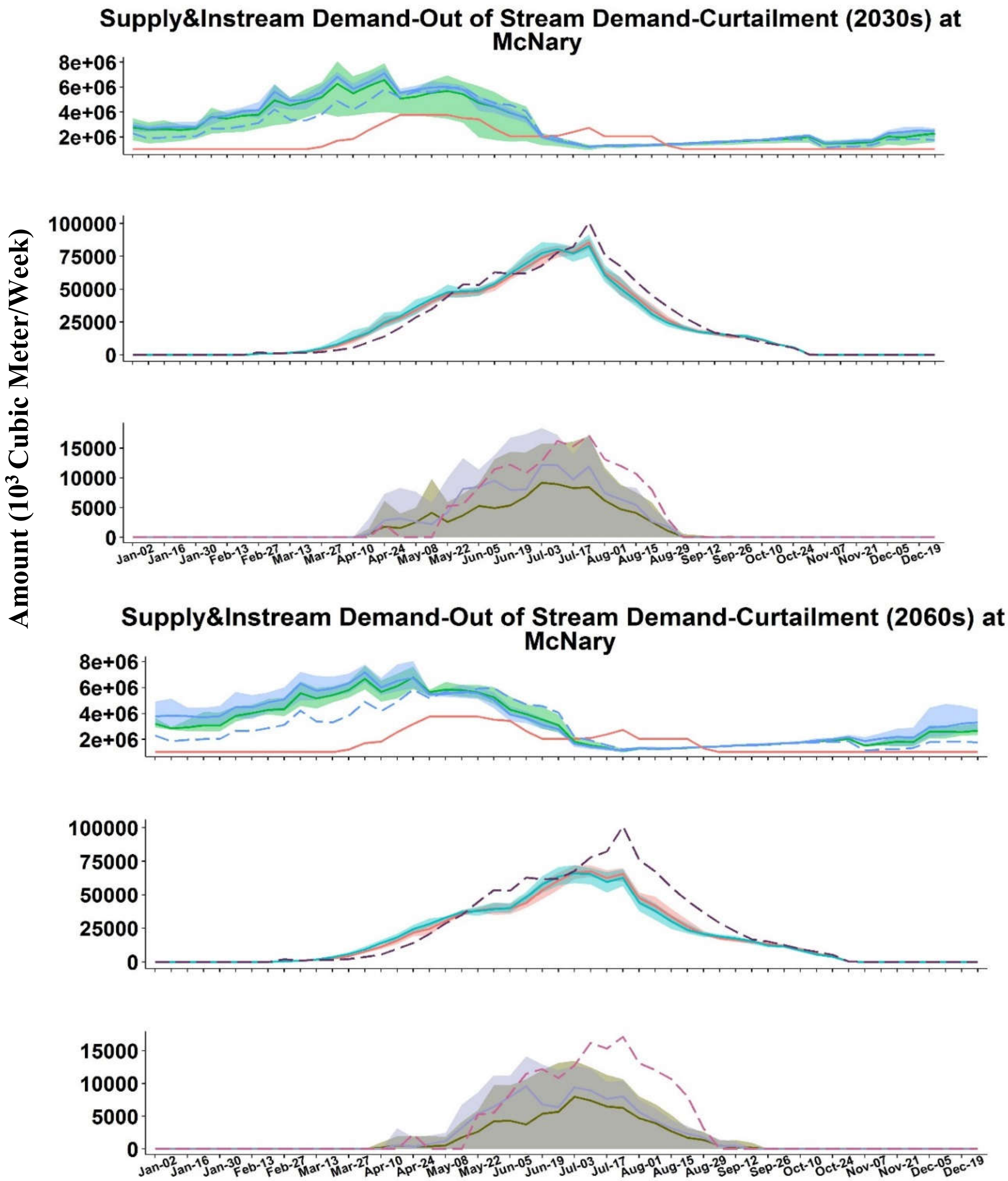


Figure C.1: Supply, Out of Stream, Demand and Curtailment at different dam locations

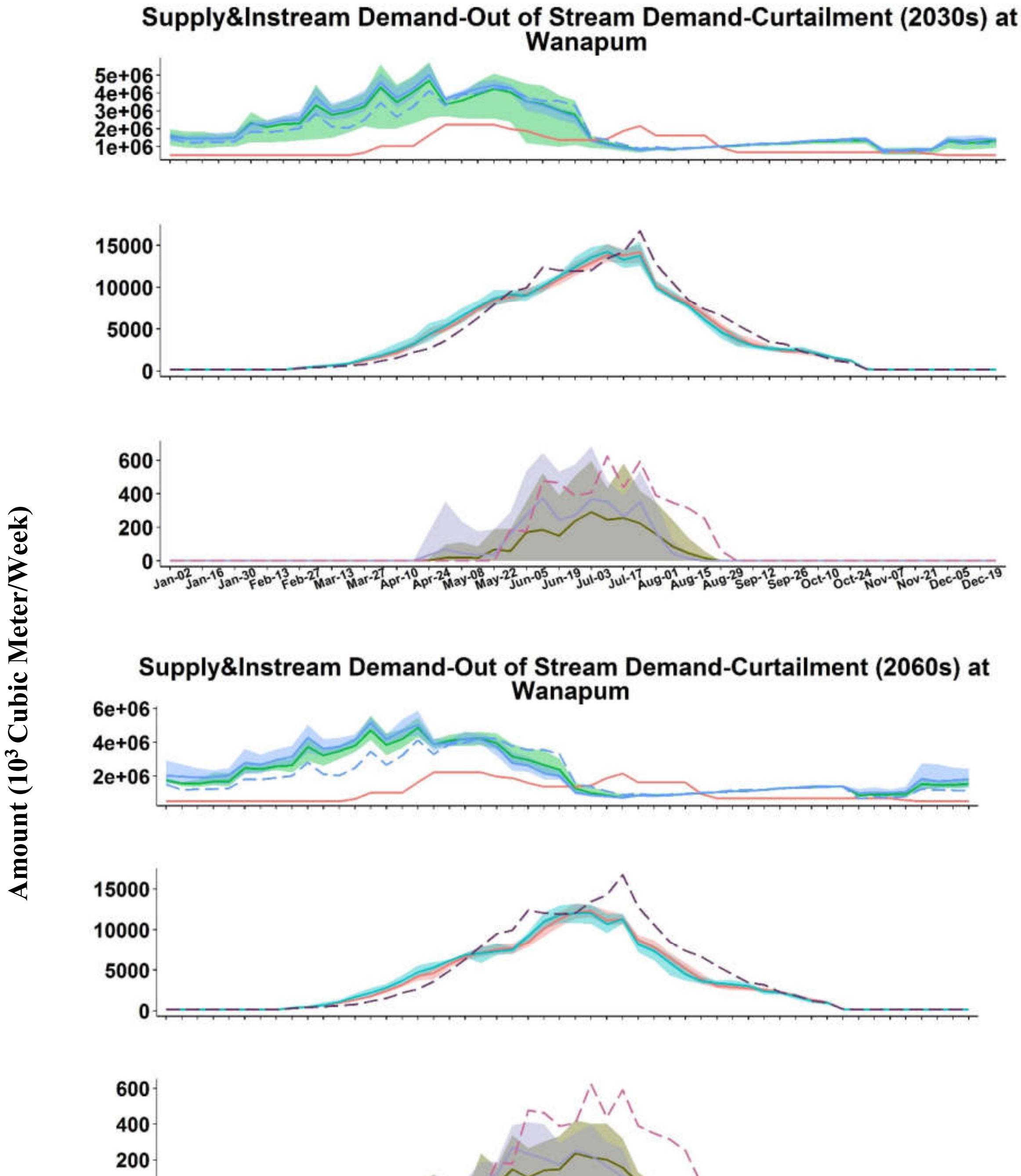


Figure C.2: Supply, Out of Stream, Demand and Curtailment at different dam locations

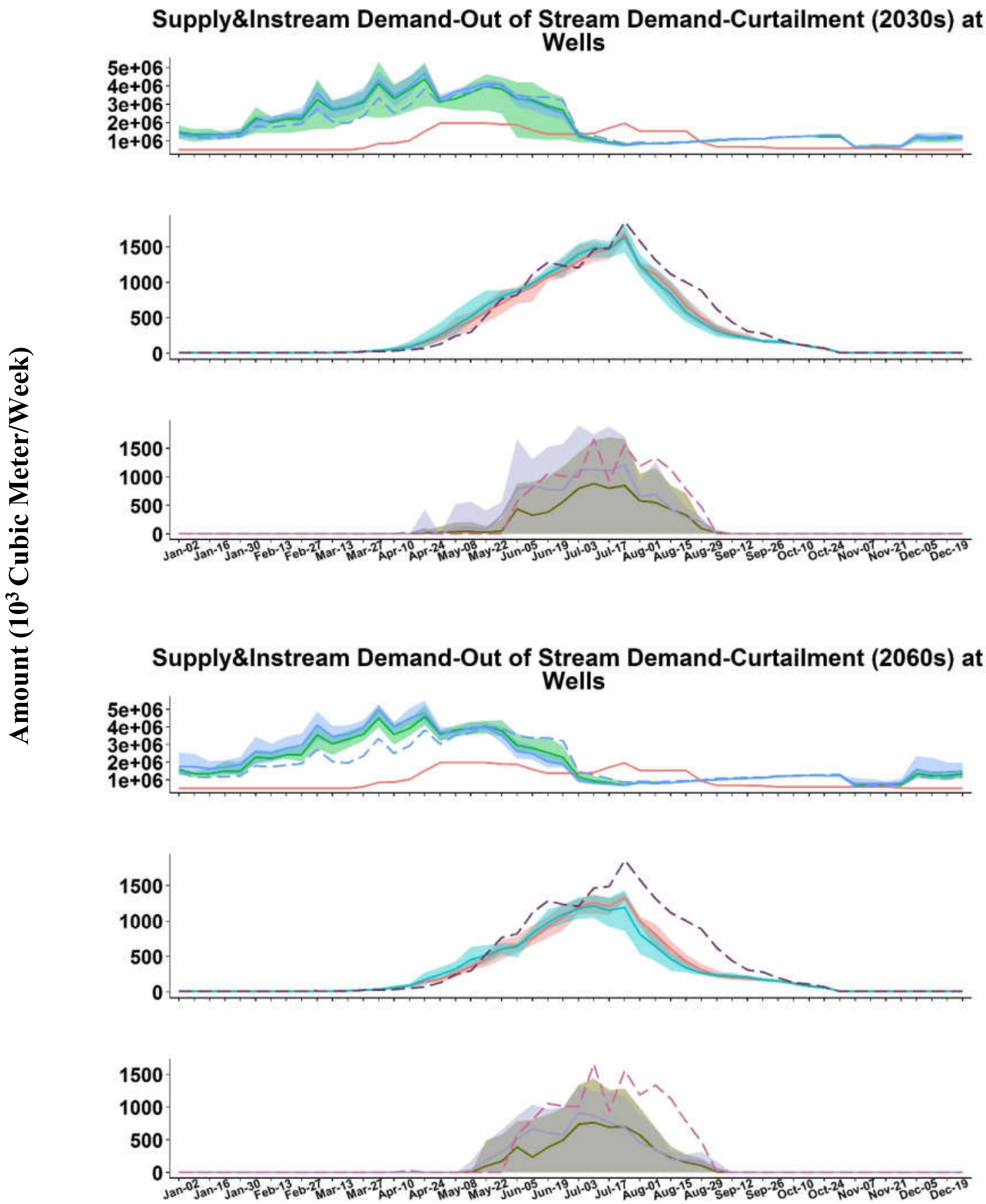


Figure C.3: Supply, Out of Stream, Demand and Curtailment at different dam locations

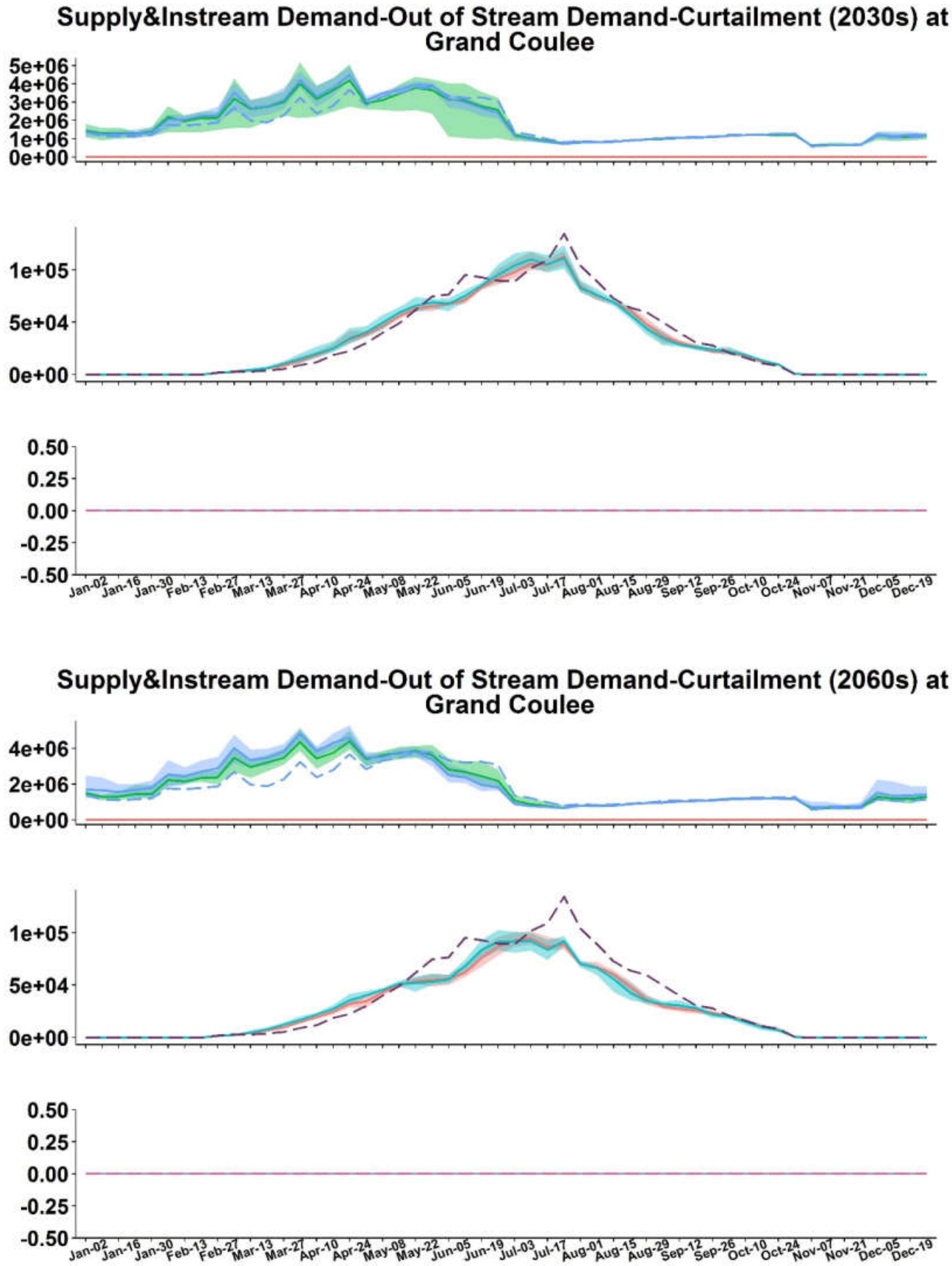
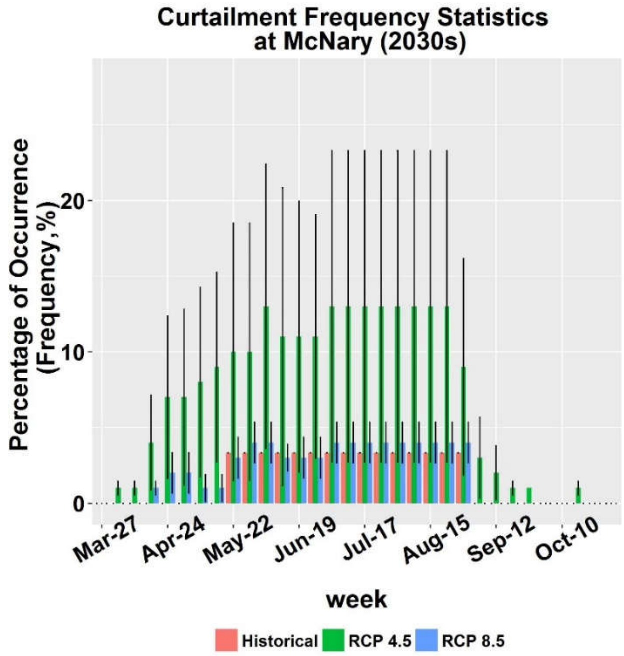


Figure C.4: Supply, Out of Stream, Demand and Curtailment at different dam locations

Appendix-D: Percentage of Curtailment Frequency in Future Climate



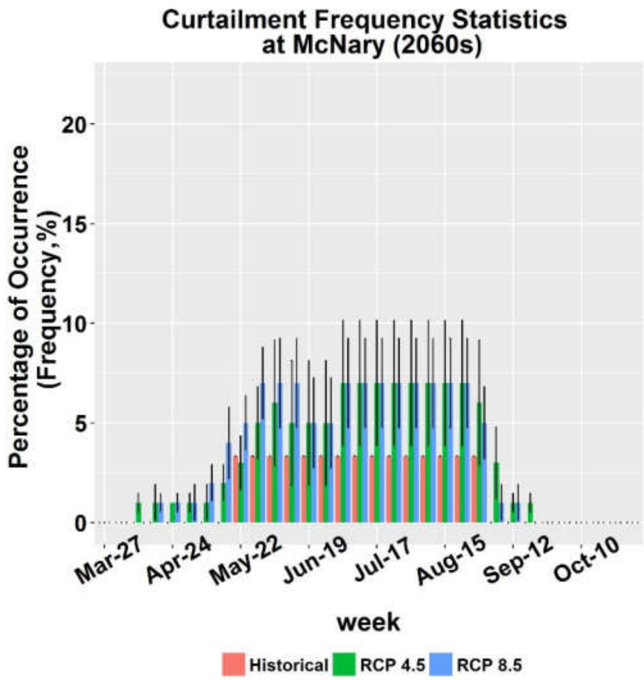
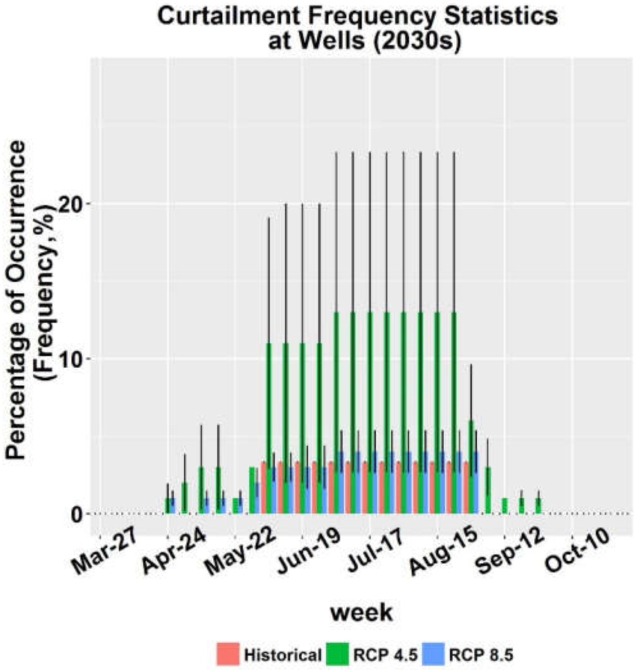


Figure D.1: Percentage of Curtailment Frequency at different dam locations



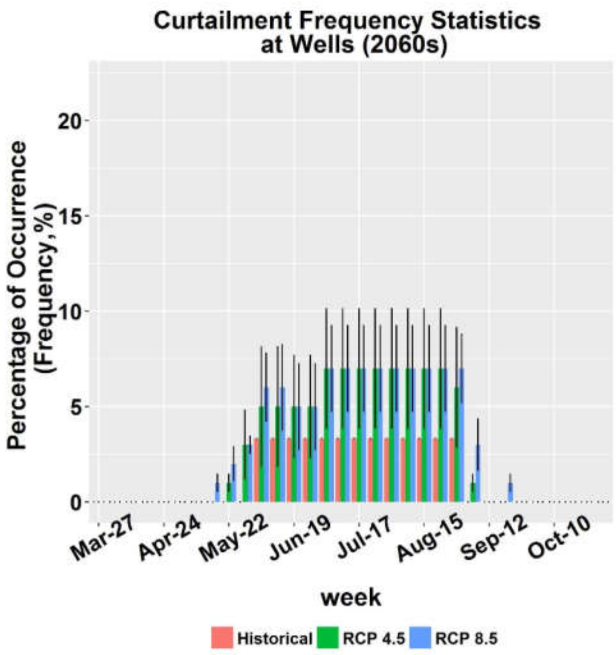
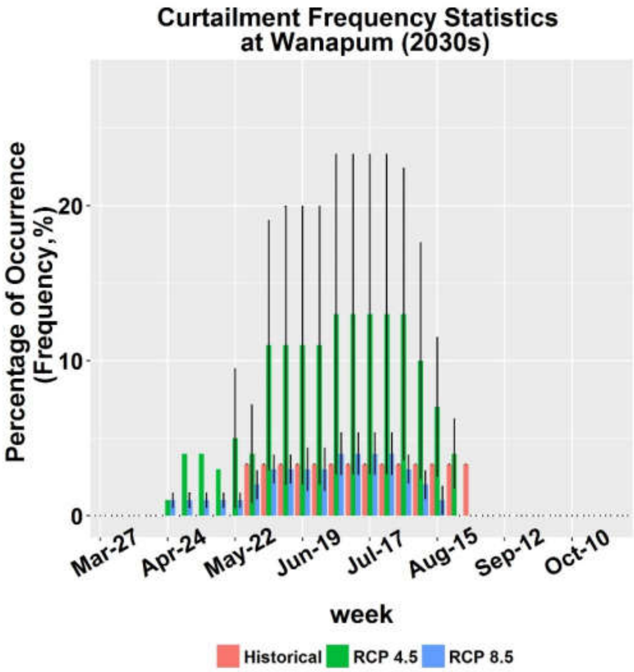


Figure D.2: Percentage of Curtailment Frequency at different dam locations



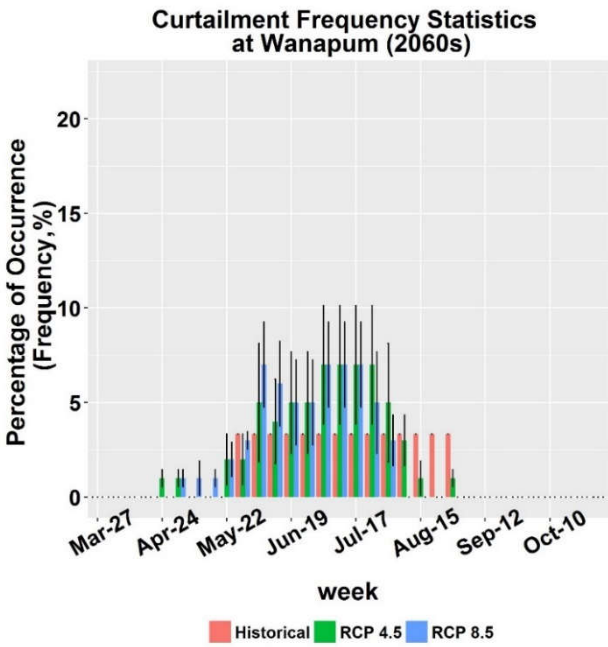
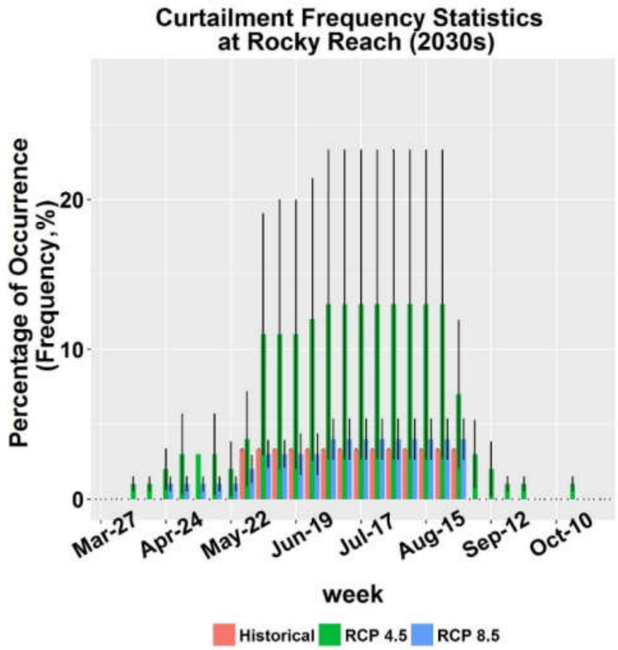


Figure D.3: Percentage of Curtailment Frequency at different dam locations



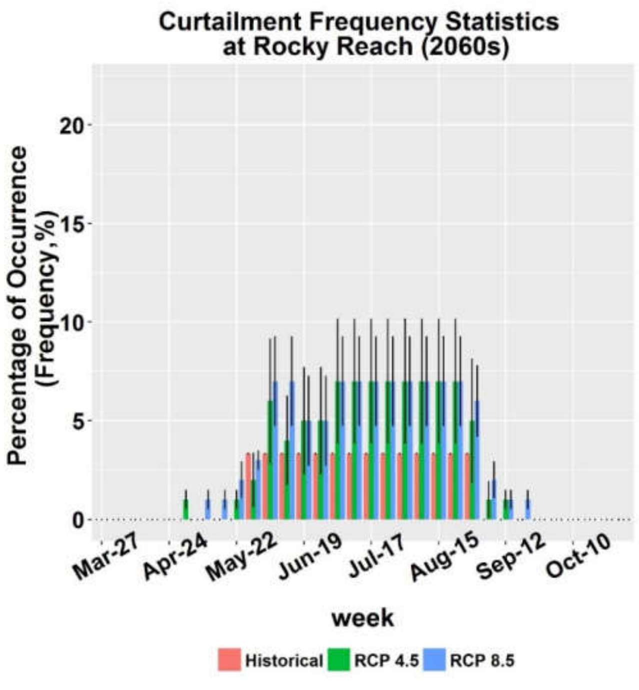


Figure D.4: Percentage of Curtailment Frequency at different dam locations

Appendix – E: Combined impacts of alternative CRT and climate change scenarios on Percentage of Curtailment Frequency

CRT-I:

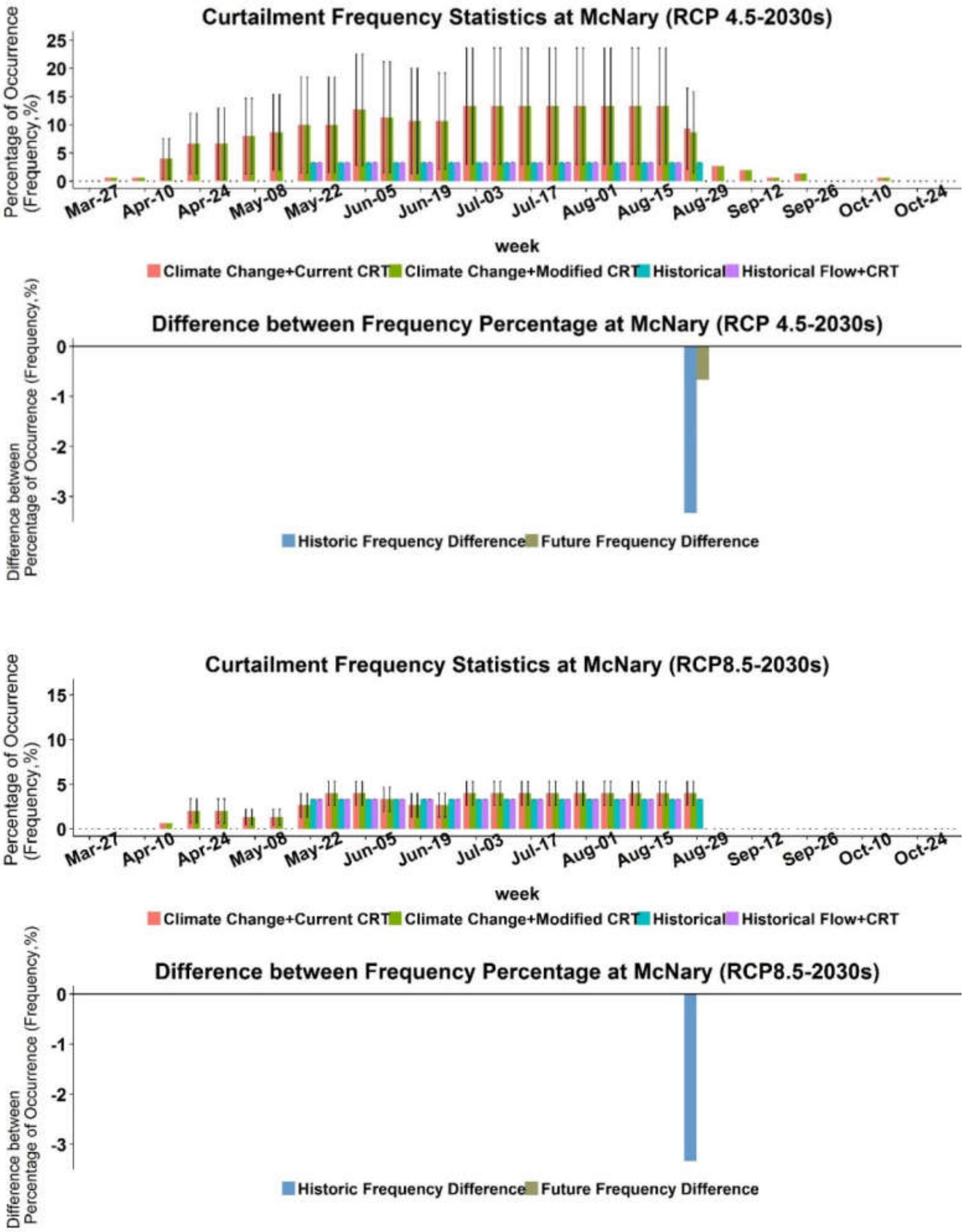


Figure E.1: Percentage of Curtailment Frequency under CRT-I scenario at McNary

CRT-I:

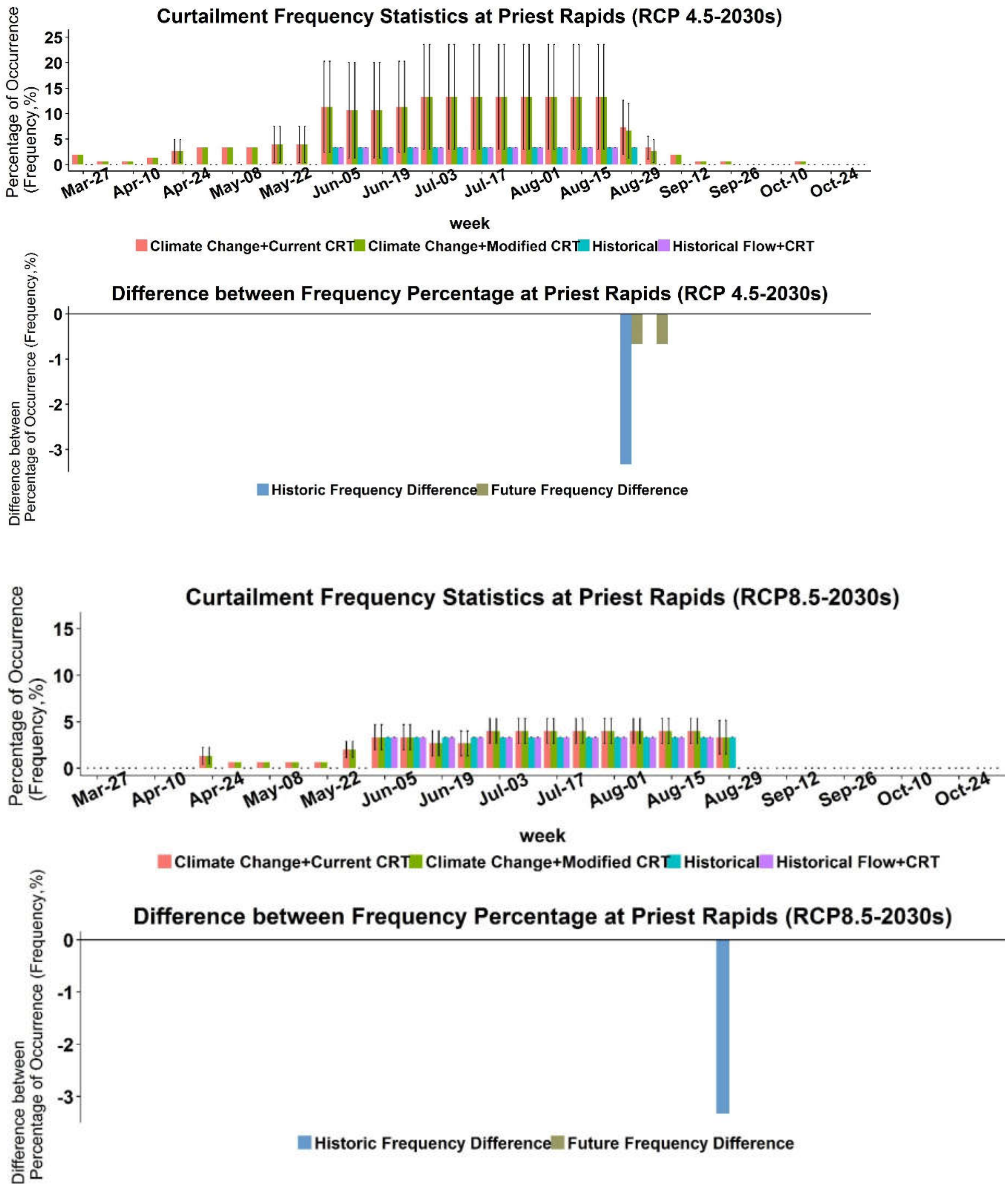


Figure E.2: Percentage of Curtailment Frequency under CRT-I scenario at Priest Rapids

CRT-I:

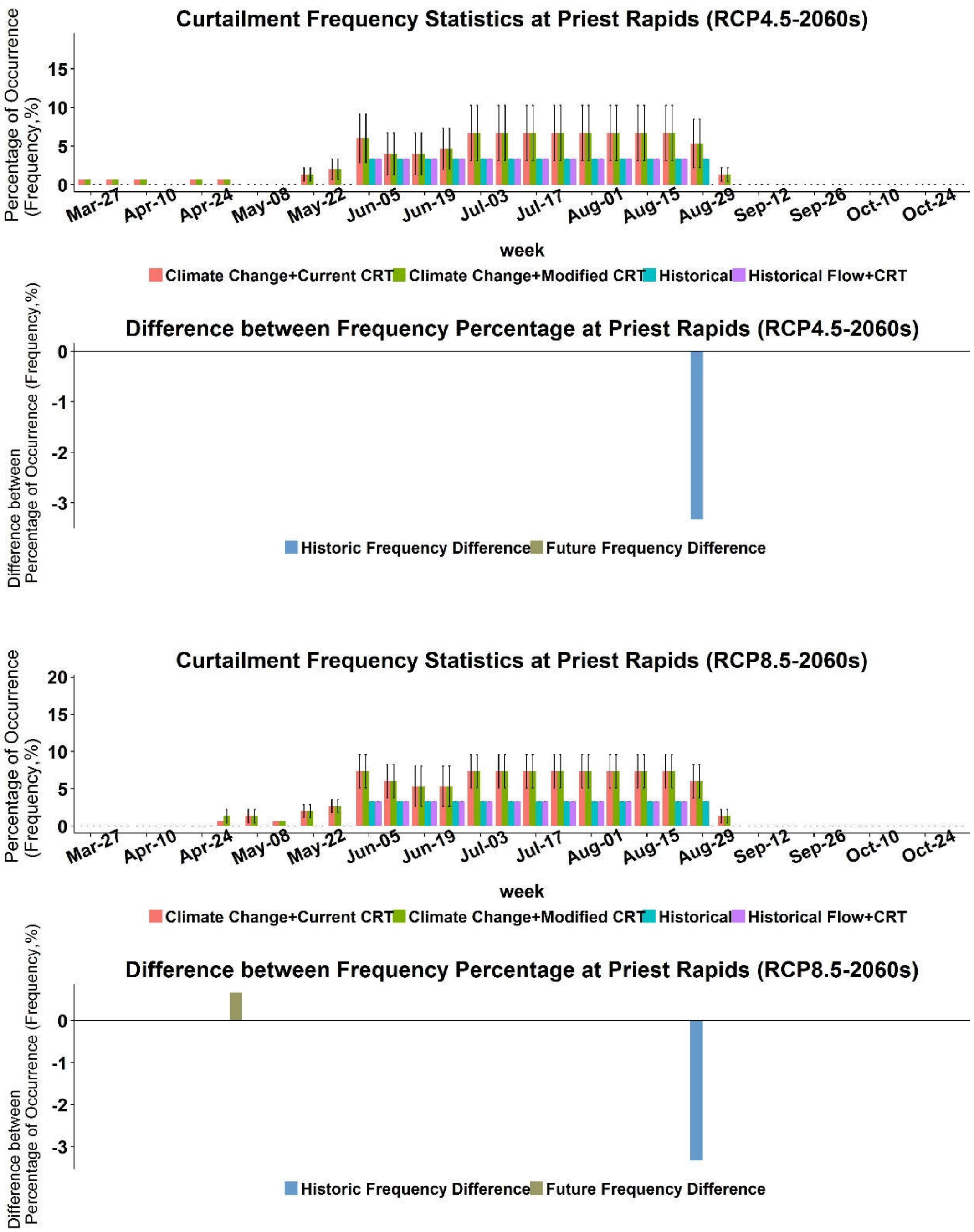


Figure E.3: Percentage of Curtailment Frequency under CRT-I scenario at Priest Rapids

CRT-II Scenarios:

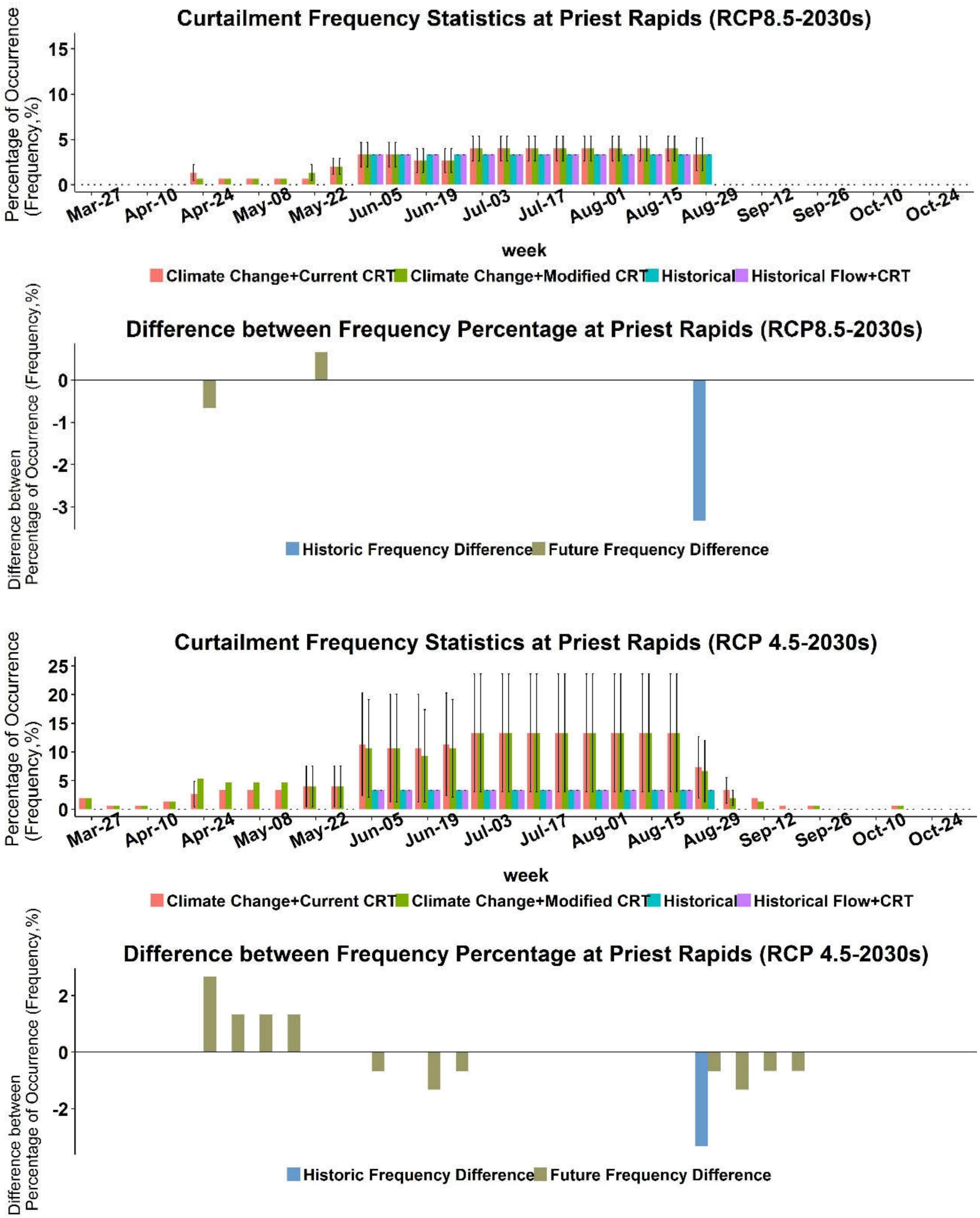


Figure E.4: Percentage of Curtailment Frequency under CRT-II scenario at Priest Rapids

Appendix – F: Monthly Reliability of Hydropower Targets

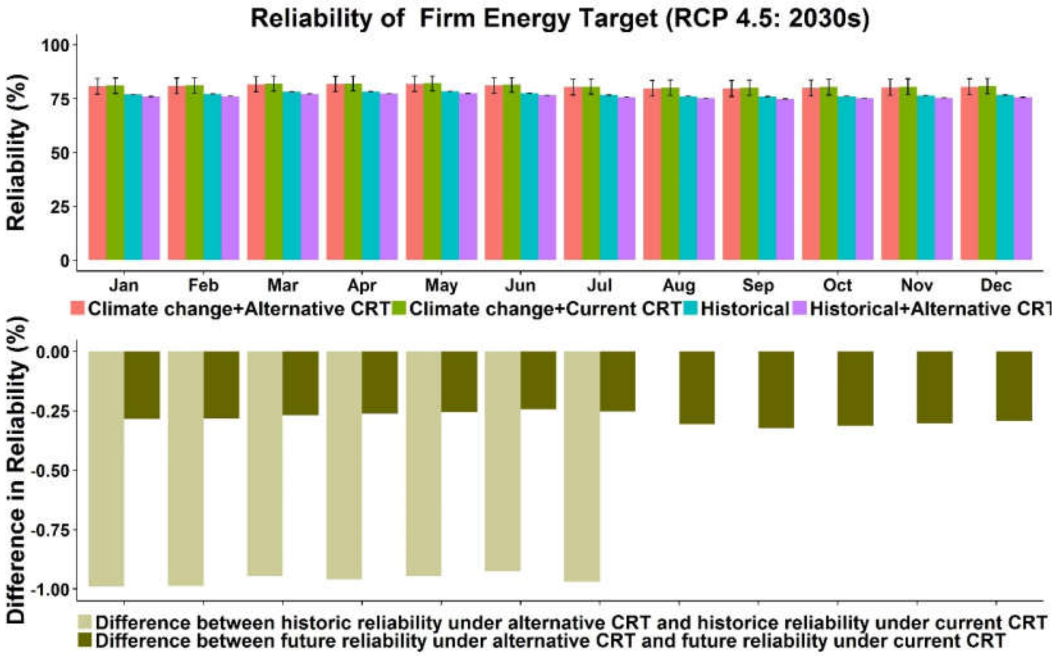


Figure F.1: Reliability of Firm Hydropower Target under CRT-II (RCP 4.5-2030s)

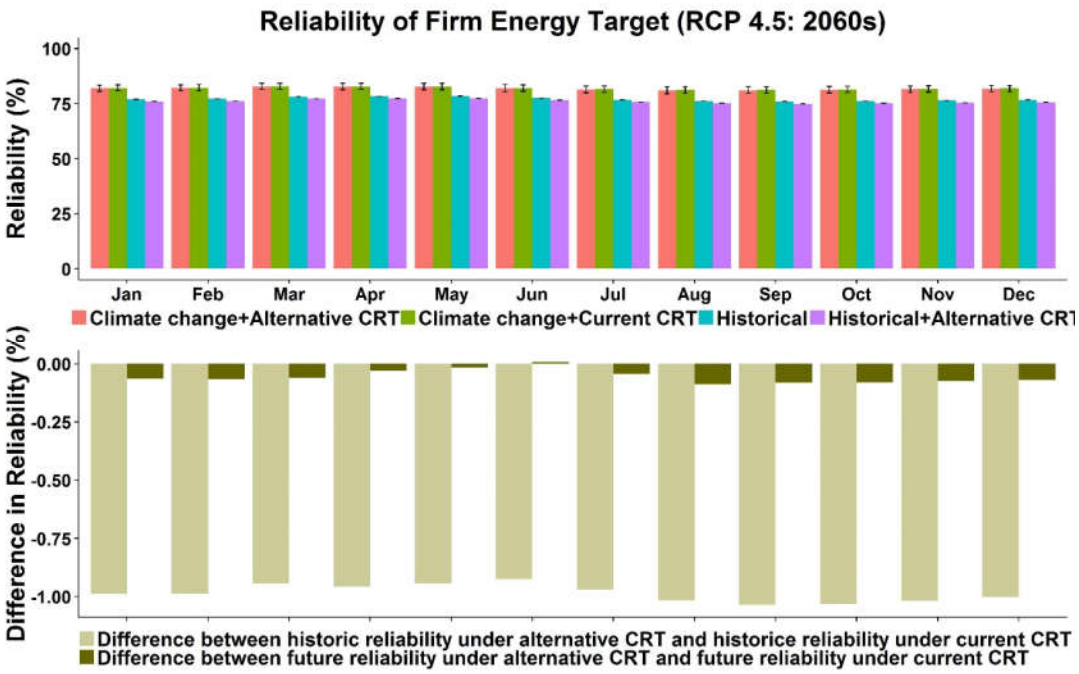


Figure F.2: Reliability of Firm Hydropower Target under CRT-II (RCP 4.5-2060s)

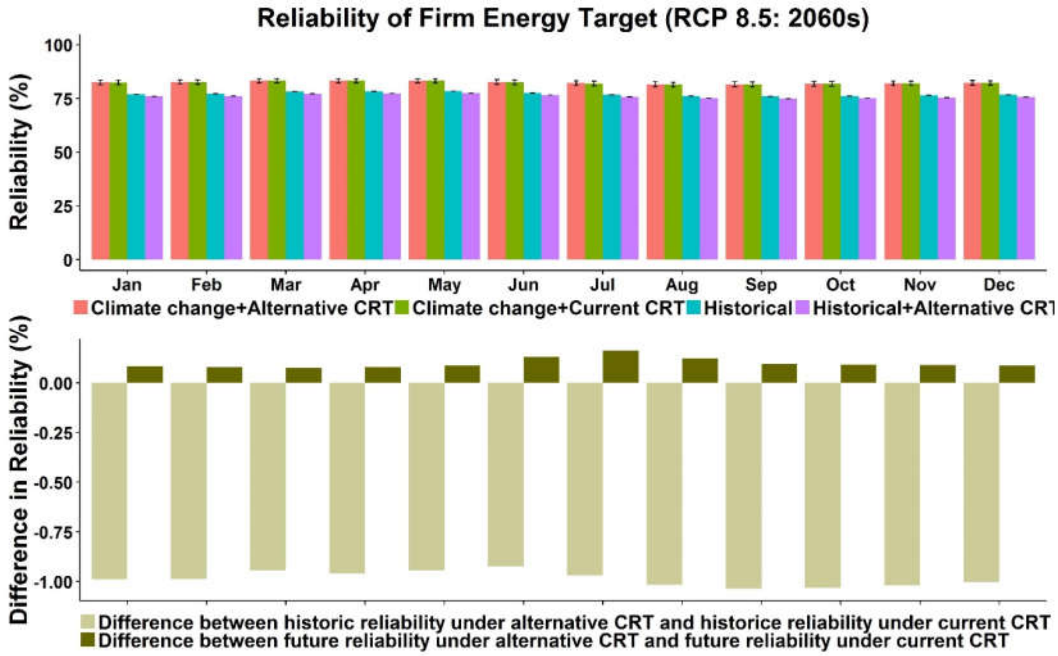


Figure F.3: Reliability of Firm Hydropower Target under CRT-II (RCP 8.5-2060s)

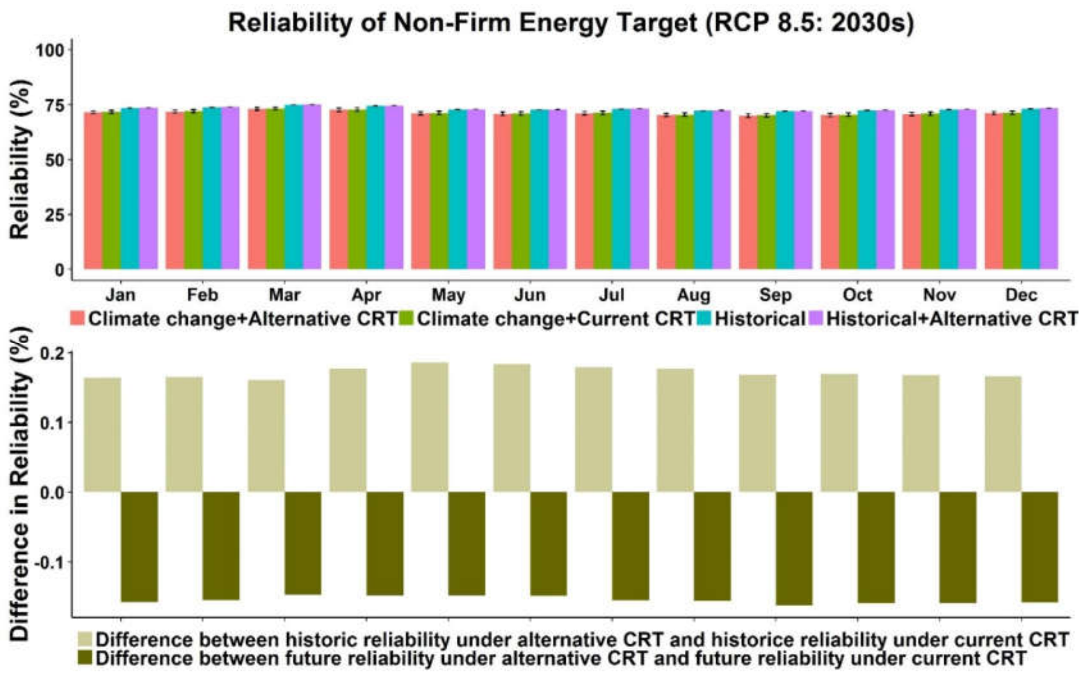


Figure F.4: Reliability of Non-firm Hydropower Target under CRT-I (RCP 8.5-2030s)

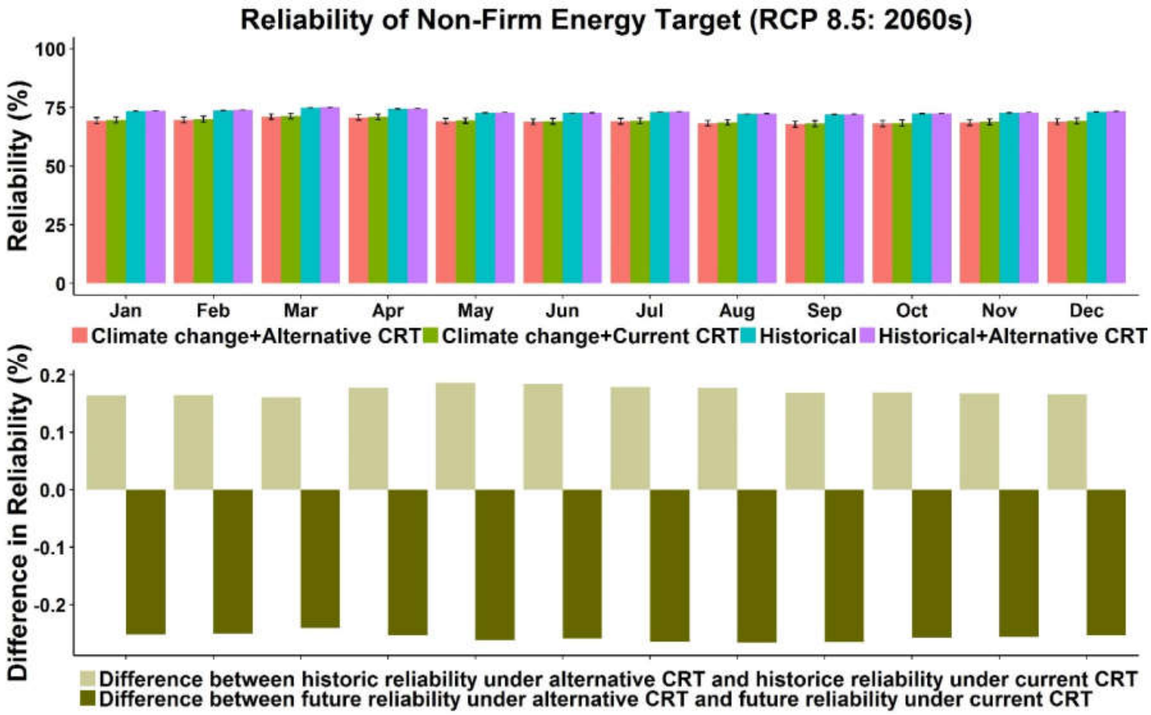


Figure F.5: Reliability of Non-firm Hydropower Target under CRT-I (RCP 8.5-2060s)

Appendix – G: Monthly Reliability of Instream Flow Target

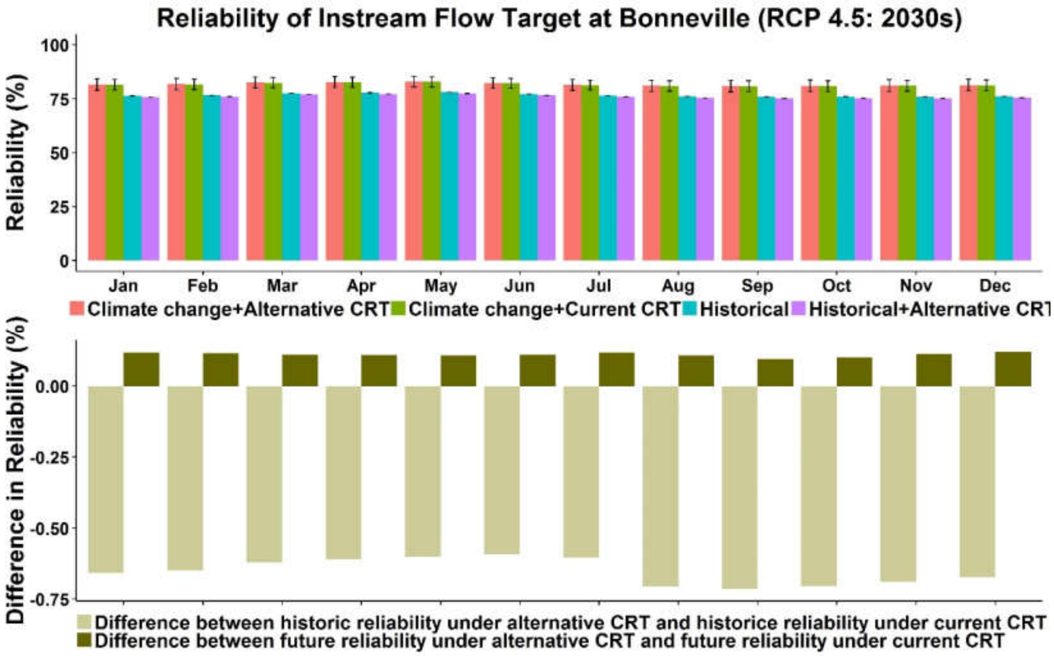


Figure G.1: Reliability of Instream Flow Target at Bonneville under CRT-II (RCP 4.5-2030s)

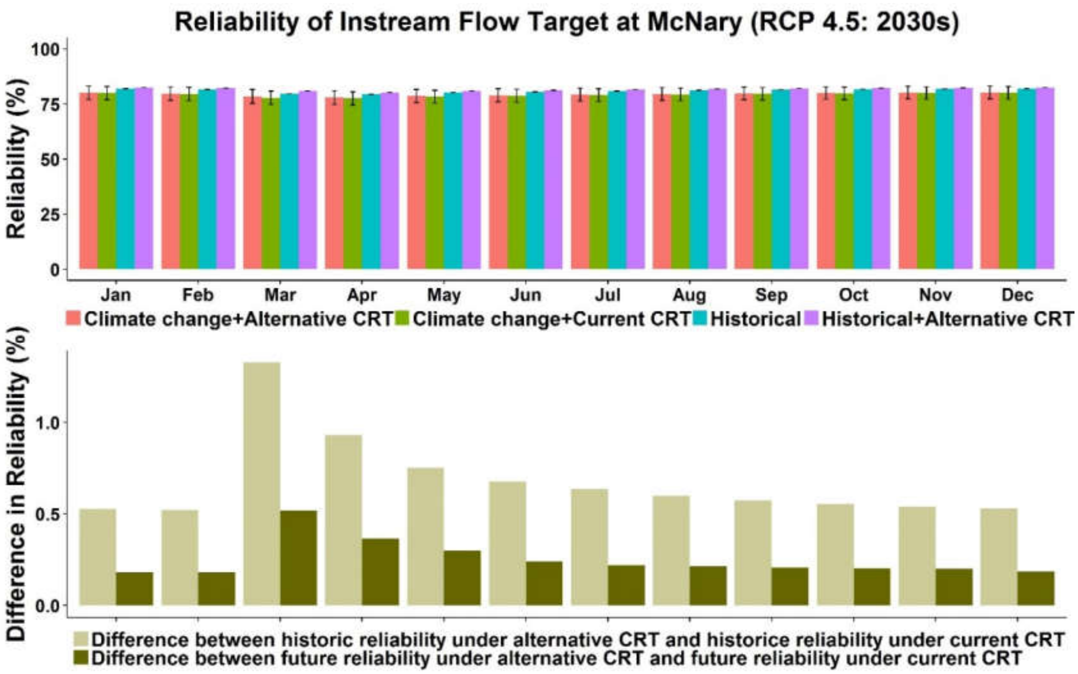


Figure G.2: Reliability of Instream Flow Target at McNary under CRT-II (RCP 4.5-2030s)

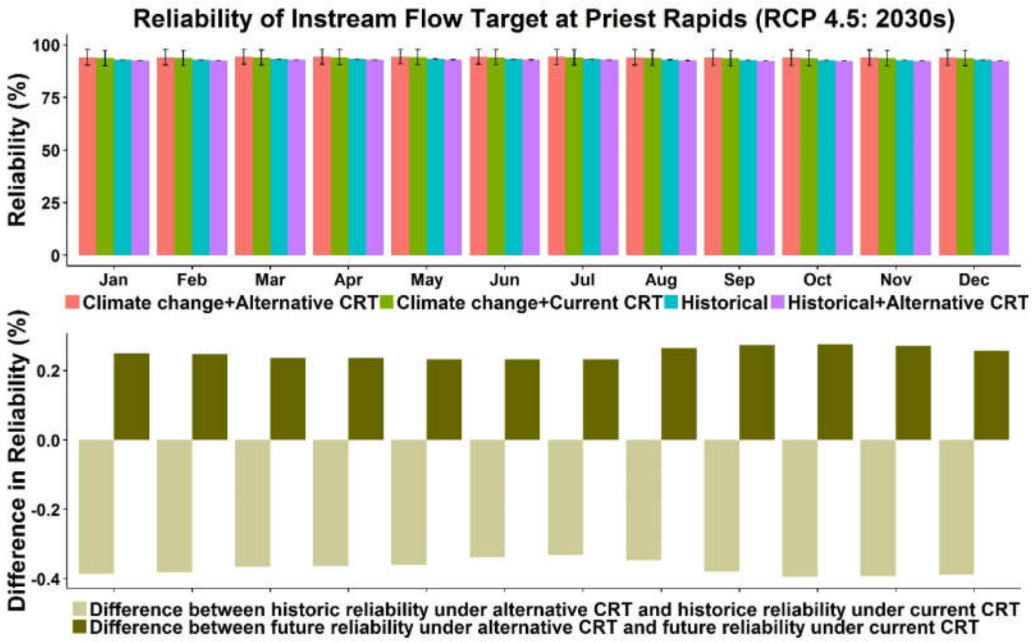


Figure G.3: Reliability of Instream Flow Target at Priest Rapids under CRT-II (RCP 4.5-2030s)

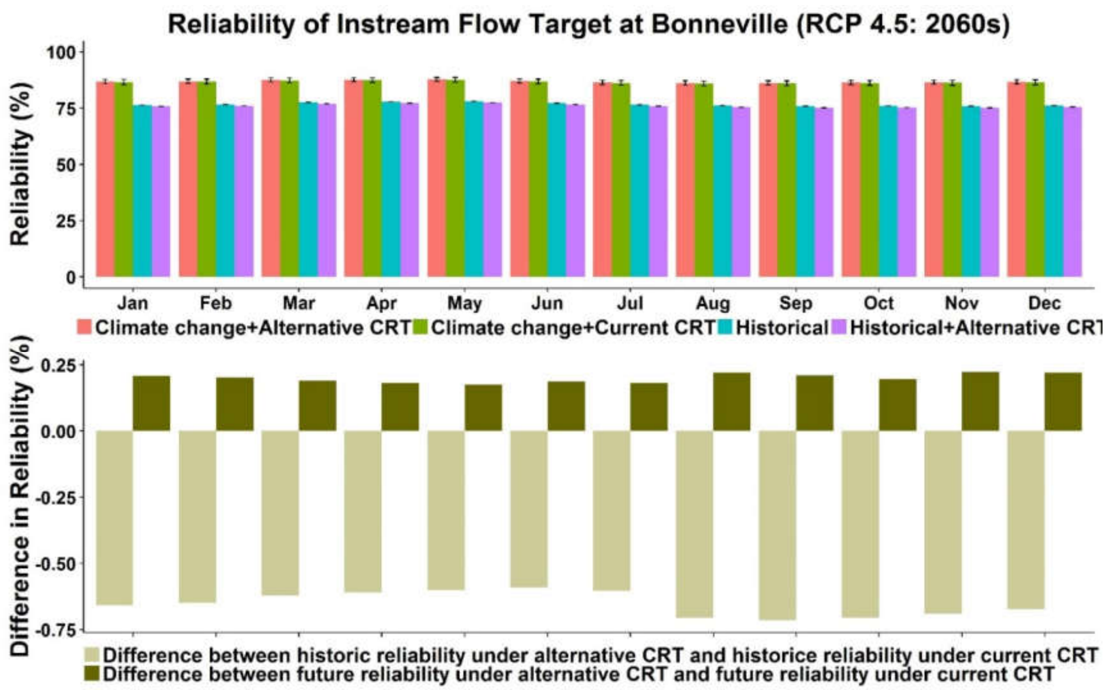


Figure G.4: Reliability of Instream Flow Target at Bonneville under CRT-II (RCP 4.5-2060s)

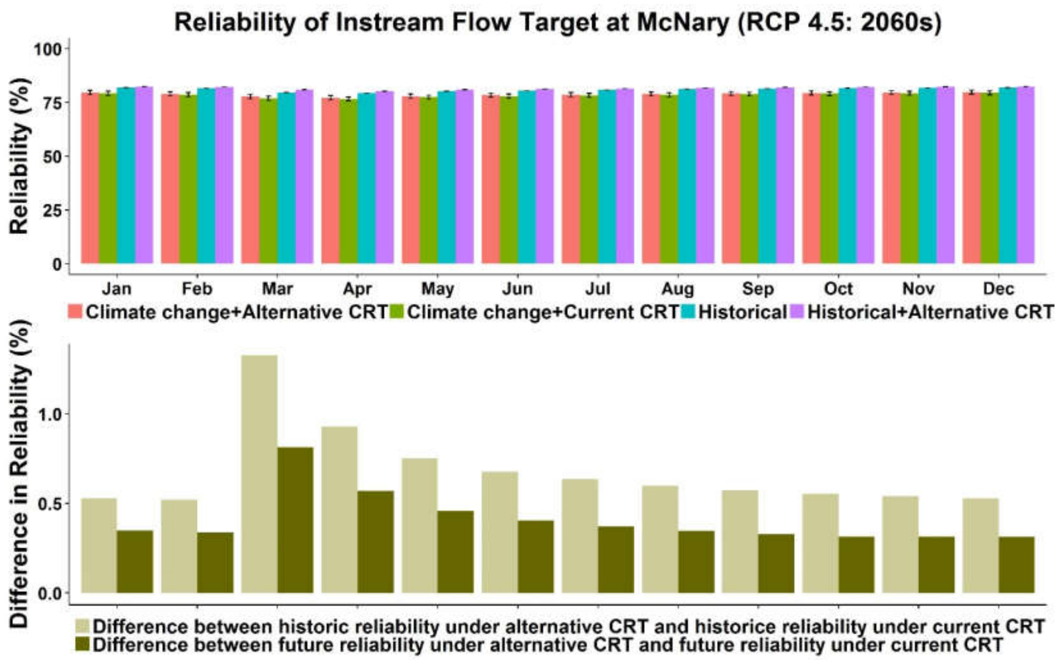


Figure G.5: Reliability of Instream Flow Target at McNary under CRT-II (RCP 4.5-2060s)

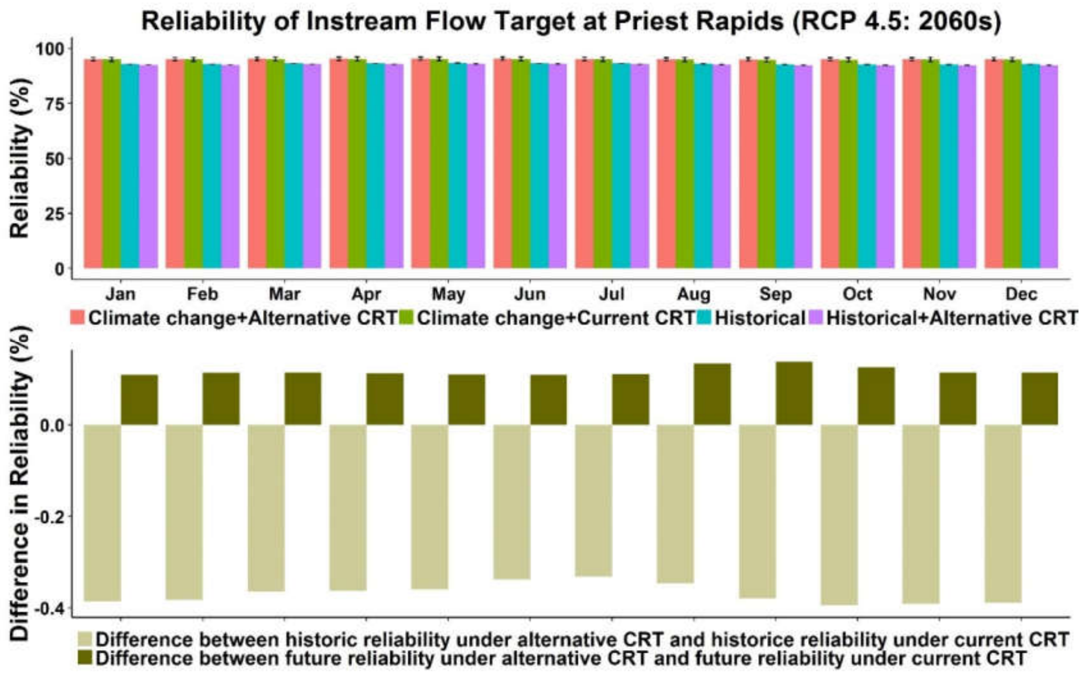


Figure G.6: Reliability of Instream Flow Target at Priest Rapids under CRT-II (RCP 4.5-2060s)

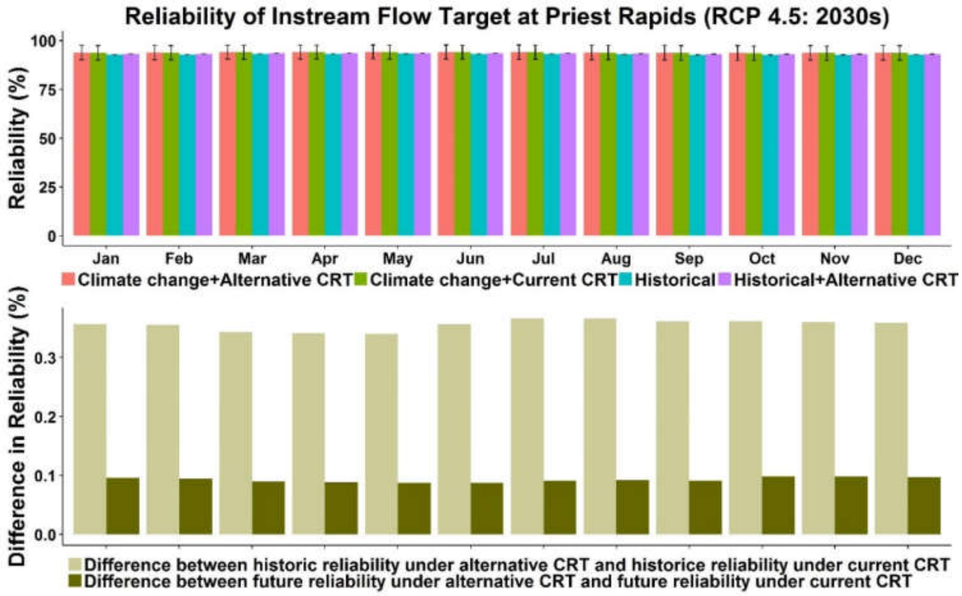


Figure G.7: Reliability of Instream Flow Target at Vernita Bar near Priest Rapids under CRT-I (RCP 4.5-2030s)

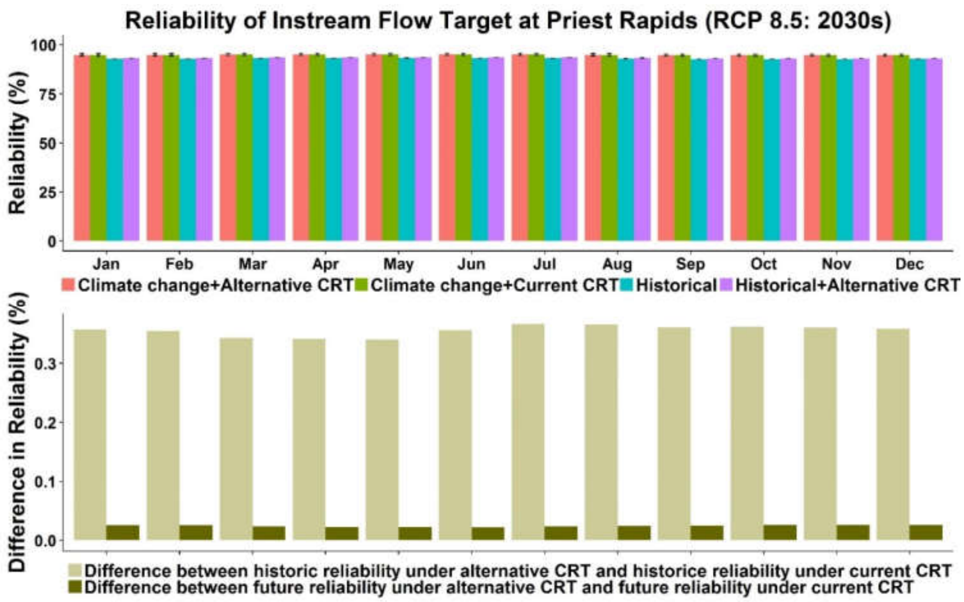


Figure G.8: Reliability of Instream Flow Target at Vernita Bar near Priest Rapids under CRT-I (RCP 8.5-2030s)

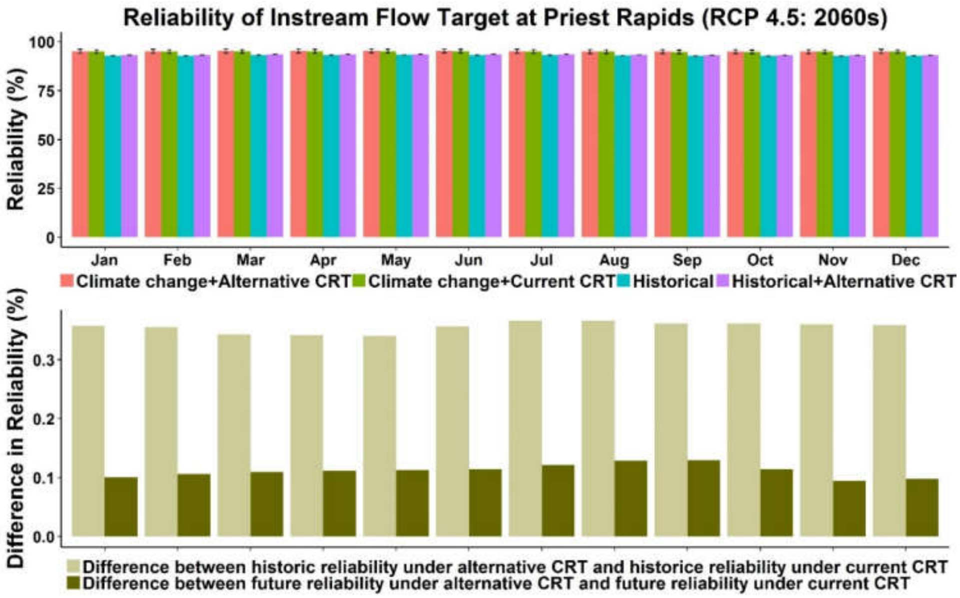


Figure G.9: Reliability of Instream Flow Target at Vernita Bar near Priest Rapids under CRT-I (RCP 4.5-2060s)

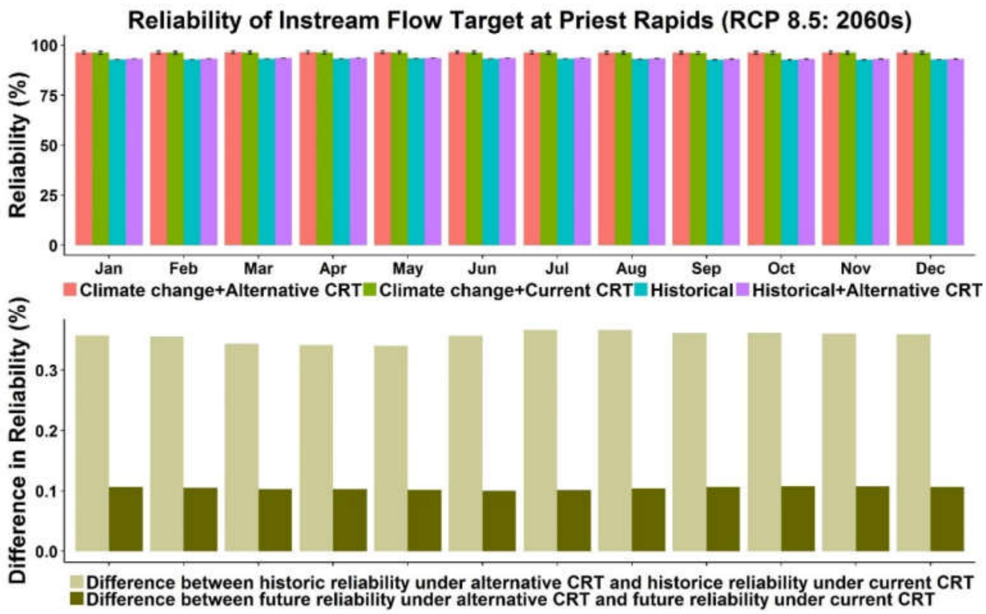


Figure G.10: Reliability of Instream Flow Target at Vernita Bar near Priest Rapids under CRT-I (RCP 8.5-2060s)