Response to RC2 on "*Socio-hydrological modeling of the tradeoff between flood control and hydropower provided by the Columbia River Treaty*" submitted to *Hydrology and Earth System Sciences*

This manuscript develops a socio-hydrological model to simulate the cooperation dynamics of flood control and hydropower in Columbia River Basin on basis of Columbia River Treaty (CRT) signed between the United States and Canada. Overall, it's an interesting study within the scope of socio-hydrology and transboundary rivers, and the proposed model has potential application value in other basins. However, I have some concerns and suggestions, which needs to be addressed. Below are detailed comments:

Major concerns

1. It's unjustified that the authors linearly aggregated the reservoirs for flood control and hydropower production. Flood control and hydropower production not only depend on reservoirs operation rules, but also related to the hydrological connections between reservoirs. The aggregated reservoirs may be applicable for the total storage, but will be bound to bring risks on flood control and hydropower production.

***Authors' response*:** Thank you for this critical comment. We understand that the risk of simplifying the physical system is that there could be model and output uncertainty. For this study lumping the storages for system dynamics model is appropriate for the reasons as discussed below:

1. The actual reservoir operations for the treaty dams is different from their designed operation plan and depends on the number of variables including future projection of streamflow. Modeling the exact reservoir operations for all the treaty dams is outside our scope of the research objective and is not necessary to investigate our research questions.
2. All the treaty dams work in coordination to achieve either of the hydropower benefits (by U.S. dams) or flood control (by Canadian dams). This coordinated operation supports that lumping the reservoirs is a valid approach.
3. The system dynamics model is not for prediction but inference of the observed data to understand the dynamics of cooperation along with the socio-hydrological system behavior. For this purpose, we have used the observed streamflow, particularly inflow hydrograph, to simulate outflow hydrograph and quantify the socio-economic variables (i.e., benefits) as a function of outflow.
4. In lumping the system, we have considered external input variables such as tributaries and added to the outflow from Canadian reservoir, or inflow to the U.S. reservoir. Using the calibration process, we have also ensured that the hydropower benefits is well captured.
5. The historical database for the flood control benefits or flood damages over the regular time interval is not available as per our knowledge and search. Thus, the most reliable approach we have adopted as discussed in "3.2.3 Economic benefit equations", using the data from the past study by Sopinka and Pitt (2014) to infer the flood control benefit is the appropriate option for this study. Moreover, the independent variable here is also the outflow hydrograph.

2. The flood damage is typically estimated based on the peak daily water flow in a year. However, I notice the proposed model in study conducted with a monthly time step, which

indicates that the peak daily water flow have been smoothed. The flood damage will be thereby remarkably underestimated, significantly challenging current results.

***Authors' response*:** Thank you for this comment. We have selected monthly temporal resolution because some processes like increasing environmental (i.e., fish spill) flow is relevant in monthly time scale, as well as data such as hydropower production is available at the monthly time scale. The possible error in flood damage from using monthly streamflow is an important and valid point. We are exploring different approaches to address this. We will certainly check for this error and will address this in our revision.

Minor concerns

1. How to distinguish the positive and negative feedbacks between variables in Figure 2?

***Authors' response*:** The causal loop diagram is revised and will be updated in the revised manuscript to include the loop polarity.

2. I am puzzled about equation (3) and (4):

(1) The simplified reservoir operation rule indicated by equation (3) and (4) is used to determine the outflow, which is considered as vital factor in the model. It's suggested to cite corresponding references and add justification description for these equations.

(2) It's worth noting that n_{CA} is an important parameter for outflow of Canada. What's the explicit connotation of n_{CA} and how to determine it?

(3) The outflow is dominated by storage thresholds (i.e., $S_{CAthreshold}$ and $S_{USthreshold}$). The storage threshold is always between the target flood control storage ($S_{FCthreshold}$) and target hydropower storage ($S_{HPthreshold}$) as shown in Figure 3, as storage threshold is estimated by linearly aggregating $S_{FCthreshold}$ and $S_{HPthreshold}$ in equations (5) and (6), which is prone to simultaneously increase flood damage and decrease hydropower production. Please give more justification description.

***Authors' response*:** Thank you for these comments and suggestions.

(1) The outflow from reservoirs are indeed the important variables, to which the variables for benefits, and feedback to the cooperation are dependent on. We have developed those sets of simplified reservoir operation equations (3-6) ourselves based on the conceptual understanding of the reservoir operation processes, including reviews of USACE (2003), to infer outflow from inflow and storage level. These three variables – storage, inflow, and outflow are presented in Section S1 of the supplementary material.

To simply describe the equations 3-4, it is a sequence of conditional statements. Here is a description for the U.S. outflow (Q_{oUS}). The first check is to examine whether the reservoir storage is full. In case the incoming volume of water with current level exceed the maximum capacity (Note, maximum capacity for U.S. is also their operating level to maximize hydropower), it should release incoming flow with addition of certain portion of the reservoir too. If the volume check is fine, the second check is whether the inflow is greater than the historical peak outflow that have occurred in the past (i.e., ~8000 m^3/s as shown in Fig. S3 (average monthly outflow)). In case its true then release should be the historical peak outflow. Otherwise if inflow is less than the historical peak flow then the release is inflow with addition of certain volume from the existing storage level.

Similarly, for the Canadian reservoir, the conditions are mostly similar to the U.S. If the first storage volume check is above the maximum capacity, there is additional second check if the inflow is higher than historical peak outflow, if true the release is that peak flow (i.e., ~2700 m^3/s as shown in Fig. S9 (Mica monthly outflow)), otherwise release is inflow in addition of the certain volume from existing storage. However, if the first storage volume check is below the capacity, there is a second check which determine if the portion of the inflow (determined by n_{CA}) is greater than the historical peak, then release is only that peak flow. Otherwise, just release the portion of that inflow in addition to certain volume from the reservoir.

(2) Note that releasing only the portion of the inflow was necessary in order to prevent over release of water to make space for incoming flood flow later. That drawdown is not necessary over the year round. So, $0<n_{CA}<=1$ as a fraction ensure less water is released and stored in the reservoir when not necessary. The n_{CA} is parameterized during calibration.

(3) You are correct the $S_{CAthreshold}$ and $S_{USthreshold}$ represent the current operation determined by the level of probability to cooperation. It is to be noted that $S_{HPthreshold}$ and $S_{FCthreshold}$ for the U.S. and Canada is different, and as we can see in equations 5 and 6. In the case when probability to cooperation is ~1 the second expression of the both equations tend to 0, and Canada operates its reservoir in full flood control mode, similarly the U.S. opt for maximum hydropower production mode. Also note that for flood control the reservoir should draw down to make space for oncoming flow, similarly for hydropower production the reservoir should be kept at full to achieve the maximum head. You are also correct the U.S. may need to operate their own dams to prevent flood damages downstream, while Canada can just produce their own hydroelectricity. This chaotic case only happens when there is no-cooperation, or only when conflict occurs. And this kind of behavior wouldn't happen in the current modelled scenarios. However, numerically that is possible as the system can model cooperation and conflict.

3. Please check whether the second 'C_{CA}' is a typo in equation (6).

***Authors' response*:** Thank you for pointing to this error. It is indeed C_{US} in equation 6.

4. The motivation of applying logit dynamics functions to simulate the cooperation probability variables C_{CA} and C_{CA} should be detailed in line 378.

***Authors' response*:** We will clarify the motivation for logit dynamics in the revised manuscript.

5. It's unjustified to determine the hydropower without considering water head in equation (20), despite that the simulated series can fit the observed series well. Moreover, the threshold water flow is directly selected as 400 m^3 /s, which needs more description.

***Authors' response*:** Thank you for this question. The total hydropower benefits from the U.S. treaty dams is the sum of Grand Coulee and other five dams. Only the Grand Coulee dam is the storage hydropower dam where we established the relation between past hydropower production (as a response variable) vs. forebay level and outflow (as independent variables) (Fig. S14). Other dams do not have significant head and are mostly run of river type hydropower plants. For this we have established the relation between past hydropower produced by five dams (as a response variable) vs. outflow from Grand Coulee and weighting factor that considers the operations to meet environmental demands (as independent variables). This later relationship was not the linear, so we have separated the data into two halves (below and higher than 4000 m^3 /s) (Fig. S15). The 400 m^3 /s is a typo and correct is 4000 m^3 /s. We will correct this.

6. It's suggested to add another section in Methodology to describe the feedback loops on basis of the dynamic equations in Section 3.2.

***Authors' response*:** We will revise the Fig.2 and elaborate in the feedback links of the system dynamics.

7. In line 677, how to determine whether the stability is achieved?

***Authors' response*:** Thank you for this comment. In the warmup period of the simulation, the initial value of cooperation changes without the repetition of particular pattern, after which the pattern of the dynamics is well observed. For clarification, as shown in Fig.7b the initial increase in probability took three-time (month) step in simulation. We will clarify this in the revised manuscript.

8. In Figure 7(b), the trajectories of probability to cooperate perform notable periodicity, which needs to be well accounted.

***Authors' response*:** The periodicity is due to the dynamics of the change in cooperation tied to the streamflow which has seasonal pattern. We will clarify this in the revised manuscript.

References

Sopinka, A. and Pitt, L.: The columbia river treaty: Fifty years after the handshake, Electr. J., 27(4), 84–94, doi:10.1016/j.tej.2014.04.005, 2014.

USACE: COLUMBIA RIVER TREATY FLOOD CONTROL OPERATING PLAN, Hydrologic Engineering Branch, Water Management Division, 220 NW 8th Ave Portland, OR 97209-3503. [online] Available from: https://www.nwd-wc.usace.army.mil/cafe/forecast/FCOP/FCOP2003.pdf, 2003.