

1 **Socio-hydrological modeling of the tradeoff between flood
2 control and hydropower provided by the Columbia
3 River Treaty**

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18 **Abstract.** The Columbia River Treaty (CRT) signed between the United States and
19 Canada in 1961 is known as one of the most successful transboundary water treaties.
20 Under continued cooperation, both countries equitably share collective responsibilities of
21 reservoir operations, and flood control and hydropower benefits from treaty dams. As the
22 balance of benefits is the key factor of cooperation, future cooperation could be
23 challenged by external social and environmental factors which were not originally
24 anticipated, or change in the social preferences of the two actors. To understand the
25 robustness of cooperation dynamics we address two research questions – i) How does
26 social and environmental change influence cooperation dynamics? and ii) How do social
27 preferences influence the probability of cooperation for both actors? We analyzed
28 infrastructural, hydrological, economic, social, and environmental data to inform the
29 development of a socio-hydrological system dynamics model. The model simulates the
30 dynamics of flood control and hydropower benefit sharing as a function of the probability
31 to cooperate, which in turn is affected by the share of benefits. The model is used to
32 evaluate scenarios that represent environmental and institutional change, and changes in
33 political characteristics based on social preferences. Our findings show that stronger
34 institutional capacity ensures equitable sharing of benefits over the long term. Under
35 current CRT, the utility of cooperation is always higher for Canada than non-cooperation
36 which is in contrast to the U.S. The probability to cooperate for each country is lowest
37 when they are self-interested but fluctuates in other social preferences scenarios.

39 **1. Introduction**

40 The Columbia River Treaty (CRT) was signed in 1961 to manage shared waters
41 between the United States and Canada. Under the treaty, both countries share collective
42 responsibilities of reservoir operations, and benefits from flood control and hydropower
43 production from the treaty dams equitably. CRT is known as one of the most successful
44 transboundary water treaties in the world, as evidenced by continued cooperation and
45 equitable benefit sharing (Hyde, 2010). However, since the CRT was established, external
46 social and environmental factors not originally anticipated, such as the degradation of
47 valued fish species, have affected the balance of benefits each country receives
48 (Bowerman et al., 2021; Trebitz and Wulffhorst, 2021). In competition and cooperation,
49 actors' decisions are guided by their or social preferences (also referred to as other-
50 regarding preferences). Actors exhibit social preferences if the actor not only cares about
51 their own material benefit but also cares about the material benefits of other actors (Fehr
52 and Fischbacher, 2002). The perceived fairness of allocated material resources or balance
53 of benefits, in concert with the social preferences of each actor, can significantly affect
54 the stability of cooperation over time (Abraham and Ramachandran, 2021; Hirshleifer,
55 1978; Kertzer and Rathbun, 2015; Rivera-Torres and Gerlak, 2021; Sadoff and Grey,
56 2002; UNESCO, 2021). Understanding these social preferences between the U.S. and
57 Canada helps us to understand the interplay of competition, cooperation or conflict. The
58 U.S. and Canada are currently renegotiating the CRT beyond 2024 with the aim of
59 maintaining cooperation in a changing environment. This ongoing renegotiation
60 motivates and raises two research questions, (1) How does social and environmental
61 change influence cooperation dynamics? and (2) How do social preferences influence the
62 probability of cooperation for both actors?

63
64 Globally, 276 transboundary river basins cover almost half of the Earth's land
65 surface and are the source of 60% of freshwater supplies (UN-Water, 2015; United
66 Nations, n.d.). Transboundary water management compounds the challenges of managing
67 water between competing users because the river is managed between different
68 jurisdictions and under different policy structures (Bernauer and Böhmelt, 2020).
69 Successful management of these river basins depends not only on understanding the
70 hydrology but also consideration of social comparison, economic needs, and political
71 dynamics of the upstream and downstream riparian states (Gain et al., 2021; Gober and
72 Wheater, 2014). Development in transboundary river basins can result in conflict or

73 cooperation (Bernauer and Böhmelt, 2020). For example, the construction of dams
74 upstream in the Lancang-Mekong River Basin has affected the environmental conditions
75 and livelihood opportunities of downstream countries (Lu et al., 2021). Social factors that
76 can explain cooperation and conflict dynamics include asymmetric access to water
77 resources due to upstream-downstream locations, and varying levels of dependence on
78 different uses of the river (Warner and Zawahri, 2012). Transboundary rivers are
79 managed by multiple heterogeneous stakeholders with different sovereignty, governance
80 structures and economic conditions; while diverse, basin populations may be
81 interdependent not just hydrologically but also economically and socially (FAO, n.d.;
82 Rawlins, 2019). Further, the ability to sustain cooperation can be critically affected by
83 how benefits (e.g., water supply, hydropower) and risks (e.g., floods, droughts) are shared
84 under changing conditions (Wolf, 2007; Zeitoun et al., 2013). The Nile River Basin is an
85 example of inequitable benefit sharing where Egypt and Sudan hold absolute rights to
86 use, motivating conflict and international deliberation (Kameri-Mbote, 2007; Wiebe,
87 2001).

88

89 The history of transboundary river basins shows the challenges of cooperation in
90 transboundary river basins when benefits and risks are distributed inequitably. If no
91 agreements are in place to govern the sharing of benefits and risks, they may be
92 distributed according to existing levels of political or economic power or following
93 geographic advantages (Dombrowsky, 2009). Further, these imbalances in power can
94 decrease the likelihood of successfully negotiating such an agreement (Espey and
95 Towfique, 2004; Song and Whittington, 2004). When riparian actors cooperate, they can
96 achieve a wide variety of benefits, including: (1) benefits to the river; (2) benefits from
97 the river; (3) the reduction of costs because of the river; and (4) benefits beyond the river
98 (Sadoff and Grey, 2002, 2005). Examples of these benefits include flood and drought
99 mitigation, improved environmental conditions, and economic benefits from hydropower
100 or agriculture (Qaddumi, 2008).

101

102 In the case of the Columbia River, the upstream actor (Canada) operates its dams
103 in a way that provides a greater benefit to the downstream actor (the U.S.) in the form of
104 flood protection because the benefit sharing provision of the CRT ensures that Canada
105 receives a share of those benefits in return. The U.S. operates its dams to maximize
106 hydropower production and, in exchange, compensates Canada for half of the estimated

107 increase in hydropower benefit generated by the Treaty, which provides an economic
108 incentive to cooperate. This is consistent with the theory that countries tend to cooperate
109 when the net economic and political benefits of cooperation are greater than the benefits
110 from unilateral action, and when the generated benefits are shared in a way that is
111 perceived to be “fair” by both parties (Grey et al., 2016; Jägerskog et al., 2009; Qaddumi,
112 2008). The CRT was established on these grounds, as both actors agreed that the greatest
113 benefit of the Columbia River could be secured through cooperative management (BC
114 Ministry of Energy and Mines, 2013; Yu, 2008). This agreement focuses on the equitable
115 sharing of benefits created from cooperation, rather than on water allocation itself, which
116 is a key provision of some of the world’s most successful water agreements (Giordano
117 and Wolf, 2003). The interplay of cooperation and conflict between actors can be better
118 understood by considering the actors’ social preferences (Fehr and Fischbacher, 2002;
119 Kertzer and Rathbun, 2015). Behavioral economics states that decision makers have
120 social preferences and that the cooperating actors care about gain not only for themselves
121 but also for others (Kertzer and Rathbun, 2015). In general, social preferences can be
122 classified into four types – inequity aversion, social welfare, selfishness, and
123 competitiveness (Charness and Rabin, 2002). Inequity aversion is defined as actor
124 preferring fairness, and when benefits are evenly distributed among all group members
125 (Fehr and Schmidt, 1999). It is now widely accepted that humans have a strong social
126 preference for inequity aversion at both individual and organizational level, and that this
127 type of social preference is often a key to why cooperation emerges and is sustained
128 among unrelated individuals (Choshen-Hillel and Yaniv, 2011; Kertzer and Rathbun,
129 2015). Social welfare refers to actors sacrificing from their own gains to enhance the
130 payoffs for all group members, especially for recipients with disadvantages (Charness
131 and Rabin, 2002). Selfishness describes a scenario where actors only care about their own
132 benefits, but do not care about the payoff others receive. Finally, competitiveness assumes
133 that actors prefer higher payoffs than others. Understanding the social preferences
134 between actors (here the U.S. and Canada), could suggest how their cooperation behavior
135 may change, impacting the robustness of CRT.

136

137 Traditional water resource management assumes values and preferences to be
138 exogenous to the water resources systems, but values and preferences can co-evolve with
139 natural systems (Caldas et al., 2015; Sivapalan and Blöschl, 2015). Socio-hydrology, the
140 study of coupled human-water systems, fills this need by providing tools to represent

141 dynamic feedback between the hydrological and social systems (Sivapalan et al., 2012;
142 Troy et al., 2015). Socio-hydrological studies have explored a variety of emergent
143 phenomena that result from such feedback, including the levee effect, the irrigation
144 efficiency paradox, and the pendulum swing between human and environmental water
145 uses (Khan et al., 2017). In the study of transboundary rivers, socio-hydrology allows for
146 the explicit inclusion of changing values or preferences, and enabling assessment of
147 cooperation and conflict as values and preferences shift (Sivapalan and Blöschl, 2015).
148 Thus, we develop a socio-hydrological system dynamics model motivated by the
149 experience of the Columbia River to answer the research questions defined above. This
150 research builds upon the work of Lu et al. (2021), where the authors applied socio-
151 hydrological modeling to the case of the transboundary Lancang-Mekong River, by
152 assessing how preferences and attitudes toward cooperation affect their probability of
153 adhering to the agreement. The objective of this study is to quantify the balance of
154 benefits under cooperative reservoir operations to assess the impact of changing social
155 and environmental conditions as well as shifts in the social preferences of the U.S. and
156 Canada. While the study does not aim to provide specific recommendations for treaty re-
157 negotiations, it explores the role that changes in environmental priorities play in
158 cooperation and presents scenarios to inform future renegotiations of the CRT.

159

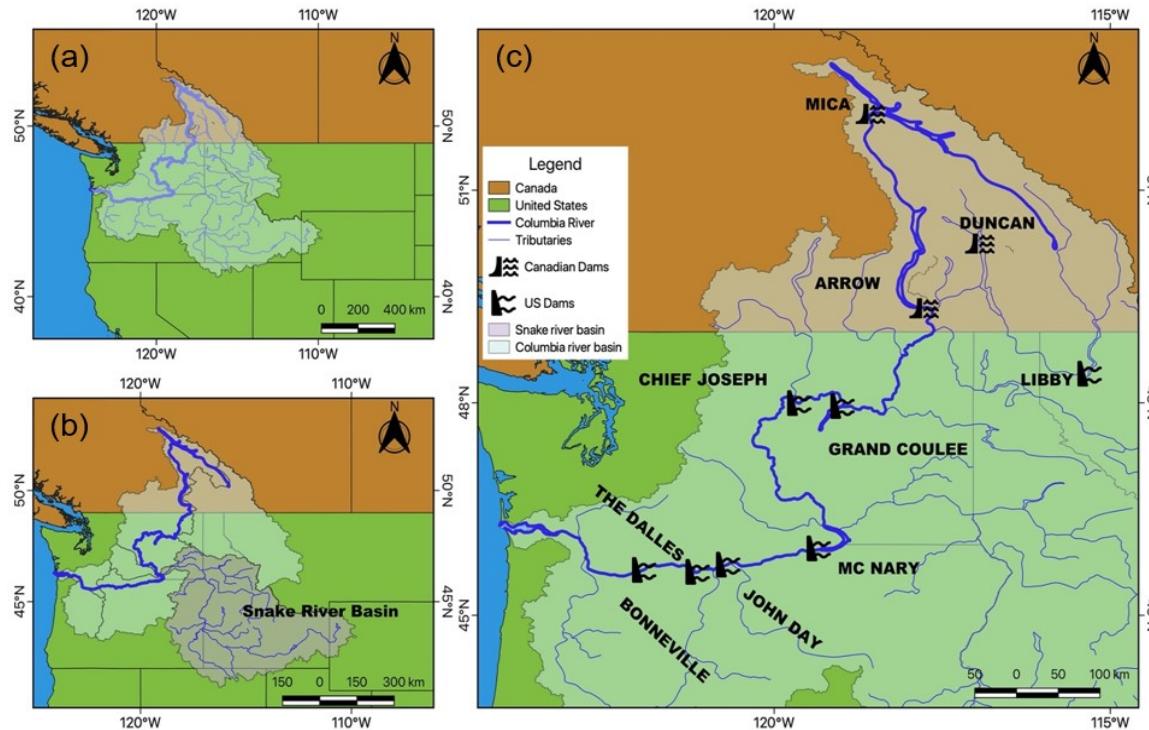
160 This article is organized as follows. Sect. 2 provides a general background of the
161 Columbia River system and treaty dams. Sect. 3 discusses the conceptualization and
162 formulation of the socio-hydrological model. Four scenarios based on environmental and
163 institutional change, and four scenarios based on behavioral economics using social
164 preferences are presented here. Sect. 4 explains the model testing and scenario analysis.
165 Sect. 5 discusses the findings of this study, draws out major conclusions gained through
166 this study and identifies remaining questions for future research.

167

168 **2. Columbia River system and treaty dams**

169 The Columbia River as depicted in Fig. 1, with its headwaters located in the
170 mountains of British Columbia, has a basin that extends 670,807 km² into seven U.S.
171 states – Washington, Oregon, Idaho, Montana, Nevada, Utah, and Wyoming – before
172 reaching the Pacific Ocean in Oregon (Cosen, 2012). Figure 1 also shows the location
173 of the treaty dams along the Columbia River. While only 15% of the river’s length flows
174 through Canada, 38% of the average annual flow originates there (Cosen, 2012). By

175 volume it is the fourth largest river in North America producing 40% of all the U.S.
176 hydropower, and millions of people in the Pacific Northwest (including 8 million people
177 in Columbia Basin (Lower Columbia Estuary Partnership, n.d.)) rely on the river for
178 hydropower, fishing, irrigation, recreation, navigation, and other environmental services
179 (White et al., 2021).



180
181 **Figure 1.** Map showing (a) the Columbia River Basin across Canada and the U.S., (b)
182 the Snake River Basin and its tributaries within the Columbia River Basin, and (c)
183 location of treaty dams along Canada and the U.S. which are also included in the socio-
184 hydrological system dynamics model
185

186 Hydropower development started in the Pacific Northwest in 1933 and expanded
187 after the CRT was established. Between 1938 and 1972, eleven dams were built on the
188 U.S. portion of the Columbia River, which generate over 20,000 megawatts of power (BC
189 Ministry of Energy and Mines, 2013). In total, there are 31 federal dams in the Columbia
190 River Basin that are owned and operated by the U.S. Army Corps of Engineers (USACE)
191 and the U.S. Bureau of Reclamation, which produce around 40 percent of electricity for
192 the Pacific Northwest (Bonneville Power Administration, 2001; Northwest Power and
193 Conservation Council, 2020c, 2020d; Stern, 2018). Dams along the Canadian side of the
194 Columbia River produce around half of the province's hydropower generation
195 (Government of British Columbia, 2019). Figure 1c shows the locations of major CRT

196 dams considered in the system dynamics model. The reservoir capacity of Canadian treaty
 197 dams is 36,810 million m³ of which 28,387 million m³ is allocated for flood protection in
 198 the U.S. and the capacity of the U.S. treaty dams is 11,577 million m³. Grand Coulee is
 199 the largest and furthest upstream dam on the U.S. side. Thus, inflow to the Grand Coulee
 200 includes the outflow from the Canadian dams and external tributaries that intersect with
 201 the river. Flooding had been the major concern in the downstream portion of the Columbia
 202 River. For example, the flood in Vanport, Oregon, in 1948 motivated the construction of
 203 additional storage dams along the river (Sopinka and Pitt, 2014). This flood was the
 204 impetus for the U.S. to seek cooperation with Canada because it was not possible to build
 205 sufficient storage along the downstream portion of the river to protect from large floods.
 206 The summary of dams along the Columbia River is given in Table 1.

207

208 **Table 1.** List of dams represented by the model. Projects that do not present Usable
 209 Storage Capacity are run-off-the-river dams. Treaty Storage Commitment refers to the
 210 room available to accommodate glacier waters under the CRT.

Project	Reservoir formed	Country	Total Storage capacity (km ³)	Usable Storage capacity (km ³)	Treaty Storage Commitment (km ³)	HP Capacity (MW)	Year of Completion
Mica Dam	Kimbasket Lake	Canada	24.7	14.8	8.6	1,736	1973
Duncan Dam	Duncan Lake	Canada	1.77	1.73	1.73	-	1967
Keenleyside Dam	Arrow lake	Canada	10.3	8.76	8.8	185	1968
Grand Coulee	Franklin D. Roosevelt Lake	The USA	11.6	6.4	-	6,809	1941
Chief Joseph	Rufus Woods Lake	The USA	0.6	-	-	2,069	1955
McNary	Lake Wallula	The USA	0.23	-	-	980	1994
John Day	Lake Umatilla	The USA	0.54	-	-	2,160	1971
The Dalles	Lake Celilo	The USA	0.41	-	-	2,100	1957
Bonneville	Lake Bonneville	The USA	0.66	-	-	660	1938

211

212 The original agreement during 1960s prioritized flood control and hydropower, but
 213 emerging social and environmental concerns have shifted the way that reservoirs are
 214 operated within the Columbia River Basin. Dam construction altered the hydrology
 215 significantly by moderating the strong seasonal flow variability, impacting ecosystem

216 health. For example, changes to salmon spawning habitat, elevating smolt and adult
217 migration mortality and leading to declines in the salmon population (Kareiva et al.,
218 2000; Karpouzoglou et al., 2019; Natural Resource Council, 1996; Northwest Power
219 Planning Council, 1986; Williams et al., 2005). After the 1970s, mounting social
220 pressure to protect the aquatic environment resulted in changes in dam operations that
221 shifted the economic benefits that the countries receive from cooperation (Bonneville
222 Power Administration, 2013; Leonard et al., 2015; Northwest Power and Conservation
223 Council, 2020b, 2020a). This increased prioritization of ecosystem health is also seen in
224 other transboundary river basins (Giordano et al., 2014). With changing priorities and
225 operations affecting both actors' share of benefits, incentives to cooperate are shifting.
226

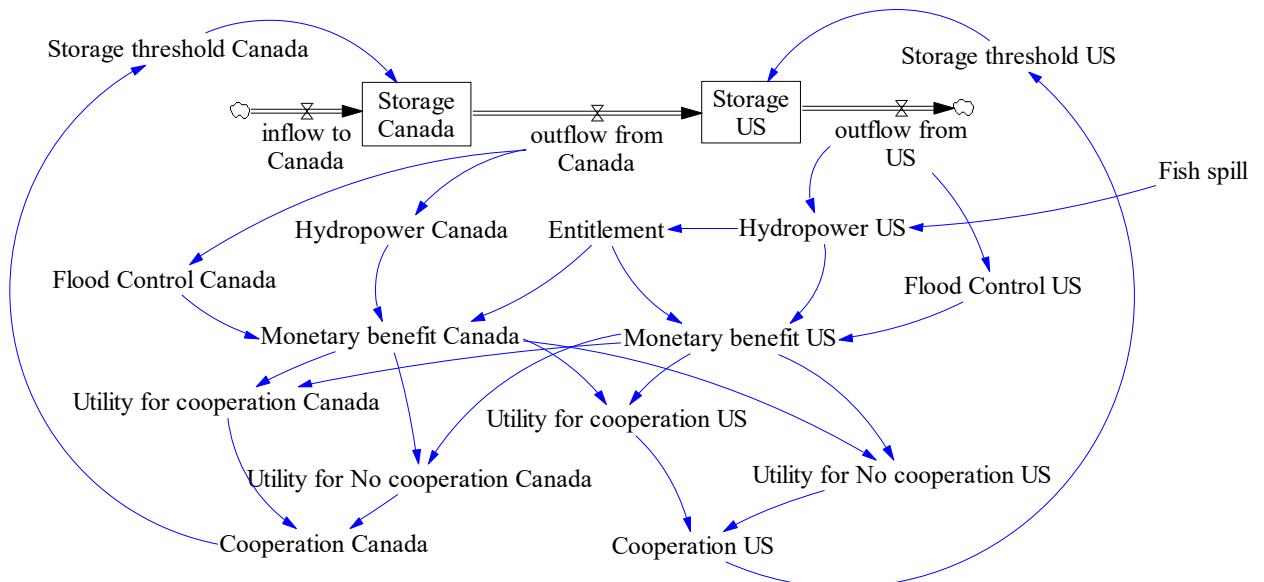
227 **3. Methodology**

228 In this section we present the conceptual model of Columbia River system under
229 CRT, the formulation of a system dynamics model, model calibration and validation, and
230 scenario analysis. To incorporate the transboundary dynamics and feedback between the
231 hydrological and social systems, we simplify the representation of the hydrology and
232 reservoir operations by aggregating the CRT treaty dams for Canada and the U.S. To
233 understand the long-term dynamics of cooperation and robustness of the cooperation
234 under change, four scenarios based on plausible cases of environmental and institutional
235 change, and four scenarios based on social preferences were developed and tested as
236 discussed below.

237

238 **3.1 Socio-hydrological system dynamics model**

239 The overview of the modeling framework is illustrated with a causal loop (CL) diagram
 240 in Fig. 2.



241
 242
 243 **Figure 2.** The causal loop diagram presents the hydrological and cooperation feedbacks
 244 between the upstream and downstream countries
 245

246 The storage capacity of Canada (upstream) and the U.S. (downstream) are two
 247 important state variables which represent the aggregated storage of the treaty dams (Fig.
 248 2). Three Canadian dams namely Mica, Duncan and Keenleyside are lumped into a single
 249 storage as all three dams are multifunctional for flood control and hydropower
 250 production. In the U.S., the Grand Coulee dam is the only multifunctional dam with
 251 useable storage for flood control. These dams along the Columbia River either have
 252 significant flood control capacity or significant hydropower production capacity (Table
 253 1). Other hydrological components in the model (i.e., flows in the CL diagram) are inflow
 254 into Canadian storage, outflow from Canadian storage plus intermediate tributaries,
 255 inflow into U.S. storage, and outflow from U.S. storage. The outflow of each country's
 256 storage is used to calculate flood control and hydropower production for each country,
 257 which is converted into monetary units as shown in the CL diagram (Fig. 2). The U.S.
 258 provides additional benefits to Canada through the Canadian Entitlement, a payment
 259 equal to half of the expected additional hydropower generated due to cooperative
 260 management of the CRT dams. Thus, the simplified reservoir operation described below

261 in Sect. 3.2.1 was implemented in the lumped storages on each side of the border, which
262 represent collective operation of all the treaty dams within each country.

263
264 The basis of the model is that each country has responsibility over operating its
265 own dams. Under the cooperative regime both countries operate their dams to fulfill the
266 requirements of the CRT. This means that Canada operates to maximize flood control
267 while the U.S. operates to maximize hydropower, and the benefits are shared between
268 both countries. As discussed in the literature (BC Ministry of Energy and Mines, 2013;
269 Giordano and Wolf, 2003; Grey et al., 2016; Jägerskog et al., 2009; Qaddumi, 2008; Yu,
270 2008), countries are expected to continue cooperating if they perceive the benefits to be
271 shared equitably. On the other hand, under the non-cooperative regime, the balance of
272 benefits is not perceived to be equitable; thus, the countries would operate their reservoirs
273 for their own benefit. Reservoir operation to maximize flood control and to maximize
274 hydropower production are in opposition for Canada and the U.S. This is because
275 operation for maximizing flood control requires drawdown of reservoir storage to provide
276 space for incoming high flows, while operation for maximizing hydropower production
277 requires reservoir storage to be maintained at higher levels to achieve the highest
278 hydraulic head possible. In a non-cooperative regime, Canada would likely switch
279 operations to maximize hydropower production while the U.S. would have to decrease
280 storage or water level to provide flood control, at the detriment of U.S. hydropower
281 production.

282
283 ***3.2 Equations and parameters***

284 Equations describing the links between stocks and flow variables as shown in the
285 CL diagram (Fig. 2) are categorized into reservoir operation, cooperation dynamics,
286 economic benefits, and environmental spills. These equations mathematically describe
287 hydrological processes, as well as feedback from social and economic variables. The
288 following sections describe the formulation of equations for each part of the system in
289 greater detail. The inflow, outflow, water level and storage data are presented in Fig. S2–
290 S10, supplemental material (SI 1).

291
292 ***3.2.1 Reservoir operation***

293 The monthly change in Canadian and the U.S. storage ($\text{m}^3 \text{ month}^{-1}$) as the function
294 of inflow and outflow is given in Eq. (1) and (2).

$$\frac{dS_{CA}}{dt} = Q_{i_{CA}} - Q_{o_{CA}} \quad (1)$$

$$\frac{dS_{US}}{dt} = Q_{i_{US}} - Q_{o_{US}} \quad (2)$$

295 The Canadian inflow ($Q_{i_{CA}}$) corresponds to the streamflow observed upstream of Mica
 296 and Duncan dams and the difference between Mica outflow and Arrow inflow (i.e. flow
 297 from intermediate tributaries). The data was retrieved from the Bonneville Power
 298 Administration (Bonneville Power Administration, 2020). The U.S. inflow ($Q_{i_{US}}$) is
 299 equal to the outflow from Canadian storage ($Q_{o_{CA}}$) plus the tributaries between the outlet
 300 of Duncan and Arrow dams and inlet of the Grand Coulee reservoir. The flow from
 301 tributaries on the Canadian side were calculated as the difference between the streamflow
 302 at the International Border and outflow from Duncan and Arrow dams, while the
 303 tributaries between the International Border and the Grand Coulee reservoir were
 304 estimated by a linear regression (Fig. S12).

305 The regulated Canadian ($Q_{o_{CA}}$) and U.S. ($Q_{o_{US}}$) outflows were simulated using Eq. (3)
 306 and (4).

$$Q_{o_{CA}} = \begin{cases} \begin{cases} Q_{CA_{max}}, & \text{for } n_{CA} * Q_{i_{CA}} \geq Q_{CA_{max}} \\ n_{CA} * Q_{CA_{max}} + \max \left[0, \min \left(Q_{CA_{max}} - n_{CA} * Q_{i_{CA}}, \frac{S_{CA} - S_{CA_{threshold}}}{2592000} \right) \right], & \text{, (for } I_1) \end{cases} \\ \begin{cases} Q_{CA_{max}}, & \text{for } Q_{i_{CA}} \geq Q_{CA_{max}} \\ Q_{i_{CA}} + \max \left[0, \min \left(Q_{CA_{max}} - Q_{i_{CA}}, \frac{S_{CA} - S_{CA_{threshold}}}{2592000} \right) \right], & \text{, (otherwise)} \end{cases} \end{cases} \quad (3)$$

where I_1 is the condition when $S_{CA} + Q_{i_{CA}} * 2592000 < S_{CA_{threshold}}$, and
 n_{CA} parameter maintains the dynamic storage threshold required for flood control.

$$Q_{o_{US}} = \begin{cases} \begin{cases} Q_{i_{US}}, & \text{for } Q_{i_{US}} \geq Q_{US_{max}} \\ Q_{i_{US}} + \max \left[0, \min \left(Q_{US_{max}} - Q_{i_{US}}, \frac{S_{US} - S_{US_{threshold}}}{2592000} \right) \right], & \text{, (for } I_2) \end{cases} \\ Q_{i_{US}} + \frac{S_{US} - S_{US_{threshold}}}{2592000}, & \text{otherwise} \end{cases} \quad (4)$$

where I_2 is the condition when $S_{US} + Q_{i_{US}} * 2592000 < S_{US_{max}}$.

307
 308 Outflow was computed as a dependent variable of:
 309 a) inflows ($Q_{i_{CA}}$ and $Q_{i_{US}}$),

- b) maximum outflows observed in the Canadian side (Arrow and Duncan dams - $Q_{CA_{max}}$), and in the U.S. side (Grand Coulee - $Q_{US_{max}}$),
- c) the maximum storage capacity of Canadian lumped dam ($S_{CA_{max}}$) and the Grand Coulee dam ($S_{US_{max}}$),
- d) the updated storage stage at each time step in the lumped Canadian reservoir and the Grand Coulee reservoir (S_{CA}, S_{US}) and
- e) the dynamic storage threshold for each side ($S_{CA_{threshold}}, S_{US_{threshold}}$)

The dynamic storage thresholds (m^3) variable, mentioned in Eq. (3) and (4), was estimated according to the simplified reservoir operation given by Eq. (5) and (6) and is schematically represented by Fig. 3. It determines the operational level of the reservoirs based on the probability of cooperation (i.e., the higher the cooperation, higher coherence with the CRT agreement).

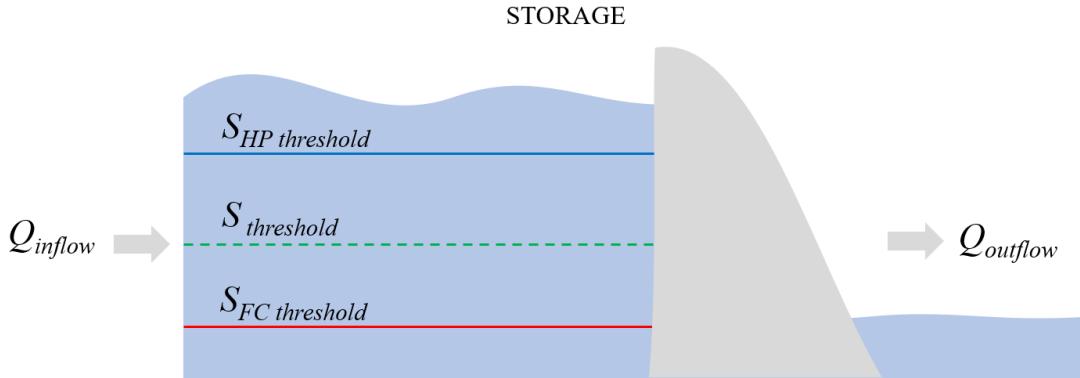
$$S_{CA_{threshold}} = S_{CA_{FC}} * C_{CA} + (1 - C_{CA}) * S_{CA_{HP}} \quad (5)$$

$$S_{US_{threshold}} = S_{US_{HP}} * C_{US} + (1 - C_{CA}) * S_{US_{FC}} \quad (6)$$

As explained above, we consider two operation schemes for each country: (1) operate to maximize for flood control or (2) operate to maximize for hydropower production. Depending on the state of cooperation, the choice will change. In most cases, the system will depend on what Canada chooses, and the U.S. will have to alter its operations in response. Therefore, when the Canadian probability to cooperate parameter (C_{CA}) approaches one, Canada is fully cooperating. Under cooperation, we assume that Canada operates to maximize flood control and the U.S. operates to maximize hydropower. Conversely, when C_{CA} approaches zero, this would indicate lack of cooperation. Under non-cooperation, the Canadian side does not provide flood storage to the U.S. and, after a few simulation time steps where the U.S. endures higher flood damages, the U.S. switches from the hydropower production regime ($S_{US_{HP}}$) to the flood control regime to optimize its benefits ($S_{US_{FC}}$). The target flood control storage in Canada ($S_{CA_{FC}}$) was

determined based on average historical storage in the three treaty reservoirs, while the hypothetical hydropower scheme was assumed as the dams operating at 95% of their full production capacity. The U.S. monthly target storages under the hydropower scheme ($S_{US_{HP}}$) were determined based on the historical monthly average, while the hypothetical target storage to provide themselves protection against floods was calculated as the additional room that Canada would not provide in case of switching to the hydropower

341 scheme $S_{CA_{HP}}$ as presented in Eq. (5) and (6). Therefore, the storage will be dependent on
 342 cooperation. The probability to cooperate variables C_{CA} and C_{US} are described in the Sect.
 343 3.2.2.



344
 345 **Figure 3.** Schematic representation of the dynamic storage threshold ($S_{threshold}$),
 346 represented by the green line. $S_{threshold}$ can range between the blue line, that represents
 347 the target storage to optimize hydropower production ($S_{HP_{threshold}}$), and the red line,
 348 that represents the target storage to avoid flood damages downstream the dam
 349 ($S_{FC_{threshold}}$)
 350

351 3.2.2 Cooperation dynamics

352 Cooperation amongst the two actors both impacts and is impacted by reservoir
 353 operations and benefit sharing. Unequal distribution of benefits alters the sense of fairness
 354 and reciprocity. To conceptualize and understand the cooperation dynamics between two
 355 actors in the context of CRT, the theory of social preferences is drawn from the field of
 356 behavioral economics. Social preferences refer to the behavior of actors (where here
 357 actors are countries not individuals) depending not only on their own material payoffs but
 358 also about the material benefits of other actors (Fehr and Fischbacher, 2002). These
 359 preferences are formalized as the utility function u_i , represented by Eq. (7),

$$u_i = w_i - \alpha_i * \max(w_i - w_j, 0) + \beta_i * \max(w_j - w_i, 0) \quad (7)$$

360 where w_i is actor i 's expected wealth, and w_j is actor j 's expected wealth. The
 361 value for α represents disutility from having more than the other actor (the guilt
 362 coefficient), and β represents disutility from having less than the other actor (the jealousy
 363 coefficient). Among the four types of social preferences described in Sect. 1, this model
 364 uses inequity aversion for the behavioral model of Canada and the U.S. because the
 365 balance of benefits (Bankes, 2017; Shurts and Paisley, 2019) between these two countries
 366 is believed to be a key factor to explain the level of cooperation.

367

368 The utility function is composed of two parts: utility from each actor's own
 369 monetary benefits and from the other's monetary benefits. We defined the utility function
 370 U of each country in Eq. (8–11),

$$U_{CA} = w_{CA} - \alpha_{CA} * \max(w_{CA} - w_{US}, 0) + \beta_{CA} * \max(w_{US} - w_{CA}, 0) \quad (8)$$

$$U_{US} = w_{US} - \alpha_{US} * \max(w_{US} - w_{CA}, 0) + \beta_{US} * \max(w_{CA} - w_{US}, 0) \quad (9)$$

$$w_{CA} = \omega * (HP_{CA} + FC_{CA} + E) \quad (10)$$

$$w_{US} = \omega * (HP_{US} + FC_{US} - E) \quad (11)$$

371 where w of each country is the utility from monetary benefits, HP of each country is the
 372 hydropower benefit, FC of each country is the benefit from flood prevention, E is the
 373 Canadian entitlement, and ω is the coefficient that can convert the monetary values to
 374 utility. Therefore, the sum of the second term (α) and the third term (β) in Eq. (8) and (9)
 375 represents the utility from the other country's monetary benefits because the country has
 376 inequity aversion.

377

378 We use logit dynamics functions to capture the rate of change of cooperation
 379 probability (Iwasa et al., 2010), represented by Eq. (12) and (13),

$$\frac{dC_{CA}}{dt} = \chi \left[\frac{e^{\gamma * E[U_{CA_coop}]}}{e^{\gamma * E[U_{CA_coop}]} + e^{\gamma * E[U_{CA_NoCoop}]}} - C_{CA} \right] \quad (12)$$

$$\frac{dC_{US}}{dt} = \chi \left[\frac{e^{\gamma * E[U_{US_coop}]}}{e^{\gamma * E[U_{US_coop}]} + e^{\gamma * E[U_{US_NoCoop}]}} - C_{US} \right] \quad (13)$$

380 where C_{CA} and C_{US} represent the probability of each country to cooperate (ranging from
 381 0 for Non-Cooperation to 1 for Full Cooperation), and the probability χ if each country
 382 is given an opportunity to choose between two strategies, independent of their last choice.
 383 With stronger institutions or governance, χ is higher (i.e., > 0.5), with weaker institutions,
 384 χ is lower (i.e., < 0.5). $E[x]$ stands for the expected value and γ describes the sensitivity
 385 of cooperation changes to the differences between expected utility values. A large γ
 386 represents a deterministic model that actors always choose the option with the higher
 387 expected utility value. On contrary, a small γ indicates that the actor is likely to switch
 388 their strategy randomly at each time step, independent of the expected utility difference.
 389 We assumed γ to be large and constant as both actors aims for higher expected utility.
 390 For probability to cooperate, if C_{CA} equals to 0.9 that means there is 90% likelihood that
 391 Canada will cooperate with the U.S. and 10% likelihood it will not cooperate. Low values
 392 of χ indicate the policy of the country over whether to cooperate or not would be less

393 sensitive to the current probability to cooperate and the expected utility (Hofbauer and
 394 Sigmund, 2003).

395

396 Actors are willing to cooperate if they are confident that the other actor involved
 397 in the cooperation problem will also cooperate; this is the basis for cooperative outcomes
 398 as demonstrated in the context of social dilemma situation like prisoner's dilemma by
 399 Fehr and Fischbacher (2002). A mixed strategy prisoner's dilemma is used to calculate
 400 the expected monetary payoffs, $E[w]$, according to the combination of strategic decisions
 401 across countries (Table 2). For example, $w_{CA_{CN}}$ is the monetary benefit of Canada when
 402 the U.S. chooses to cooperate and Canada chooses to not cooperate. In this case, the
 403 expected utility of Canada from monetary benefits is calculated by Eq. (14). Similar,
 404 equation not shown here was used for the U.S. to calculate its expected utility.
 405 Afterwards, the expected utility of Canada is calculated involving disutility of inequity
 406 aversion using Eq. (15) and (16), and similar equations not shown here was used for the
 407 U.S.

$$E[w_{CA}] = E[w_{CA_{Coop}}] * C_{CA} + E[w_{CA_{NoCoop}}] * (1 - C_{CA}) \quad (14)$$

$$\begin{aligned} E[U_{CA_{Coop}}] = & E[w_{CA_{Coop}}] - \alpha_{CA} * \max(E[w_{CA_{Coop}}] - E[w_{US}], 0) \\ & + \beta_{CA} * \max(E[w_{US}] - E[w_{CA_{Coop}}], 0) \end{aligned} \quad (15)$$

$$\begin{aligned} E[U_{CA_{NoCoop}}] = & E[w_{CA_{NoCoop}}] - \alpha_{CA} * \max(E[w_{CA_{NoCoop}}] - E[w_{US}], 0) \\ & + \beta_{CA} * \max(E[w_{US}] - E[w_{CA_{NoCoop}}], 0) \end{aligned} \quad (16)$$

408

409 **Table 2.** The payoff matrix of the mixed strategy prisoner's dilemma between Canada
 410 and U.S. showing monetary benefit for Canada ($w_{CA_{-}}$) and the U.S. ($w_{US_{-}}$) in four
 411 conditions: *CC* – the U.S. and Canada both cooperate, *CN* - the U.S. cooperate and
 412 Canada do not, *NC* - the U.S. do not cooperate and Canada do, and *NN* – the U.S. and
 413 Canada both do not cooperate

		Canada	Coop (C_{CA})	No Coop ($1 - C_{CA}$)
		US		
US	Coop (C_{US})		$(w_{US_{CC}}, w_{CA_{CC}})$	$(w_{US_{CN}}, w_{CA_{CN}})$
	No Coop ($1 - C_{US}$)		$(w_{US_{NC}}, w_{CA_{NC}})$	$(w_{US_{NN}}, w_{CA_{NN}})$

414

415 **3.2.3 *Economic benefit equations***

416 The model simulates the benefits that both countries receive from the river. The default
417 operation assumes that the countries cooperate to maximize benefits across the whole
418 system, while in the counter case benefits are based on operation of each side individually.
419 The economic benefits related to flood control are accounted as the damages prevented
420 by the reservoir storage operations. Although the U.S. Corps of Engineers reports that
421 flood damages in Trail, British Columbia, a city near the International Border, occur when
422 streamflow exceeds $6,371 \text{ m}^3 \text{ s}^{-1}$ (225,000 cfs) (USACE, 2003), we did not find details
423 about the damages related to the seasonal flows in Canada. Therefore, the associated
424 economic benefit due to the damages prevented for the Canadian side due to reservoir
425 operation was assumed to be negligible.

426

427 In the U.S., significant damages occur when streamflow exceeds $12,742 \text{ m}^3 \text{ s}^{-1}$ at
428 Dalles, Oregon, and major damages are caused when flows reach $16,990 \text{ m}^3 \text{ s}^{-1}$ (Bankes,
429 2012). Therefore, when they are operating jointly, Canada must draw down storage
430 reservoirs before April 1 to accommodate spring runoff and avoid peak flows
431 downstream. Otherwise, we assume that the U.S. must switch to a flood control scheme.
432 Flood damages prevented because of reservoir management under CRT were explored by
433 Sopinka and Pitt (2014). They compared the maximum annual daily peak flows at Dalles
434 after the implementation of the CRT, and the corresponding monetary damages they
435 could have caused without flood control storage provided. The results of their study were
436 fitted to an exponential curve using Eq. (17) which gives economic benefit in the U.S.
437 due to flood control,

$$FC_{US} = 4.007 * \exp(2*10^{-4}*Q_{Dalles}) \quad (17)$$

438 which presented a R-squared value equal to 0.76. This function was used to estimate the
439 value of flood protection. More details on flood control benefit are presented in Fig. S11–
440 S13, supplementary material (SI 2).

441

442 The economic benefit in the U.S. due to flood damages avoided (FC_{US}) is based
443 on inflow ($\text{m}^3 \text{ s}^{-1}$) into the Dalles dam (Q_{Dalles}). Thereafter, we found the correlation
444 between the Dalles's inflow and the combined outflow of Grand Coulee ($Q_{Grand\ Coulee}$)
445 and the Snake River ($Q_{Snake\ River}$) (Eq. 18).

$$Q_{Dalles} = 1.132 * (Q_{Grand\ Coulee} + Q_{Snake\ River}) + 0.0137 \quad (18)$$

446 The Snake River discharge was included in this analysis because its basin is the major
 447 tributary to the Columbia River, contributing to flow at the Dalles.

448

449 The other economic benefit resulting from management of the Columbia River is
 450 the electricity produced by the hydropower facilities installed in the dams listed in Table
 451 1. Although other dams on the Canadian side of the Columbia Basin have capacity to
 452 generate hydropower, the model only considers those three that are part of the CRT.
 453 Similarly, we only consider the six federal dams on the U.S. side whose surplus
 454 production contributes to the determination of the Canadian Entitlement. Since all six
 455 dams produce energy but only the Grand Coulee operations were modeled, we split the
 456 economic benefit from hydropower generation in two parts. Equation 19 resulted from
 457 the regression performed between the product of the forebay level (h) times Grand
 458 Coulee's monthly average outflow (Q_{out}) versus the average monthly historical
 459 hydropower produced by Grand Coulee ($HP_{Grand\ Coulee}$) (MWh), which resulted in an
 460 R-squared equal to 0.89.

$$HP_{Grand\ Coulee} = 1.2797(Q_{out} * h) + 288616 \quad (19)$$

461

462 In addition, we calculated the electricity produced by the other five dams in Eq.
 463 (20):

$$HP_{5\ dams} = \begin{cases} 1208.9 * (W_{fish} * Q_{out}) & \text{for } W_{fish} * Q_{out} \leq 400m^3s^{-1} \\ 833.9 * (W_{fish} * Q_{out}) & \text{for } W_{fish} * Q_{out} > 400m^3s^{-1} \end{cases} \quad (20)$$

464 where $HP_{5\ dams}$ is the hydropower in MWh produced by Chief Joseph, McNary, John
 465 Day, the Dalles and Bonneville dams. The variable Q_{out} is Grand Coulee's monthly
 466 outflow and W_{fish} is the weighting factor that considers the operations to meet
 467 environmental demands, which is detailed in Sect. 3.2.4. The correlation for the first and
 468 second conditions in Eq. (20) presented R-squared values equal to 0.99 and 0.94,
 469 respectively. Correlation to predict hydropower generation from outflows and forebay
 470 levels are presented in Fig. S14–S15, supplementary material (SI 2). In Eq. (21) we
 471 calculate the total economic benefit due to hydropower production (HP_{US}) in USD,

$$HP_{US} = (HP_{Grand\ Coulee} + HP_{5\ dams}) * HP\$_{US} \quad (21)$$

472 where $HP\$_{US}$ is the average energy price of Oregon and Washington states according to
 473 the (U.S. Energy Information Administration, n.d.).

474

475 For the Canadian dams, historical data on hydropower production is not available.
476 Therefore, Eq. (22) estimates the economic benefit due to electricity produced in Canada
477 (HP_{CA}) in USD based on the generation flow capacity (Q_{turb}), the maximum hydraulic
478 head (H), the hydropower facility efficiency (μ), the specific water weight (γ) and the
479 electricity price in British Columbia according to (BC Hydro, n.d.).

$$HP_{CA} = \frac{\mu * \gamma * Q_{turb} * H}{10^3} * HP\$_{CA} \quad (22)$$

480 Since this equation is based on the Mica dam and, in the model, the three Canadian dams
481 are modeled together, the Q_{turb} and H were interpolated according to the actual and
482 maximum recorded Canadian outflow and Canadian storage, respectively.

483
484 The last economic benefit modeled in this study is the entitlement that U.S. returns
485 to Canada as a payment for increased hydropower generation due to the collaboration
486 between both countries. The Canadian Entitlement (E) simulated in USD is a function of
487 the actual Entitlement in MWh provided by the U.S., the κ parameter, which corresponds
488 to a dimensionless correction factor of the total energy produced by the US, and the
489 average energy price $HP\$_{US}$ of Oregon and Washington states (Eq. 23).

$$E = Entitlement * \kappa * HP\$_{US} \quad (23)$$

490 491 3.2.4 *Impact of environmental spills*

492 The Fish Operation Plan (FOP) details the spills dams must release to meet
493 biological requirements. Fish passage facilities have decreased hydropower generation
494 (Northwest Power and Conservation Council, n.d.). The Bonneville Power
495 Administration, which operates the U.S. treaty dams, estimates that loses due to forgone
496 revenue and power purchases are about \$27 million to \$595 million per year (Northwest
497 Power and Conservation Council, 2019). Although the historical data between 1985 and
498 2018 of hydropower generated by the 6 U.S. dams listed in Table 1 reveal hydropower
499 production increased after the FOP implementation, when normalized as the ratio of
500 hydropower production to inflows, there is in fact a decrease in production after FOP is
501 implemented.

502
503 In order to address the impact of biological spills on hydropower production, we
504 created a weighting factor in the hydropower benefit equation for the U.S., which is
505 detailed in Eq. (24).

$$W_{fish} = \frac{\sum_{i=1}^5 \frac{Q_{fish_i}}{Q_{outflow_i}} * MaxHP_i}{\sum_{i=1}^5 MaxHP_i} \quad (24)$$

506 This weighting factor (W_{fish}) accounts for the fraction of flow ($\frac{Q_{fish_i}}{Q_{outflow_i}}$) that no longer
 507 goes through the hydropower turbines between April and August because it is released
 508 through a spillway or a regulating outlet to meet the biological demands. We calculated
 509 the average monthly fraction for each of the i dams downstream of Grand Coulee and
 510 multiplied it by the maximum hydropower produced by each dam ($MaxHP_i$) to address
 511 individual contributions and the particular effect of FOPs at treaty dams.

512

513 **3.3 Model setup and testing**

514 The equations described above are formulated into the system dynamics model
 515 and implemented in R, a statistical programming environment. In this study we used the
 516 library package *deSolve* Version 1.28 (Soetaert et al., 2010, 2020) to solve the initial value
 517 problem of ordinary differential equations (ODE), differential algebraic equations and
 518 partial differential equations. The ordinary differential equations wrapper (i.e., *lsoda*) that
 519 uses variable-step, variable-order backward differentiation formula to solve stiff
 520 problems or Adams methods to solve non-stiff problems (Soetaert et al., 2010) was used
 521 to compute dynamic behavior of the lumped reservoir system, and to assess how the
 522 reservoir level and operation rules change as a function of time and different variables.
 523 The model was simulated using monthly time steps. Sensitivity analysis was conducted
 524 to test the sensitivity of the parameters and identify the parameters that are most
 525 important. However, all unknown parameters were used in calibration due to the limited
 526 computational cost. The details of the sensitivity analysis are presented in supplementary
 527 material (SI 3).

528

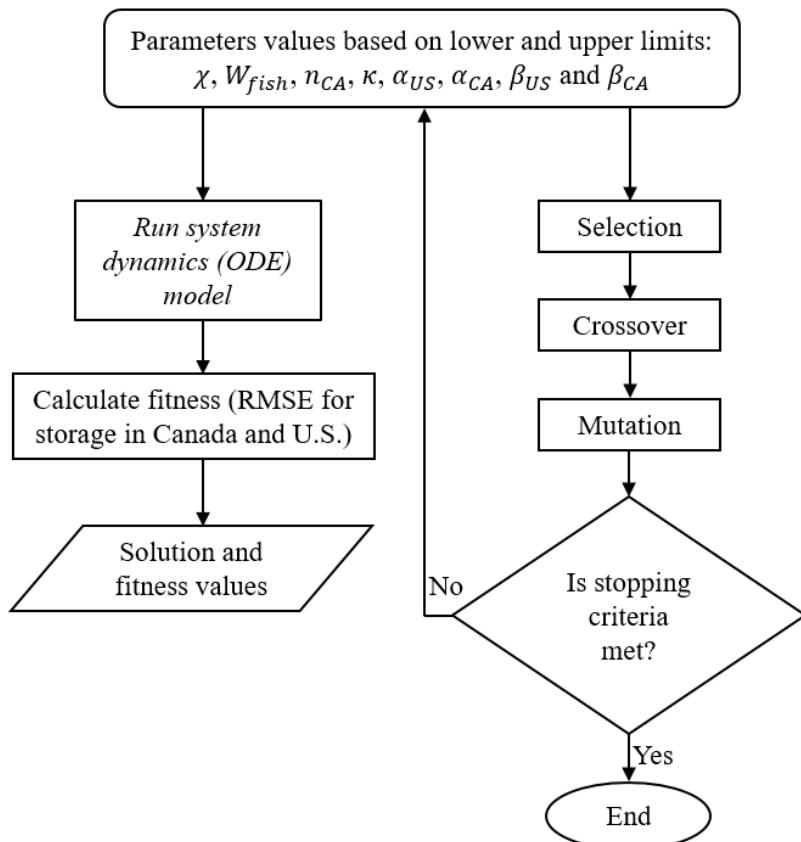
529 **3.3.1 Calibration and validation**

530 The calibration and selection of appropriate parameter values are essential to
 531 accurately reproduce the system's behavior. The calibration parameters can be found in
 532 Fig. 4. These parameters are related to both the hydrological and socio-economic
 533 components of the system. A genetic algorithm (GA) (Scrucca, 2021) was used to
 534 optimize the system dynamics model, using observation for the period from 1990 to 2005.
 535 The methodological framework for model calibration is presented in Fig. 4. A single

536 objective function was defined as minimizing the average root mean square error of
 537 reservoir water levels in Canada and the U.S. (Z), which is given by Eq. (25).

$$Z = \frac{RMSE_{Sca} + RMSE_{Sus}}{2} \quad (25)$$

538 A maximum of 200 iterations and a population size of 200 were used to run the algorithm
 539 with a stopping criteria of 70 iterations before the algorithm stops when no further
 540 improvement can be found. The selected larger population size and iterations, for eight
 541 parameters, ensures that search space is not restricted. The range of parameter values
 542 assigned was, 0.01 to 0.8 for χ , 0.95 to 1.05 for W_{fish} , 0.1 to 0.5 for n_{CA} , 0.95 to 1.05 for
 543 κ , 0 to 1.3 for α_{US} and α_{CA} , -4 to -0.01 for β_{US} and β_{CA} . The model was calibrated using
 544 monthly time series data from 1990 to 2005, and fitted parameters were used to validate
 545 the model using data from 2006 to 2017.



546
 547 **Figure 4.** Overview of calibration process to optimize parameters values using genetic
 548 algorithm. The stopping criteria includes either the maximum iteration for algorithm to
 549 run which is set at 200 generations, or number of iterations before algorithm stop incase
 550 no further optimal fitness value can be found, which is set at 70 generations

551

552 The model assessment for the goodness-of-fit between modeled and observed
553 values was done using four goodness-of-fit metrics, including root mean square error
554 (RMSE), percent bias (PBIAS), volumetric efficiency (VE) and relative index of
555 agreement (rd). RMSE gives the standard deviation of the model prediction error, with
556 lower RMSE indicating better fitness. PBIAS measures average tendency of the simulated
557 values to be higher or lower than the observed data, which range from $-\infty$ to $+\infty$, and its
558 optimal value being 0. VE is a modified form of mean absolute error in which absolute
559 deviation is normalized by total sum of observed data, which could range from 0 to 1,
560 with 1 indicating better agreement. Lastly, rd measures the agreement between simulated
561 and observed data, with its values ranging from $-\infty$ to 1, and 1 indicating better fit. For
562 mathematical expressions of these metrics readers are referred to Zambrano-Bigiarini
563 (2012).

564

565 **3.4 Scenario analysis**

566 Scenario analysis explores dynamics within cooperation and benefit sharing as a result of
567 external environmental factors, institutional capacity, and social and behavioral
568 preferences.

569

570 **3.4.1 Scenarios based on environmental and institutional change**

571 The CRT's success has been based on benefit sharing between the two countries (Hyde
572 2010). However, due to increased environmental flows in the U.S., some parties feel
573 benefits are no longer equitable. Based on these issues, four scenarios were developed to
574 represent the changes in institutional capacity and environmental factors that could affect
575 the probability of cooperation. The model was used to simulate the probability of
576 cooperation under these scenarios for 28 years between 1990 to 2017, which was
577 compared with the baseline scenario that represents the existing system obtained from
578 calibrated model. These scenarios are:

579 i. *Chi (χ) decreases* – The calibrated value of 0.5 decreases to 0.05. χ represents the
580 institutional capacity which determines the growth potential of the probability of
581 cooperation. This type of condition could occur due to a more tense relationship
582 between the U.S. and Canada that could arise due to lack of cooperation in other
583 areas or weaker institutions.

584 ii. *Chi (χ) increases* – The calibrated value of 0.5 increases to 0.7. This scenario
 585 represents the strengthening of institutions. Note: The selection of χ values for
 586 scenarios “*Chi (χ) increases*” and “*Chi (χ) decreases*” was done based on
 587 experimentation where drastic change in C_{ca} and C_{us} is observed at both ends of
 588 increasing and decreasing χ from calibrated value.

589 iii. *High fish spills* – Environmental concerns result in prioritization of spills for fish
 590 passage. Water for fish spills increases by 40% from April through August.

591 iv. *Chi (χ) decreases and high fish spills* – Chi (χ) decreases to 0.05 and fish spills
 592 increases by 40%. It represents the scenario when environmental pressure is high,
 593 and institutions are weaker.

594

595 ***3.4.2 Scenarios based on social preferences***

596 As discussed by Fehr and Fischbacher (2002) and Kertzer and Rathbun (2015),
 597 consideration of social preferences is required to understand mechanisms of cooperation
 598 and the effect of material or benefit payoffs. The key assumption in economic science
 599 that economic reasoning is mostly based on self-interest or that all actors are exclusively
 600 motivated by their material self-interest is invalid as this assumption rules out the
 601 heterogeneity arising from social preferences which substantial fraction of people exhibit
 602 (Fehr and Fischbacher, 2002). To explore the effect of inequality aversion of each country
 603 on the cooperation dynamics, we develop four scenarios with different configuration of
 604 α and β values for Canada and the U.S. (shown in Table 3). Theoretically, the value of
 605 the two coefficients should range from $\beta < 0 < \alpha \leq 1$, and jealousy is more likely than
 606 guilt ($|\beta| > |\alpha|$) (Fehr and Schmidt, 1999). The four scenarios are:

607 i. *Scenario 0* – we posit that both Canada and the U.S. have the same inequality
 608 aversion ($\alpha_{ca} = \alpha_{us} = 0.9$, $\beta_{ca} = \beta_{us} = -1$). Same inequality aversion means that the
 609 actors prefer the benefits to be equally distributed i.e., each actor wants to
 610 increase/decrease their benefits up-to the equitable benchmark when there is
 611 imbalance in benefits. This scenario is not the same as the “baseline” scenario
 612 discussed above in Sect. 3.4.1, where four scenarios based on environmental and
 613 institutional change are compared.

614 ii. *Scenario 1* – the U.S. has less guilt than Canada ($\alpha_{ca} = 0.9$, $\alpha_{us} = 0.3$, $\beta_{ca} = \beta_{us} =$
 615 -1). That means the U.S. is willing to have more benefits than Canada.

616 iii. *Scenario 2* – Canada has more jealousy than the U.S. ($\alpha_{ca} = \alpha_{us} = 0.9$, $\beta_{ca} = -3$,
617 $\beta_{us} = -1$). This means Canada is unwilling to have less benefits than the U.S.

618 iv. *Scenario 3* – we assume that the both countries have no social preferences ($\alpha_{ca} =$
619 $\alpha_{us} = \beta_{ca} = \beta_{us} = 0$), which signifies self-interest or selfishness. In this scenario,
620 each country is only concerned with its own utility and indifferent to the utility of
621 the other.

622
623 We did not include the change of the jealousy of the U.S. or the guilt of Canada
624 in the scenario analysis. This choice is justified because the net monetary benefit of the
625 U.S. is always higher than that of Canada, so the U.S. never feels jealousy nor does
626 Canada feel guilt. In each scenario, we impose a small amount of white noise to each
627 country's α and β values which introduces an element of stochasticity.

628
629 **Table 3.** The configuration of different other-regarding preferences of Canada and the
630 U.S. for scenario analysis. In the scenario 0 both countries have the same level of
631 inequality aversion, while in scenario 1 the U.S. has less guilt than the scenario 0, in
632 scenario 2 Canada is more jealous than in the scenario 0, and in scenario 3 both countries
633 are only concerned with their own utility.

	α_{ca}	α_{us}	β_{ca}	β_{us}
Scenario 0	0.9	0.9	-1	-1
Scenario 1	0.9	0.3	-1	-1
Scenario 2	0.9	0.9	-3	-1
Scenario 3	0	0	0	0

634 635 4 Results

636 This section presents results of model parameterization using genetic algorithm
637 including results from the sensitivity analysis, and results from the scenario analysis.

639 4.1 System dynamics model parameterization and testing

640 During the calibration period from 1990 to 2005 (and to the present) Canada and
641 the U.S. have conformed to the treaty, irrespective of changes in benefit sharing and
642 probability to cooperate. The selection of these social, economic and behavioral
643 parameters therefore represents conditions of cooperation regime. Based on the objective
644 function, the goal was to calibrate the model to simulate reservoir levels that match past
645 observations. Figure 5a–d shows the simulated and observed time series, during 1990 to
646 2005, of the stock (storages) and flow (outflow) variables along with the economic

647 variable of hydropower benefits for the U.S. The model performance metrics for the
 648 calibration period are shown in Table 4. The metrics show good calibration results with
 649 respect to all four metrics. The root mean square error and percent bias are minimal and
 650 volumetric efficiency is higher, for both stock and flow variables. Although the
 651 magnitude of the RMSE is large, it is considered a good fit when compared proportionally
 652 with reservoir volumes, streamflow, and benefits.

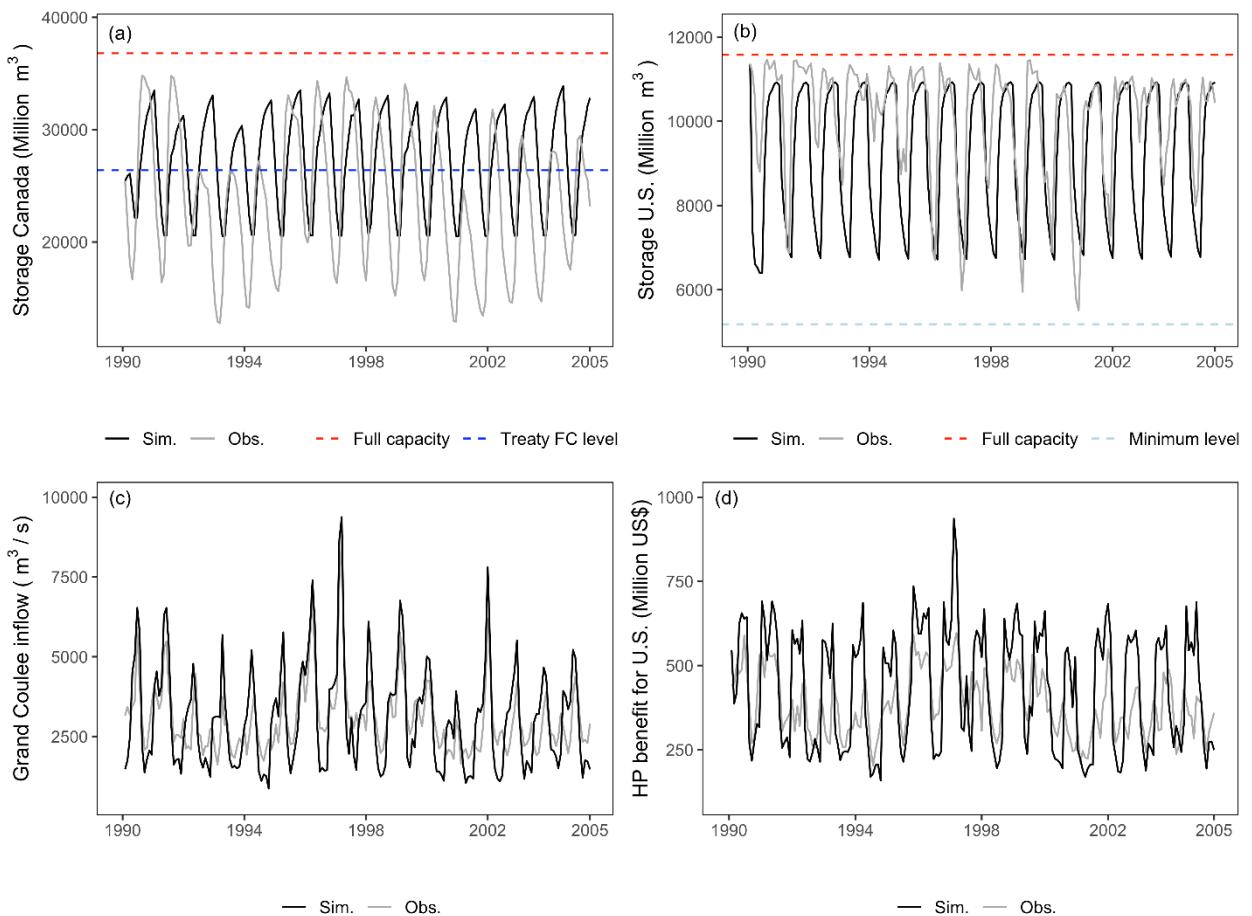
653

654 As seen in Fig. 5a–b, the total reservoir capacity in the Canadian treaty dams far
 655 exceeds the capacity of the U.S. treaty dams and it is to be noted that the treaty flood
 656 control (FC) level in the Canadian dams is 28,387 million m³ (equivalent to the 8.95 MAF
 657 flood storage requested by U.S.). Grand Coulee inflow is the primary input to the U.S.
 658 storage. Thus, the observed and computed inflows are compared to ensure accurate model
 659 behavior (Fig. 5c). The hydropower benefit for Canada depends on U.S. hydropower
 660 production due to the Entitlement; thus, only the benefit of the U.S. was selected for
 661 assessing the calibration results, as estimating hydropower benefit of the U.S. correctly is
 662 an important process in the model (Fig. 5d). Here, the Canadian Entitlement provided in
 663 terms of energy supply is converted into monetary units to compare hydropower with
 664 other benefits. The simulated hydropower production for the U.S. is compared to the
 665 observed cumulative energy production data retrieved from the U.S. Army Corps of
 666 Engineers database. The benefit in terms of the monetary value is obtained by multiplying
 667 the average unit cost (\$ MWh⁻¹) of energy by the hydropower quantity (MWh).

668

669 **Table 4.** Calibration (1990-2005) and validation (2006-2017) result

Stock and flow variables	Metric	Calibration	Validation
Storage Canada	RMSE	6844.14 Million m ³	5596.153 Million m ³
	PBIAS (%)	14.70	6.50
	VE	0.76	0.82
	rd	0.30	0.51
Storage US	RMSE	1682.46 Million m ³	1373.34 Million m ³
	PBIAS (%)	-8.60	-6.90
	VE	0.88	0.91
	rd	0.68	0.78
GCL inflow	RMSE	963.20 m ³ s ⁻¹	886.23 m ³ s ⁻¹
	PBIAS (%)	1.70	2.4
	VE	0.72	0.75
	rd	0.82	0.89
HP benefit	RMSE	144.24 Million US\$	139.66 Million US\$
	PBIAS (%)	11.30	15.10
	VE	-	-
	rd	0.66	0.73

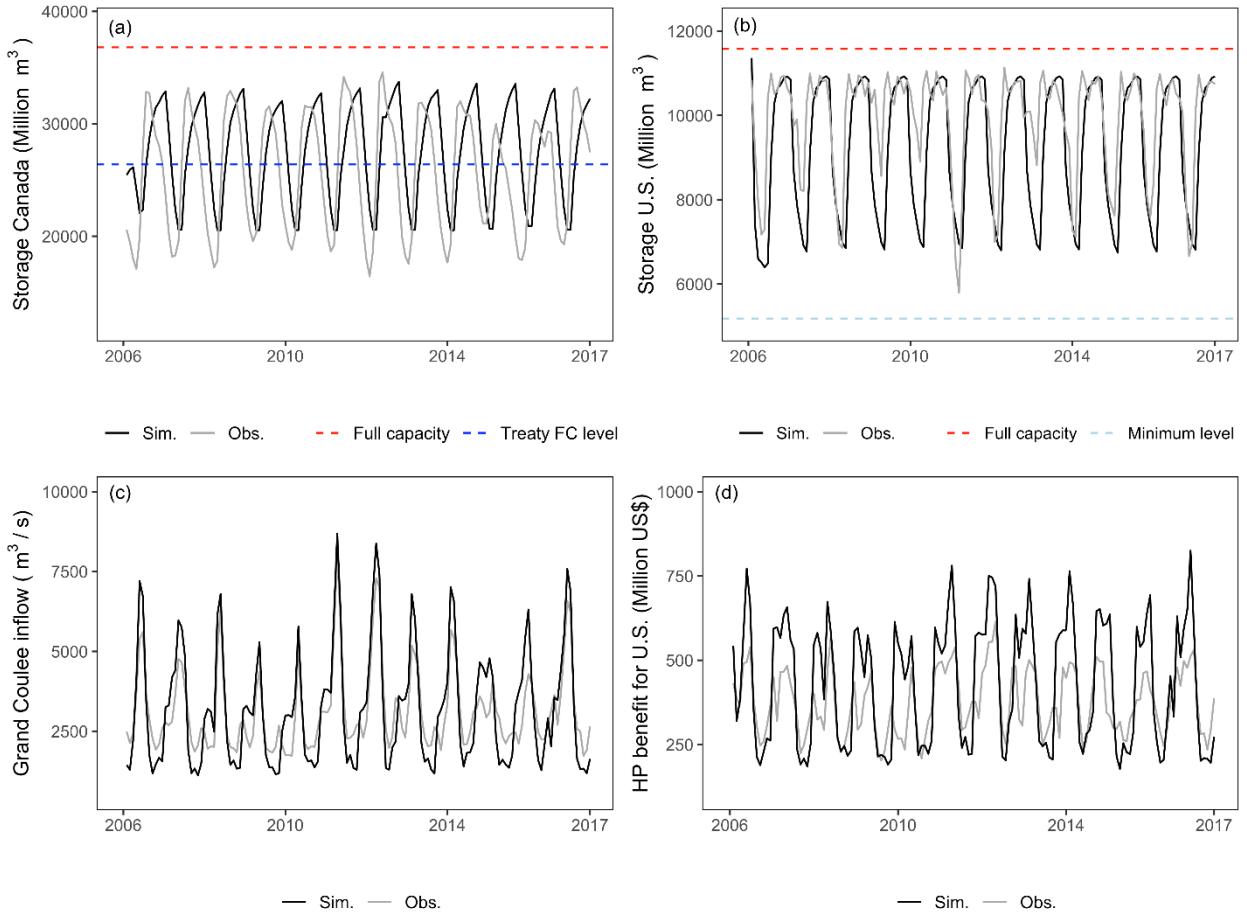


672 **Figure 5.** Calibration result from 1990-2005 showing, (a) Canadian storage, (b) U.S.
 673 storage, (c) Grand Coulee inflow and (d) hydropower benefit for the U.S.

675 The model validation period was 12 years from 2006–2017 (Fig. 6a–d). Since the
 676 warmup period during the calibration and validation simulation is only 3 months (i.e.,
 677 when model stability is achieved), the selected calibration and validation periods are long
 678 enough to yield robust results. Compared to calibration results, model validation
 679 presented slightly better results in terms of performance metrics (Table 4). The simulated
 680 behavior of the reservoir level in Canada and the U.S. during calibration and validation
 681 are quite similar (Fig. 6a–b). In Canadian reservoirs, the model accurately simulates the
 682 maximum peaks, but the simulated low reservoir level is higher than the observed (Fig.
 683 5a and Fig. 6a). Meanwhile, for the U.S. reservoirs, the simulated lower reservoir level is
 684 lower than observed (Fig. 5b and Fig. 6b). It is to be noted that the actual operating rules
 685 for these dams are dynamic based on seasonal changes and weather forecasts. In practice,
 686 they may change suddenly from the pre-determined plan given unforeseen circumstances.

687 Therefore, it is impossible to capture the exact behavior in a lumped model of this kind.
 688 The validation result for Grand Coulee inflow (Fig. 6c) and hydropower benefit for the
 689 U.S. (Fig. 6d) showed similar performance as the calibration period.

690

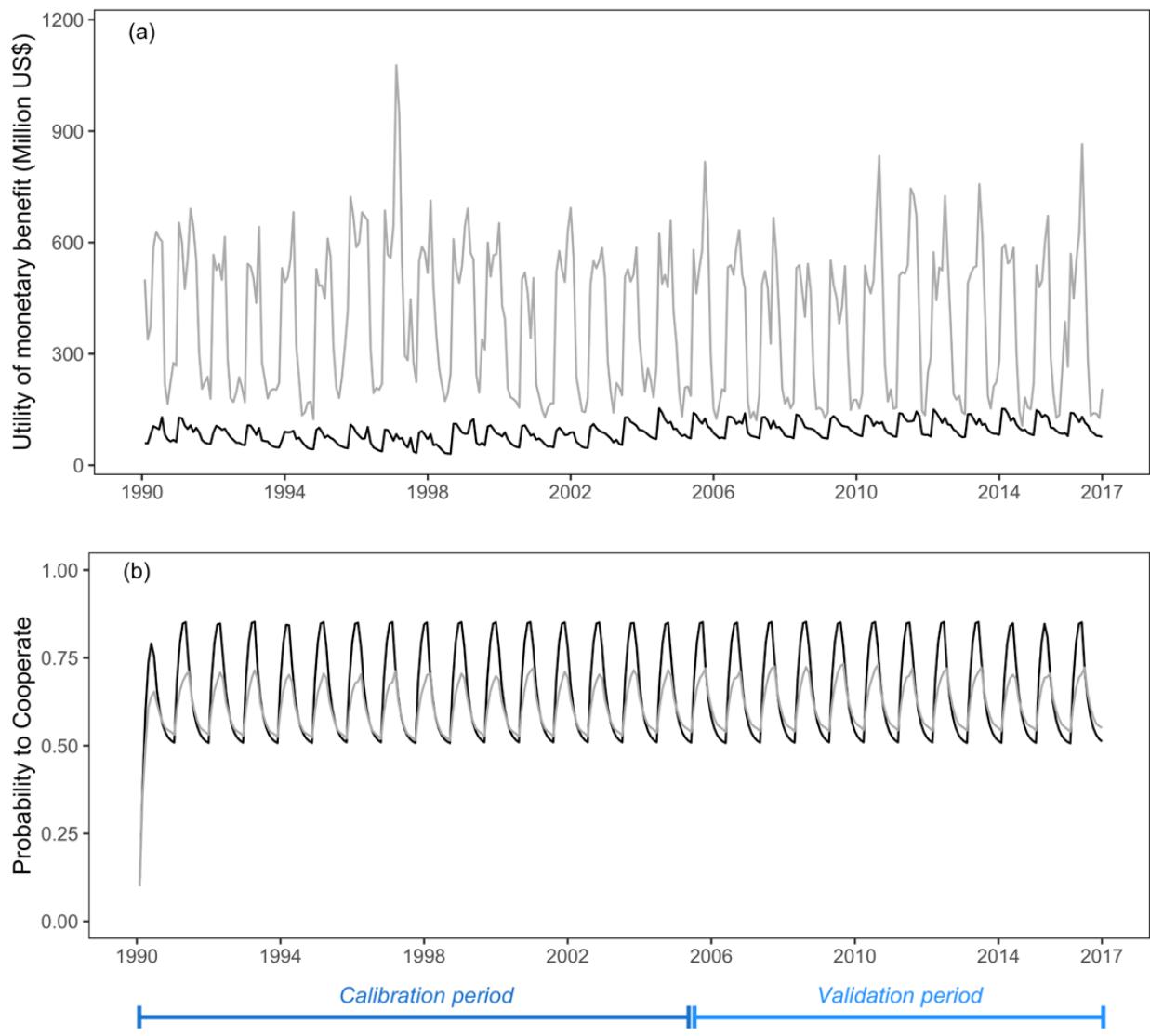


691

692 **Figure 6.** Validation result 2006 – 2017 showing, (a) Canadian storage, (b) U.S.
 693 storage, (c) Grand Coulee inflow and (d) hydropower benefit for the U.S.

694

695 PBIAS for both calibration and validation showed that the result is close to
 696 optimal, and Grand Coulee inflow showed the best fit with the PBIAS value that is closest
 697 to 0. VE is only applied to the reservoir volumes and streamflow, as per the suitability of
 698 the metric. VE values are greater than 0.72, suggesting a good fit. Similarly, agreement
 699 index or rd values indicated better performance for all the comparisons except for
 700 Canadian storage. The result of these metrics show that the model is able to replicate and
 701 predict the desired behavior.



702

703 **Figure 7.** Change in, (a) the utility of monetary benefit and (b) probability to cooperation
 704 during calibration and validation period for Canada and the U.S. Note: The lower initial
 705 probability to cooperate during 1990 is only due to the warmup period of model
 706 simulations.

707

708 Figure 7a–b shows the utility of monetary benefit and dynamics of the probability
 709 to cooperate for the U.S. and Canada during the calibration and validation periods. This
 710 model simulation with calibrated parameters over 1990 to 2017 is also referred to as
 711 baseline in the next section. The share of benefits that the U.S. receives is higher than the
 712 benefit in Canada, relatively, despite the Canadian Entitlement (Fig. 7a). The minimum
 713 probabilities to cooperate for both countries converge at 0.5, while peak amplitude for
 714 cooperation dynamics is higher for Canada compared to the U.S (Fig. 7b).

715

716 **4.2 Scenario analysis**

717 The scenario analysis results presented below is based on environmental and
718 institutional change, and social preferences. The scenario analysis covers the same time
719 period from 1990 to 2017, utilizing observed inflow, tributary streamflow, and storages,
720 and the same initial conditions as these simulations are not for projection, but rather to
721 gain a deeper understanding of dynamics in the socio-hydrological system.

722

723 **4.2.1 Scenarios based on environmental and institutional change**

724 The four scenarios tested here are based on changes in environmental and
725 institutional conditions. The results are compared with the baseline scenario which
726 represents cooperation between both countries. In the quantile-quantile plot (Fig. 8a–f),
727 the baseline scenario is shown on the horizontal axis and four scenarios on the vertical
728 axis, where each point represent a time step. The scenario “ χ decreases” significantly
729 reduces the probabilities to cooperate for both countries as the maximum C_{ca} reduced
730 from 0.85 to 0.7 and maximum C_{us} reduced from 0.75 to 0.64. The probability to
731 cooperate for Canada under the “ χ decreases” scenario is identical to the “ χ decreases
732 and high fish spills” scenario (Fig. 8a), thus blue and cyan points overlap. Reducing χ
733 showed two distinct characteristics: the rise of C_{ca} and C_{us} took almost 8 years of
734 simulation to converge and level off (which is not shown in the figure), although the
735 average value when the convergence occurred did not deviate much (thus values around
736 0.55 falls near the $y = x$ line), the maximum probability to cooperate or C_{ca} and C_{us}
737 reduced significantly. Similar results were seen for the U.S. probability to cooperate (Fig.
738 8b). Lowering the χ resulted in lower C_{ca} , and, therefore, Canada would be expected to
739 increase the level of storage in its dams to produce more hydropower as compared to
740 baseline (Fig. 8c). Lowering the χ impacted C_{us} too, along with C_{ca} , because, if Canada
741 increased its hydropower production, the U.S. would have to provide its own flood
742 control. Therefore, reservoir levels in the U.S. would decrease as compared to baseline
743 when χ decreases (Fig. 8d). Since Canada would produce its own hydropower in this
744 scenario, the monetary benefit increased slightly compared to baseline, and the result is
745 similar to the “ χ decreases and high fish spills” scenario for Canada (Fig. 8e).

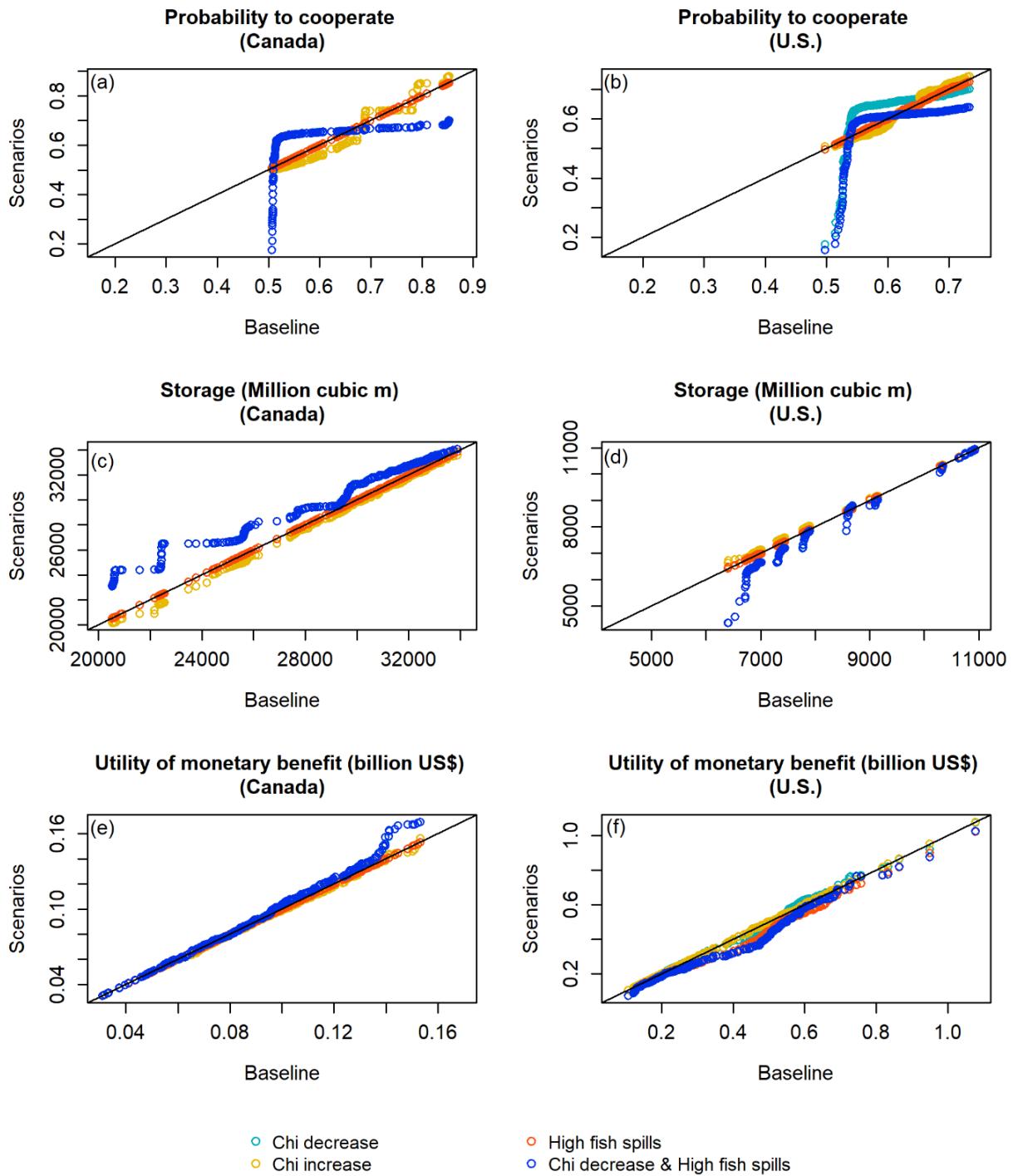
746

747 The “ χ increases” scenario indicates better institutional capacity that favors
748 cooperation. Increasing χ increased the maximum probabilities to cooperate (i.e., C_{ca} and

749 C_{us}) but the minimum remains the same (as lower quantile falls on the identity line or y
750 $= x$ line) (Fig. 8a–b). While not shown in the figure, the time it took to converge is similar
751 to the baseline. With increasing χ Canada would provide flood control to the U.S. as
752 agreed upon in the CRT. Here, a slight increase in the capacity for flood control in
753 Canadian storage was observed in the model, as storage level decreased slightly below
754 the baseline (Fig. 8c) and the U.S. continues its existing operations to produce maximum
755 hydropower, hence the storage level in the U.S. remains the same as in the baseline (Fig.
756 8d). With increasing χ , Canada’s and the U.S.’s benefit continues to be the same as the
757 baseline (Fig. 8e). When χ increases or decreases the utility benefit that the U.S. receives
758 does not change significantly. This is due to the U.S. balancing the increased flood
759 damage control while hydropower production is compromised.

760

761 The “*High fish spills*” scenario refers to strict regulation to protect fish passage
762 along the Columbia River, which has negative implications for hydropower production.
763 Increasing fish spills in U.S. dams has no effect on the Canadian probability to cooperate
764 (C_{ca}) as it does not affect Canadian dam operation (Fig. 8a). Increasing the fish spills
765 decreases peak C_{us} slightly but the average remained similar to the baseline (Fig. 8b).
766 This also does not affect the storage level in the U.S. dams (Fig. 8d), but monetary benefit
767 for the U.S. decreases due regulation as water is diverted from the hydropower turbines
768 (Fig. 8f). It is to be noted that this loss of hydropower production affects the U.S. but has
769 no effect to Canadian benefit because the U.S. remains obligated to pay the Canadian
770 Entitlement even if hydropower production is lower. The combined scenario of “ χ
771 decreases and high fish spills” has similar results to the “ χ decreases” scenario (Fig. 8a–
772 e), but reduction in monetary benefit is higher compared to the “ χ decreases” and “*High*
773 *fish spills*” scenarios.



774

775 **Figure 8.** Quantile-Quantile plot of the baseline versus other scenarios (χ decrease, χ
776 increase, high fish spills and combined χ decrease and high fish spills) comparing
777 probabilities to cooperate, reservoir storage volumes and utility of monetary benefits

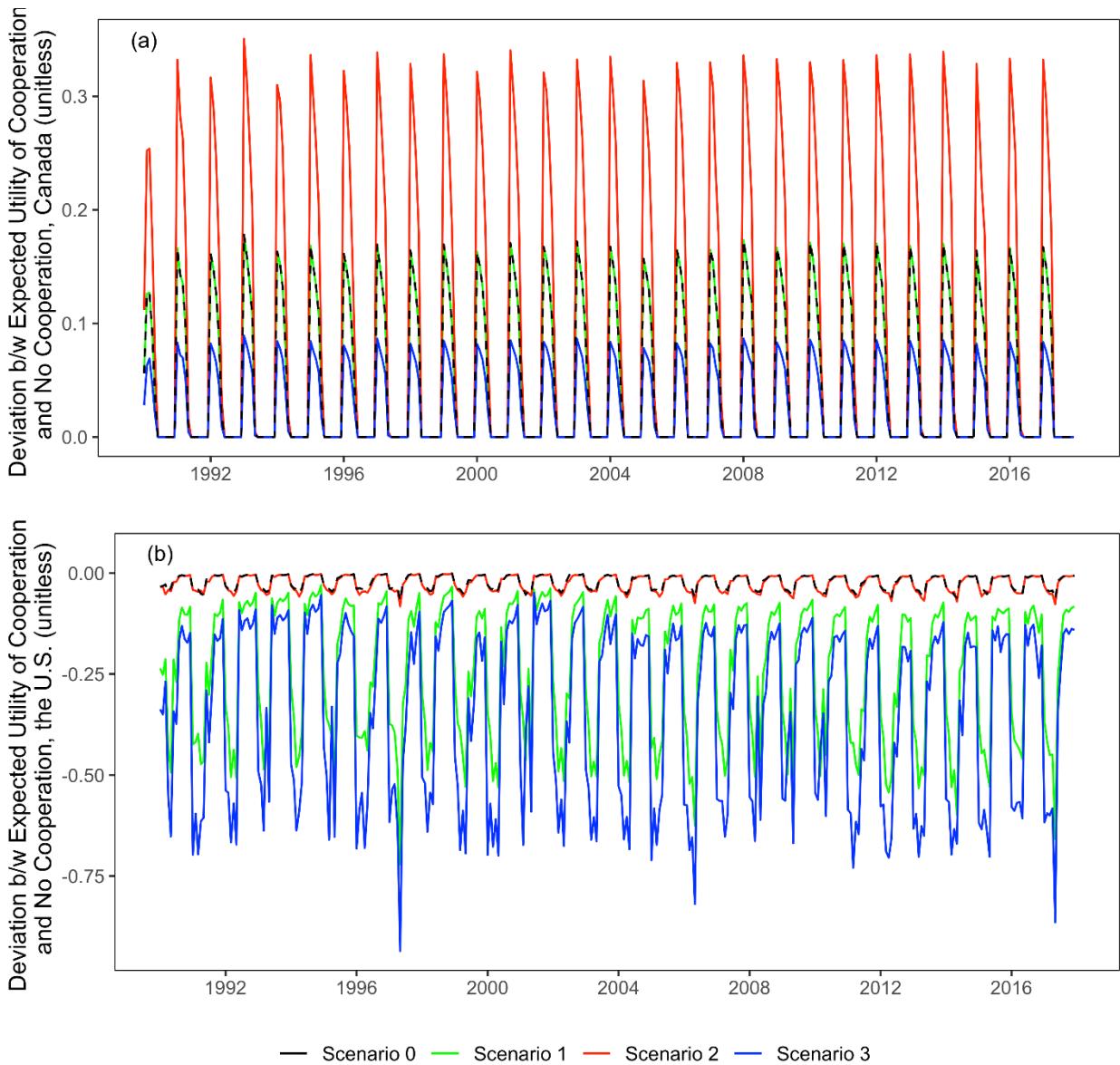
778

779 **4.2.2 Scenario analysis in terms of social preferences**

780 In addition to the scenarios above, four different scenarios of social preferences
781 were tested and compared to each other. Figure 9 shows the differences between the

782 expected utility of cooperation and non-cooperation from each country according to
783 different scenarios.

784



785

— Scenario 0 — Scenario 1 — Scenario 2 — Scenario 3

786 **Figure 9.** The differences between the expected utility of cooperation and no
787 cooperation from each country according to different scenarios for (a) Canada and (b)
788 the U.S.

789

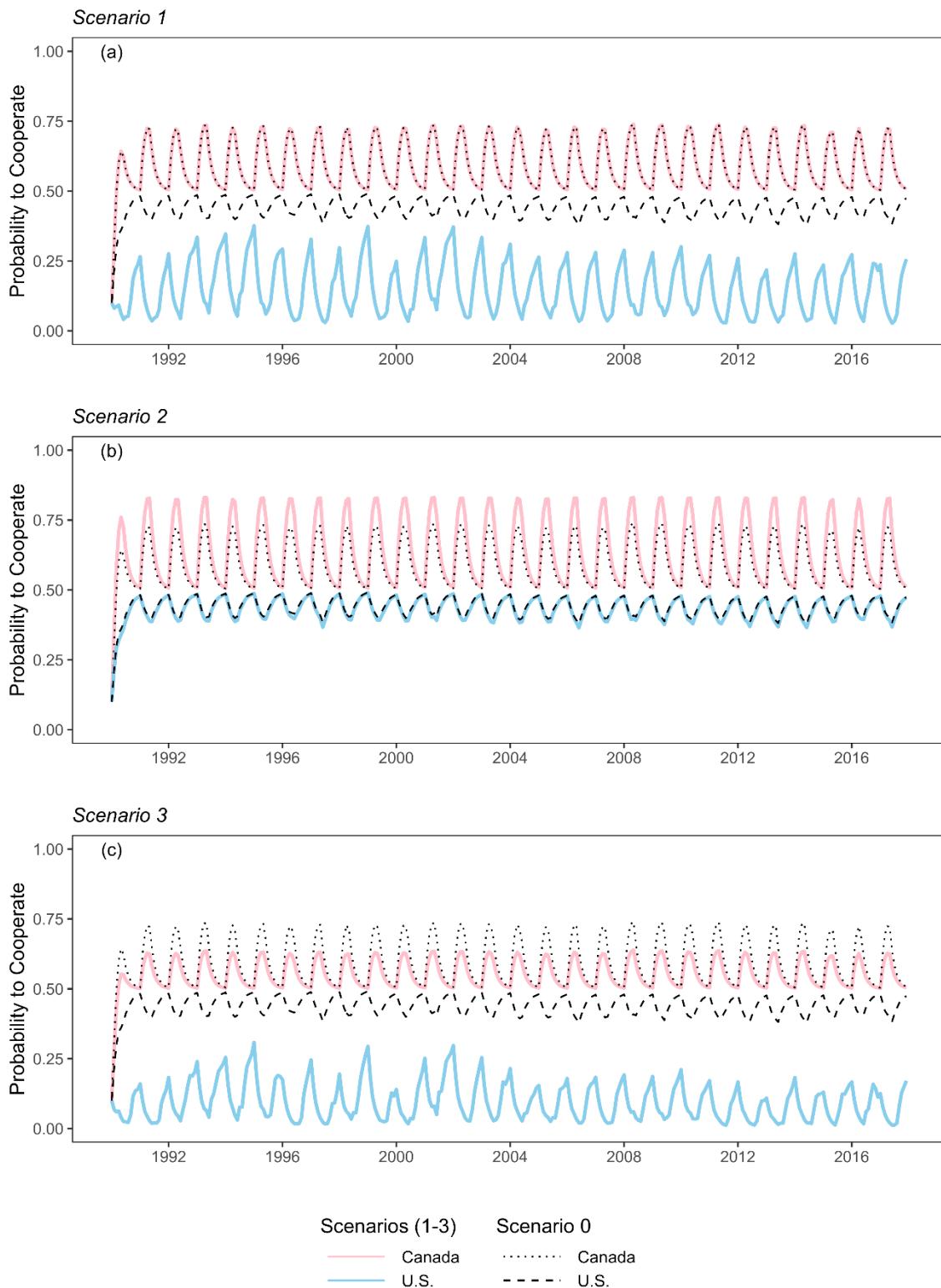
790 Figure 10a–c, shows the changes in the probability to cooperation (C_{ca} and C_{us})
791 according to the different configurations of social preferences. As shown in Fig. 10a–c,
792 Canada's probability of cooperation is always higher than 0.5 in all scenarios because
793 Canada can get higher expected utility when it chooses to cooperate no matter which
794 behavioral types the two countries possess. This explains why the probability to cooperate

795 in Canada is always higher than the U.S. in Fig. 10a–c. Conversely, since the expected
796 utility of cooperation in the U.S. is always smaller than the expected utility of non-
797 cooperation in Fig. 9b, the probability of cooperation of the U.S. is always less than
798 Canada (Fig. 10a-c).

799
800 Comparing “*Scenario 0*” and “*Scenario 1*” from the standpoint of Canada, we
801 found that there was no difference in the outputs between “*Scenario 0*” and “*Scenario*
802 *1*” (Fig. 10a). This means that a decrease in the guilt coefficient of the U.S. does not affect
803 Canadian decision-making on whether to cooperate or not. However, in “*Scenario 2*”,
804 the gap between the expected utilities with cooperation and without cooperation widens
805 and Canada is more likely to continue cooperating when Canada feels more jealousy
806 (more sensitive to disadvantageous inequity) (Fig. 9a). From the standpoint of Canada, it
807 is always economically beneficial to cooperate with the U.S. because Canada can receive
808 the Entitlement from the U.S. under the CRT. In other words, the more unfair the
809 distribution of material benefits between Canada and the U.S., and the greater the jealousy
810 of Canada, the more Canada will be motivated to cooperate due to the Entitlement (Fig.
811 10b). In “*Scenario 3*”, the differences between the expected utility of cooperation and
812 non-cooperation decreases compared to “*Scenario 0*” if Canada does not care about the
813 counterpart’s payoffs and focuses on its own payoffs (Fig. 9a). Cooperation will decline
814 as Canada is narrowly self-interested in the fair distribution of material payoffs (Fig. 10c).
815 In terms of cooperation, selfishness is worse than jealousy.

816
817 From the standpoint of U.S., there was no difference between "Scenario 0" and
818 "Scenario 2" in terms of outputs (Fig. 10b). This implies that a rise in Canada's jealousy
819 coefficient has no effect on the decision of U.S. whether to cooperate. Comparing
820 “*Scenario 0*” and “*Scenario 1*”, the difference between expected utilities with and
821 without cooperation is expanded, but the expected utilities of non-cooperation are larger
822 than those of cooperation (Fig. 9b). As a result, the U.S. is less inclined to cooperate in
823 the future when it feels less guilty (less sensitive to advantageous inequity) (Fig. 10a). In
824 other words, the more material benefits Canada receives and the less guilt the U.S. has,
825 the more driven the U.S. will be motivated to break the Treaty. Like “*Scenario 3*”, if the
826 U.S. does not care about the counterpart’s payoffs and focuses on its own payoffs, the
827 relative magnitude of expected utility of cooperation will decrease. As the guilt of the
828 U.S. decreases, the U.S. becomes less concerned about a “fair deal” with Canada and

829 loses the motivation to continue cooperation. Therefore, the U.S. can maximize its profits
830 by halting cooperation (not paying the Canadian Entitlement) and operating unilaterally.



831
832 **Figure 10.** The probability to cooperate of each country according to different scenarios
833 (a) Scenario 1, (b) Scenario 2, and (c) Scenario 3
834

835 Since Canada gets the Entitlement due to the CRT, Canada is likely to continue
836 cooperating. If the U.S. preference for a fair distribution of benefits declines during future
837 CRT negotiations, such as in “*Scenario 1*” and “*Scenario 3*”, the U.S. is more likely to
838 break the treaty or change its stance on the Entitlement. That does not mean that the U.S.
839 has zero or negative benefit from the CRT. The U.S. has some benefits, but it would not
840 continue to cooperate because the benefits of not cooperating are greater than the benefits
841 of cooperating. As environmental concerns increase, the net benefit of the U.S. is
842 expected to decline further because of lower hydropower benefit, so the U.S. is less likely
843 to agree with continuation of the treaty until it is changed to create greater benefits for the
844 U.S. from cooperation.

845

846 **5 Discussion and conclusion**

847 The CRT is regarded as one of the most successful transboundary river
848 agreements. As the upstream and downstream actors, Canada and the U.S. have
849 asymmetric access to water resources, and different positions with regard to the risk of
850 floods and potential for hydropower production. Within the Columbia River basin,
851 Canada is less susceptible to flood risk relative to the U.S. and the U.S. has capacity for
852 higher hydropower production relative to Canada. The unique feature of the CRT is that
853 the two countries developed a plan to manage the river as a unified system and to share
854 the costs and benefits equitably (Bankes and Cosen, 2013; Shurts and Paisley, 2019).
855 This collective sharing of risks from flooding and benefit from hydropower as indicated
856 by Wolf (2007) and Zeitoun et al. (2013) makes the CRT successful among other
857 transboundary river treaties. This study examines the dynamics of cooperation, and how
858 it is affected by feedback between human and natural systems. It is important to
859 understand the underlying drivers of a successful cooperative regime and the factors that
860 influence each country’s choice about whether to cooperate or not. The provisions of the
861 CRT expire in 2024, and negotiations for the next phase of the treaty are ongoing. There
862 have been many prominent discussions about what the future of the treaty should look
863 like, including issues related to hydropower generation versus fish, and how to account
864 for spills (Blumm and Deroy, 2019; Harman and Stewardson, 2005; Leonard et al., 2015;
865 Muckleston, 1990; Northwest Power and Conservation Council, 2019; United States
866 Government Accountability Office, 2018). Additionally, both countries perceive
867 imbalances in the benefits that are received from the CRT relative to what each deserves
868 or compared to what they perceive the other side’s benefits to be (Holm, 2017; Stern,

869 2018). As discussed in Gain et al. (2021) and Gober and Wheater (2014), the success in
870 treaties or institutions managing river basins depends not only on the control of hydrology
871 but in consideration of socio-political dynamics. This study shows that addressing
872 emerging social and environmental issues are critical to continued cooperation, providing
873 valuable insights for the current renegotiation process, as well as future treaty negotiations
874 on transboundary waterways similar to the Columbia River.

875

876 Natural and social systems evolve over time. Under unforeseen and uncertain
877 changes, the balance of these systems could shift. A subtle social change can be induced
878 by environmental and hydrological changes, which in turn lead to further unforeseen
879 changes in hydrologic or physical systems. For the Columbia River Basin sudden change
880 in cooperation and deviation from cooperation to conflict is not anticipated because both
881 countries that have similar economy and political power, and have shared values,
882 common interests and multi-layered economic ties. The socio-hydrological system
883 dynamics model developed for this study captures the dynamics of cooperation to reflect
884 external perturbations. Explicitly incorporating the probability to cooperate C_{CA} and C_{US}
885 (Eq. 5 and 6) into the model, enables exploration of the factors influencing cooperation.
886 This study further illustrates the utility of simplified lumped models in understanding
887 complex systems.

888

889 This socio-hydrological model presented here further allowed for the exploration
890 of scenarios under environmental and institutional changes, and social preferences, to
891 understand how robust the cooperation on this transboundary waterway is. These
892 scenarios represent current and plausible future socio-political and environmental
893 changes. We found that institutional capacity (χ) plays an important role in long term
894 cooperation (Fig. 8a–b and Fig. S17, supplementary material (SI 3)). Stronger
895 environmental regulation for increased fish spills affects the benefit for the U.S. but not
896 as substantially as when χ (institutional capacity) decreases. Canada continues to receive
897 payment through the Canadian Entitlement, even when the U.S. is producing less
898 hydropower, something that is interesting to explore further for future negotiations of the
899 CRT. Different configurations of social preferences for the behavioral model of Canada
900 and U.S. was used to demonstrate how the probability to cooperate changes. The expected
901 utility of cooperation as compared to expected utility of non-cooperation is higher for
902 Canada and lower for the U.S. (Fig. 9). Thus, the probability to cooperate was simulated

903 to be higher for Canada. The results show that both the guilt coefficient of the U.S. and
904 the jealousy coefficient of Canada affect the level of cooperation. For future CRT
905 negotiations, the ideas considered in this study could help provide insight into the long-
906 term dynamics of cooperation and the impacts of benefit sharing. For other transboundary
907 rivers (e.g., along Nepal and India, Bangladesh and India, or India and Pakistan (Ho,
908 2016; Mirumachi, 2013; Saklani et al., 2020; Thomas, 2017; Uprety and Salman, 2011)),
909 the jealousy and guilty coefficient between actors and their social preferences will not be
910 the same as in Columbia River Basin. Similarly, the tipping points for the balance of
911 cooperation arising from environmental and social change could be different and this
912 warrants future research in other transboundary river basins.

913

914 This socio-hydrological system dynamics model can be further improved by
915 considering additional variables related to climate change, land use change and water use
916 regime changes. The key limitation of this study is the explicit consideration of water use
917 for hydropower production and flood control only. The study does not consider future
918 projections of these variables, which would be a possible direction for future research.
919 Another limitation is the method of estimation of flood damages. We estimated the
920 economic benefits involving flood damage prevention, which does not include the
921 monetary benefit of flood control in Canada due to treaty dams because little information
922 is available in the scientific literature and official reports, and existing resources indicate
923 significantly less flood damage in Canada relative to the U.S. (BC Ministry of Energy
924 and Mines, 2013; Northwest Power and Conservsation Council., n.d.). However, future
925 studies should investigate the magnitude of this benefit since there are certainly flood
926 risks averted by Canadian storage.

927

928 As mentioned previously, the results of this study can help inform the
929 renegotiation of the CRT in two ways: (1) the methods of modeling the hydrological and
930 social systems in tandem, and using behavioral economics, could be used to help
931 formulate policies or management priorities and (2) understanding of the connection
932 between the share of benefits received by each side to cooperation can support negotiation
933 discussions to find solutions that would satisfy both sides. More generally, the model
934 demonstrates that understanding the motivations of each country in terms of guilt and
935 jealousy might provide insight into the factors driving each country and the thresholds

936 that might influence their decision about whether to cooperate. We also find that it is of
937 great importance to maintain institutional strength in support of cooperation.

938

939 Unlike the U.S. and Canada where a non-cooperative regime or resort to direct
940 conflict is unanticipated even if the benefits are perceived to be severely imbalanced,
941 there are many other river basins where different environmental challenges are evolving
942 (UNEP, 2016) and political tensions are high. Globally, conflicts do arise between
943 countries that share a water source, with root causes that extend far beyond the water
944 system (Sadoff and Grey, 2002). However, transboundary rivers support the livelihoods
945 of millions of people, preserve ecosystems, and provide a vital resource that needs to be
946 managed sustainably. Using the methodologies presented in this study and the insights
947 gained could be applied to other river basins around the world to help us understand what
948 behaviors and benefits are driving choices about cooperation.

949

950 **Author contribution**

951 AS, FS, SP and CC planned this work as participants of “Socio-Hydrology Summer
952 Institute on Transboundary Rivers”; AS focused on model development and analysis;
953 FS focused on data collection and data analysis; SP focused on behavior economics; CC
954 focused on review and synthesizing Columbia River treaty; AS, FS, SP and CC
955 conceptualized the system dynamics framework; FS and AS formulated stock and flow
956 equations; SP formulated cooperation dynamics equations; AS and SP formulated
957 hydropower and flood control benefit equations; CC conducted assessment of past and
958 current issues affecting treaty renegotiation; AS wrote the model script, performed
959 model testing, scenario analysis and data visualization; SP performed social preference
960 scenario analysis and assessment; AS, FS, SP and CC wrote the manuscript draft; AS
961 revised the manuscript; MG, DY, and EM provided guidance and funding, and reviewed
962 and edited the manuscript.

963

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974

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