Reply Letter

Title: Transboundary water sharing policies conditioned on hydrologic variability to inform reservoir operations

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MS No.: hess-2021-72 **MS type:** Research article

Review of HESS-2021-72:

This paper develops optimal water sharing policies for transboundary systems, focusing on the Grand Ethiopian Renaissance Dam. The technical approach is sound, and this system is an important one to study. The results are convincing because they show the tradeoff between minimizing storage variability (i.e. maximizing hydropower) and minimizing release variability for downstream water supply.

I believe that some moderate revisions to the structure and framing would make this paper a stronger contribution to HESS.

Reply: We thank the reviewer for his/her positive comments. The paper has been revised according to your suggestions as described below.

1. My biggest concern is confusion over the methodology, both what is being done, and the reason for the steps. The first step makes sense, optimizing a policy structured as a radial basis function to allow flexible use of information. In my understanding, the steps are: optimize a RBF policy, use it to infer a linear drought constraint, and then use this constraint to re-optimize another RBF policy. Is that correct?

If so, why are these last steps needed? For example, the flow of logic in Figure 3 is very unclear. It seems to repeat optimization steps in places. How is the drought mitigation policy different from the RBF policy, and why is it needed? The RBF is already a function of storage, inflow, and the month. The drought mitigation policy sets minimum annual constraints for water releases. But it seems that this could have been part of the original RBF optimization, and/or enforced in the simulation model to ensure that the constraint is met at all times.

More explanation and structure on these points throughout Sections 1-3 would be very beneficial. While the results are convincing overall, I was not sure that the drought mitigation policy is needed in the end (Fig 14), as there is only a small advantage to these extra steps.

Reply: We thank the Reviewer for highlighting this point, and agree that more clarity will be beneficial. The Reviewer's assessment of the steps involved (first paragraph above) is correct. However, it needs to be noted that the exceedance parameter z (which describes the degree of conservativeness in the policy) in equation 10 is required to obtain the final linear drought constraint. This is why the second optimization is performed. Initially, for the drought mitigation policy with a mean output of 1770 MW (Figure 4 in the original manuscript), only the linear drought constraint with an exceedance parameter z = 80% can ensure power output greater than 1770 MW (all points in the scatter plot are above the linear constraint line). For this study, the exceedance parameter z in our proposed drought mitigation policy is set as 0%, thus the last step includes re-optimization of RBF policy to verify the performance of the linear drought policy. In the example of Figure 4 (z=0%), it is very possible that the re-optimized maximum mean output could be lower than the original 1770 MW (although it was 1772 MW, according to the 'Policy 4' in Figure 11 of the original manuscript).

Thus, the optimization in the first step is used to find the trade-off between downstream and upstream benefits and build the linear drought policy, and the optimization in the last step is used to validate the drought policy performance for various exceedance levels (equation 10).

To avoid misunderstanding, we have included the reservoir inflow and water release relationship, which is used to infer the drought policy, in the revised manuscript as below (gray scatter plot points), to compare with the re-optimized results.

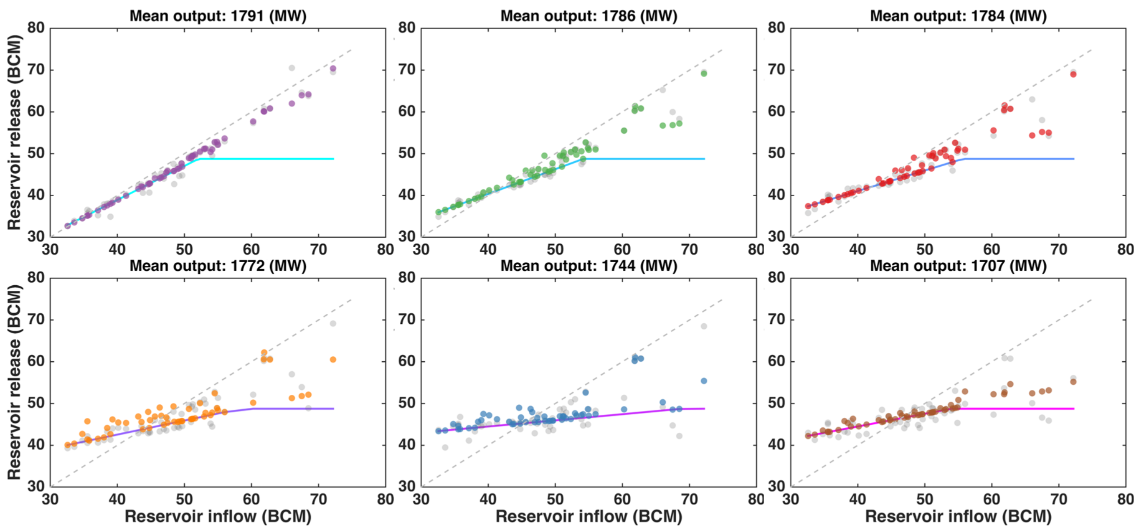

Fig. 13 Relationship between annual reservoir inflow and releases using re-optimized reservoir operating rules; drought policies represented by lines; gray points refer to the inflow and release relationship from which drought policies are derived.

The Reviewer is correct in that the drought mitigation policy sets minimum annual constraints for water releases and it could be part of the original RBF optimization (i.e., we can optimize the RBF policy and the drought mitigation policy simultaneously). However, we believe the results of this one-step optimization are not easy to interpret, considering the complex combinations between RBFs and slopes and intercepts of a linear drought policy. For example, two drought policy lines with similar power generation levels could have totally different slopes and intercepts and it is then difficult to isolate the impact of the slope or intercept. In contrast, for the development of the drought policies proposed here, the impact of slope on power generation is intuitive (see Figure 8 in the original manuscript).

Indeed, the slope of the drought policy line is highly correlated with variability in reservoir releases (a steeper gradient generally produces more variability in reservoir releases), while the intercept (which is conditional on the exceedance level z) mainly controls the degree of drought mitigation; larger z values indicate higher drought thresholds (see the intersection between the policy line and 1:1 dash line in Fig. 4). In this way we can isolate the impact of these two factors and embed them into upstream-downstream negotiations step-by-step.

We have further clarified why the drought mitigation policy and the re-optimization are advantageous in the revised manuscript as below.

The drought policy is conditioned on reservoir inflows and releases for a transparent, interpretable, and intuitive process, which is important especially when negotiations are involved. The gradient of the policy line is highly correlated with variability in reservoir releases; in general, as the slope increases, so does the variability in releases. Thus, the parameter α *can be estimated from the trade-off between reservoir power generation and downstream water release variability. The exceedance parameter z further controls the degree of drought mitigation; larger z values indicate higher drought thresholds (see the intersection between the policy line and 1:1 dash line in Fig. 4). In the drought policy design, these two parameters can be estimated separately to isolate their impact on drought mitigation performance. This case study mainly focuses on the impact of the first parameter as the exceedance parameter z is eventually set to 0%.*

Additionally, Figure 3 has been updated in the revised manuscript as below.

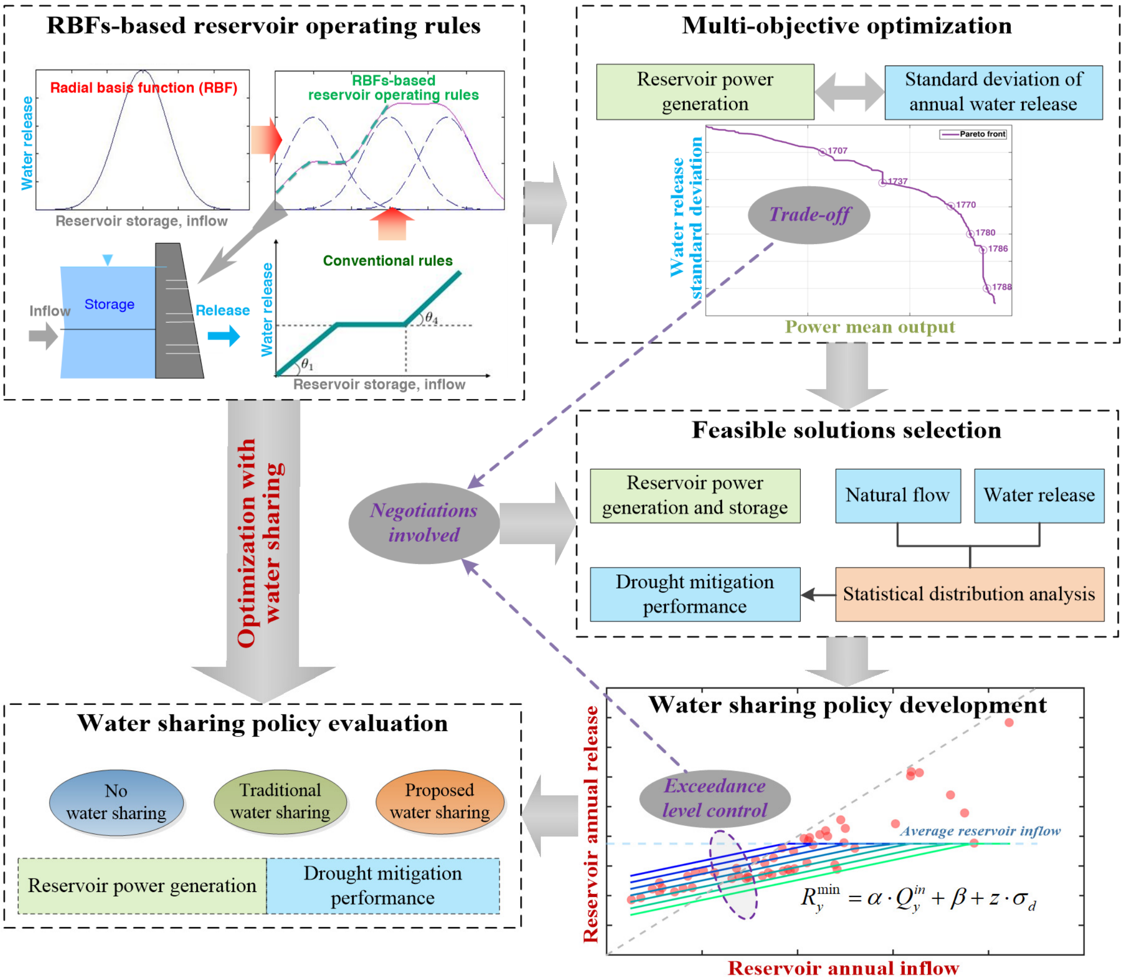

Fig. 3 Procedure of drought mitigation policy derivation and evaluation for reservoir operation in transboundary rivers.

In the revised manuscript, we now also directly optimize the RBF policy conditioned on a conventional water sharing policy (minimum annual water release constraints), with the GERD guaranteeing a fixed amount of water release every year. Compacts adopting this strategy in whole or in part include the Colorado River Compact, Arkansas River Basin Compact, and Sabine River Compact, 68 Stat. 690 (1953) (Draper 2006; McCormick 1994). We have included a comparison and corresponding discussions in the revised manuscript as below.

The reservoir operation results of the proposed drought policy are compared with those of conventional drought/water sharing policies. A conventional water sharing policy here refers to a "guaranteed quantity" or "minimum flow" strategy, i.e., GERD will guarantee a fixed volume of water release each year. Compacts adopting this strategy in whole or in part include the Colorado River Compact, Arkansas River Basin Compact, and Sabine River Compact, 68 Stat. 690 (1953) (McCormick, 1994;Draper, 2006). A comparison (Fig.

11) indicates that the flexible drought policy proposed here can generate more power than a conventional (static) drought policy with a similar statistical distribution of water releases. In addition, flexible policies can better mitigate drought conditions (see the kernel distribution as well as 10th percentile of water releases in Fig. 11) than static policies for similar power output levels.

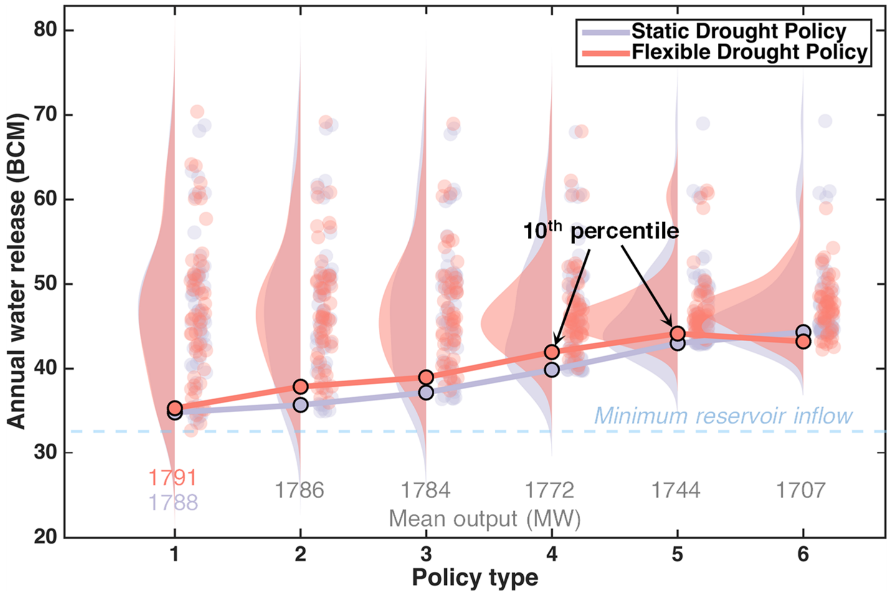

Fig. 11 Comparison of reservoir operations using flexible and static drought policies based on power generation output and water release distribution analysis. Policy type 1 refers to the comparison with a similar statistical distribution of water releases; Policy type 2-6 refer to comparisons with similar power generation outputs.

2. It is also not clear how the drought mitigation policy uses forecast information, or why the original RBF policy does not. Especially because around Line 345 the results suggest that the forecast information is not very useful in the optimized policies.

Reply: The drought mitigation policy uses annual forecast information by replacing the annual reservoir inflow in the x-axis of figure 4 with the annual reservoir inflow forecast/estimation. The original RBF policy is derived at a monthly scale and thus does not use the annual inflow forecast. The forecast information can be further incorporated into GERD operation by using monthly or annual inflow forecasts as one of the input variables (X_t in equations 8 and 9) in RBFs-based rules. Considering this study mainly focuses on drought policy, we only use the annual inflow estimation for the evaluation of drought policies.

As illustrated in line 234-238 of the original manuscript, in the last month of each year the annual reservoir inflow estimation $Q_y'^{in}$ will be equal to actual annual inflow $\sum_1^{12} Q_m^{in}$ and the estimated minimum annual release $R_y'^{\min}$ will be $R_y^{\min}$. If $Q_y^{out} < R_y^{\min}$, the reservoir water release in the last month Q_{12}^{out} will be corrected as $Q_{12}^{out}+\left(R_y^{\min}-Q_y^{out}\right)$ and the Q_y^{out} will be equal to $R_y^{\min}$. Thus annual reservoir release Q_y^{out} will be always greater than or equal to the specified minimum reservoir water release $R_y^{\min}$ and it can be inferred that the minimum annual release $R_y^{\min}$ is mainly determined by the policy parameters α , β , and z, rather than forecast accuracy.

We have further explained in the revised manuscript as below.

The estimated variables $R_y'^{\min}$, $Q_y'^{out}$, and $\sum_m^{12} Q_m'^{in}$ are updated in each time step. In the last month of each year, the annual reservoir inflow estimation $Q_y'^{in}$ will be equal to actual annual inflow $\sum_1^{12} Q_m^{in}$ and the estimated minimum annual release $R_y'^{\min}$ will be $R_y^{\min}$. If $Q_y^{out}<R_y^{\min}$, the reservoir water release in the last month Q_{12}^{out} will be corrected as $Q_{12}^{out}+\left(R_y^{\min}-Q_y^{out}\right)$ and the Q_y^{out} will be equal to $R_y^{\min}$. Thus annual reservoir release Q_y^{out} will always be greater than or equal to the specified minimum reservoir water release $R_y^{\min}$ and it can be inferred that the minimum annual release $R_y^{\min}$ is mainly determined by the policy parameters α , β , and z, rather than forecast accuracy.
As illustrated in equation (10) and Fig. 4, the minimum annual reservoir release can be estimated from the annual reservoir inflow after the drought policy line is determined. Considering actual annual reservoir inflow will not be available until the last month of each year, the annual reservoir inflow forecast is used instead.

3. Another concern is the novelty of the approach. The study follows best practices for direct policy search (DPS) and arrives at a convincing result. However, I believe this approach has been used for transboundary systems before. It seems the new component of this study is deriving water-sharing policies (i.e. annual linear constraints) that are specific to drought periods. This may be a novel contribution, but as in point (1) it is not clear why this needs to be done here. The link could also be stronger between the linear constraint and the idea of a negotiated water-sharing policy between transboundary stakeholders.

Last, if the novelty relates to transboundary basins, is there any component of the methodology that is specifically designed for this case? The contribution may be more general, although the transboundary application is critically important.

Reply: Thank you for your suggestions. The novelty of this work is the water-sharing policy design, which combines trade-off analysis of upstream-downstream benefits and drought mitigation based on hydrological variability. Traditional water-sharing policies generally control the reservoir water release or storage in a static way, for example, a "storage limitation" strategy limits the amount of water that an upstream entity may impound annually, seasonally, etc., while a "minimum flow" strategy guarantees a fixed volume of releases every year or other time period. In this way, most of the risk in water shortages or hydrological variability will fall upon the upstream or downstream parties and the trade-off of upstream-downstream benefit/risk is rarely considered in water sharing policy design.

To support water sharing in a more flexible way, some literature develops benefits sharing policies (Teasley and McKinney 2011) and strategies (Degefu et al. 2016; Li et al. 2019; Wheeler et al. 2016) based on cooperative water resources operations and simulations. These policies and strategies rely heavily on hydro-economic modeling and cost-benefit analysis (Jeuland et al. 2014), which strives to maximize overall aggregated benefits and subsequently allocate benefits in an equitable way. However, (1) the aggregation of benefits can hide important trade-offs and may increase the risk of floods and droughts for maximum economic benefit; (2) there is no standard that regulates how benefits of water use from various sectors (e.g., drinking, agriculture, industry, recreation, and navigation) are quantified and what mechanism should be applied to equitably allocate/share the benefits (Acharya et al. 2020); and (3) there is presently no basin-wide authority to enforce benefit allocations (e.g. payments from one country to another) although institutions such as the Nile Basin Initiative could serve in this role (Arjoon et al. 2016). Thus, water sharing policies considering the trade-off between economic benefits and drought risk, rather than benefit sharing policies based on cooperative operation strategies analysis, are investigated in this study.

The water sharing policy proposed here inherits the flexibility of the aforementioned benefit sharing policies by incorporating reservoir operation optimization and maintains the intuitiveness of traditional water-sharing policies by informing reservoir operations with an interpretable and intuitive linear-regression-based rule.

We have further clarified the novelty of this work in the revised manuscript as below.

Most previous studies focus on illustrating the importance of a cooperative strategy through water system optimization and simulation (Dombrowsky, 2009;Tilmant and Kinzelbach, 2012) and evaluating the benefits of cooperative operation in transboundary river basins (Goor et al., 2010;Anghileri et al., 2013;Uitto and Duda, 2002;Luchner et al., 2019). There is less literature (Wheeler et al., 2016;Li et al., 2019;Degefu et al., 2016;Teasley and McKinney, 2011)., however, addressing strategies for reaching an agreement or consensus on water resources development amongst downstream and upstream riparian countries in transboundary river basins. Also, although cooperation in transboundary river basins can result in a win-win situation for both downstream and upstream stakeholders, cooperative water use strategies are obstructed by single-sector interests, especially when long-term commitments are involved (Wu and Whittington, 2006). More specifically, it is often difficult to achieve a mutually agreed-on cooperation strategy given divergent solution preferences by stakeholders.

Additionally, benefit sharing policies rely heavily on hydro-economic modeling and cost-benefit analysis (Jeuland et al., 2014), which strives to maximize overall aggregated benefits and subsequently allocate benefits in an equitable way. However, (1) the aggregation of benefits can hide important trade-offs and may increase the risk of floods *and droughts for maximum economic benefit; (2) there is no standard that regulates how benefits of water use from various sectors (e.g., drinking, agriculture, industry, recreation, and navigation) are quantified and what mechanism should be applied to equitably allocate/share the benefits (Acharya et al., 2020); and (3) there is presently no basin-wide authority to enforce benefit allocations (e.g. payments from one country to another) although institutions such as the Nile Basin Initiative could serve in this role (Arjoon et al., 2016). Thus, water sharing policies considering the trade-off between economic benefits and drought risk, rather than benefit sharing policies based on cooperative operation strategies analysis, are investigated in this study. The policies will be flexible, interpretable, and more importantly drought-focused such that downstream drought mitigation will become an inherent part of the water sharing framework.*

Acharya, V., Halanaik, B., Ramaprasad, A., Swamy, T. K., Singai, C. B., and Syn, T. (2020). "Transboundary sharing of river water: Informating the policies." *River Research and Applications*, 36(1), 161-170.

Arjoon, D., Tilmant, A., and Herrmann, M. (2016). "Sharing water and benefits in transboundary river basins." *Hydrology & Earth System Sciences*, 20(6).

Degefu, D. M., He, W., Yuan, L., and Zhao, J. H. (2016). "Water allocation in transboundary river basins under water scarcity: a cooperative bargaining approach." *Water resources management*, 30(12), 4451-4466.

Draper, S. E. "Sharing water in times of scarcity: Guidelines and procedures in the development of effective agreements to share water across political boundaries."

Jeuland, M., Baker, J., Bartlett, R., and Lacombe, G. (2014). "The costs of uncoordinated infrastructure management in multi-reservoir river basins." *Environmental Research Letters*, 9(10), 105006.

Li, D., Zhao, J., and Govindaraju, R. S. (2019). "Water benefits sharing under transboundary cooperation in the Lancang-Mekong River Basin." *Journal of Hydrology*, 577, 123989.

McCormick, Z. L. (1994). "INTERSTATE WATER ALLOCATION COMPACTS IN THE WESTERN UNITED STATES-SOME SUGGESTIONS 1." *JAWRA Journal of the American Water Resources Association*, 30(3), 385-395.

Teasley, R. L., and McKinney, D. C. (2011). "Calculating the benefits of transboundary river basin cooperation: Syr Darya Basin." *Journal of Water Resources Planning and Management*, 137(6), 481-490.

Wheeler, K. G., Basheer, M., Mekonnen, Z. T., Eltoum, S. O., Mersha, A., Abdo, G. M., Zagona, E. A., Hall, J. W., and Dadson, S. J. (2016). "Cooperative filling approaches for the grand Ethiopian renaissance dam." *Water International*, 41(4), 611-634.

4. The results are a bit too long, with 14 figures. These could be condensed to sharpen the contributions. In my opinion a few figures that might be removed are: Fig 7, Fig 9 (previous figures already show the change in standard deviation), and Fig 12.

Reply: Thank you for your suggestions. In the revised manuscript, we have further sharpened the contributions, removing Fig. 7 and Fig. 12, and moving Fig. 9 to the Supplemental Data.

5. In the introduction and methods, there are several places where the references are grouped together in long lists. It would be stronger to highlight individual contributions from these previous studies where possible.

A minor point about the introduction: clearly simulation-optimization is relevant, but why is policy fitting relevant to this study?

Reply: Thank you for your suggestions. We have shortened or divided these grouped references and highlight individual contributions in the revised manuscript. For example:

Thus in recent decades, many models and strategies have been investigated to inform and improve reservoir operation decision-making (Chaves and Chang, 2008;Cancelliere et al., 2002;Herman and Giuliani, 2018;Karamouz and Houck, 1982;Giuliani et al., 2014;Oliveira and Loucks, 1997). For example, Karamouz and Houck (1982) optimize monthly reservoir releases by deterministic dynamic programming and build a linear reservoir operation model conditioned on the relationship between optimal releases and reservoir state variables. Cancelliere et al. (2002) build a non-linear reservoir operation model by using neural network techniques to improve reservoir irrigation water supply during drought conditions. Herman and Giuliani (2018) design a tree-based policy which is flexible and interpretable for reservoir operation over multiple timescales.

Considering simulation-optimization is more relevant than policy fitting to this study, we have removed the highlighted references about policy fitting in the revised manuscript. Policy fitting requires an optimal set of reservoir inflows, storages, and releases and the fitted rules generally perform worse than simulation-optimization-based rules, however, the rules derivation process is interpretable and intuitive when optimal reservoir decision-making is highly correlated with state variables. This is the main reason why policy fitting is used to develop the linear drought policy in this study. We have further explained this reasoning in the revised manuscript as below.

In Introduction:

A policy fitting approach requires an optimal set of reservoir inflows, storages, and releases and its effectiveness highly depends on the performance of the optimized reservoir operation model; however, the rules derivation is interpretable and intuitive when optimal reservoir decision-making is highly correlated with state variables. In contrast, simulation-optimization-based approaches do not rely on existing optimal reservoir operations and thus it is generally more flexible than fitting-based rules.

In Models and Methods:

The drought policy is conditioned on reservoir inflows and releases for a transparent, interpretable, and intuitive process, which is important especially when negotiations are involved.

6. There are several possible discussion points that could be included briefly. First, the tradeoffs found in this study are based on a period of historical data, but what about the future? Do we expect patterns of variability to be similar? Second, is there a way to better understand the characteristics of the optimized policies so that they could be reported to stakeholders, for example? These can be points for future work but deserve some discussion.

Reply: Thank you for your suggestions. Yes, the trade-off between power generation and water release variability and the relationship between reservoir inflows and releases are based on historical data. Both of them can be affected by land use or climate changes, and if significant, the water sharing policy may need to be adjusted accordingly. Clearly, there still exists a trade-off between reservoir power generation and water release variability under changing conditions, which can still be used to inform drought policy design, and the linear feature of the drought policy makes it relatively easy to adjust. It is very important to connect the characteristics of a water sharing policy with the trade-off between reservoir storage and releases. In this study, greater variability in releases will lead to a steeper gradient of the drought policy line. These types of drought policy characteristics can provide guidance for stakeholders to effectively adjust the water sharing policy.

We have included the following discussion in the revised manuscript as below.

It is worth noting that the trade-off between power generation and water release variability and the relationship between reservoir inflows and releases are based on historical data and may be affected by future changes in land use, climate, etc. Thus, the water sharing policy may need to be adjusted accordingly to better mitigate drought conditions in the future. However, there will always exist a trade-off between reservoir power generation and water release variability, which can be used to inform drought policy design, and the linear feature of the drought policy makes it relatively easy to adjust. It is very important to connect the characteristics of a water sharing policy with the trade-off between reservoir storage and releases. In this study, greater variability in releases leads to a steeper gradient of the drought policy line. These types of drought policy characteristics can provide guidance for stakeholders to effectively adjust the water sharing policy. Thus, the interpretable drought policy proposed here can enhance the understanding of water sharing and promote multilateral negotiations between upstream and downstream countries.