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 presents a water-sharing policy framework that incorporates reservoir operating rules optimization based on conflicting uses and hydrologic variability, specifically tailer to drought conditions. The framework is illustrated using GERD as a case study. The results clearly show the trade-off between annual hydropower generation and the inter-annual variability of releases. The paper is well-written and the topic should be of interest to both researchers and practitioners. As explained below, my main concern is with the methodology, which seems to be overly "complex" given the relative simplicity of the case study.

Reply: Thank you very much for your positive comments. We have revised the paper according to your suggestions and provided a point-by-point response to your concerns as below.

Comments/questions:

1. The emphasis is put on average annual power output. However, power companies are also concerned by the firm energy, i.e. the energy output that you can guarantee 90% or 95% of the time. Can you show us what the trade-off would look like when the average energy output is replaced by the firm energy?

Reply: Thank you for your suggestions. We agree with the importance of considering firm energy and due to space limitations did not include it in the original version. Comparing the firm energy output (at a guarantee of 90%) with the standard deviation of releases, we obtain the Pareto front as below.

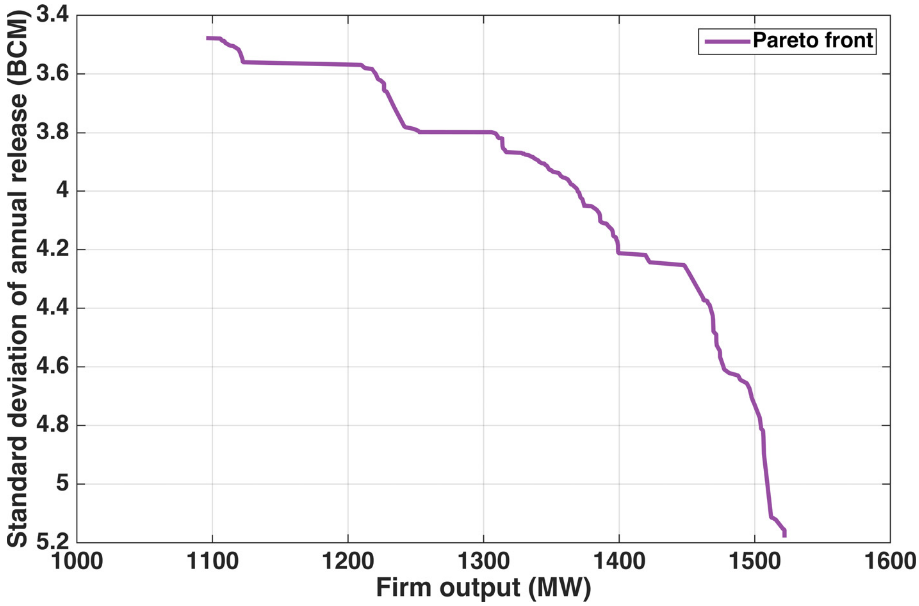


Fig. S1 Pareto front for maximum firm output (90% guarantee) and minimum annual water release variance.

We have added this trade-off in the supplementary data of the revised manuscript. Additionally, we have amended the following text:

Thus downstream countries may benefit more from reservoir operating rules favoring smaller $Std\left(Q_y^{out}\right)$ *in drought conditions; this trade-off between power generation and* $Std\left(Q_y^{out}\right)$ *can be used to balance GERD power generation and downstream water use benefits. There also exists a trade-off between* $Std\left(Q_y^{out}\right)$ *and other power indicators such as firm output (see Fig. S1 in Appendix S1).*

It needs to be noted that the firm output of GERD is mainly determined by the operation during January and April (see Figure 2 below). In contrast, both mean output and annual release variance are calculated from the operation results during the full year. Also, releasing more water downstream during dry seasons can - to some degree - increase the firm output. Thus, the trade-off between firm output and annual release variance is not stark. To better illustrate the trade-off between upstream and downstream benefits, we focus on the mean output in this study. Future studies could consider the requirement of firm energy as a constraint in GERD operations.

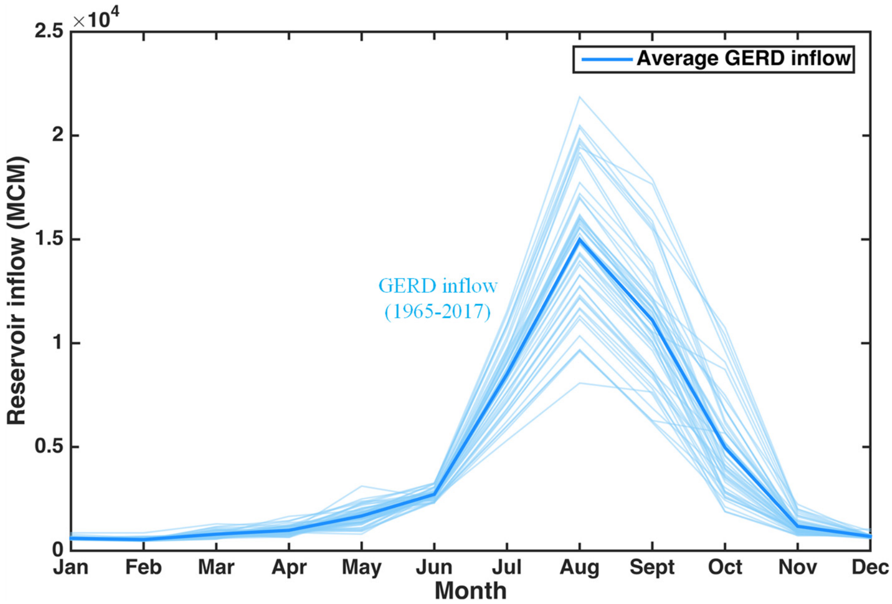


Fig. 2 Monthly inflow into the GERD reservoir during 1965-2017.

2. Does the term "water releases" include turbined outflows AND spillage losses?

Reply: Yes, "water releases" in this study includes both the turbine outflows and excessive spillages. Although spilling water in the flood season is not used for power generation, it can be used downstream. Also, to minimize adverse downstream flood conditions due to excess spilling, water release volumes are constrained to be less than the maximum reservoir inflow during the flood season (see equation 6 in the original manuscript). We have further clarified this in the revised manuscript as below.

Section 2.1:

In this study, GERD reservoir operation rules are developed considering power generation and downstream water release (including turbine outflows and spillage losses) simultaneously to mitigate upstream-downstream water use conflicts, particularly tailored to drought periods.

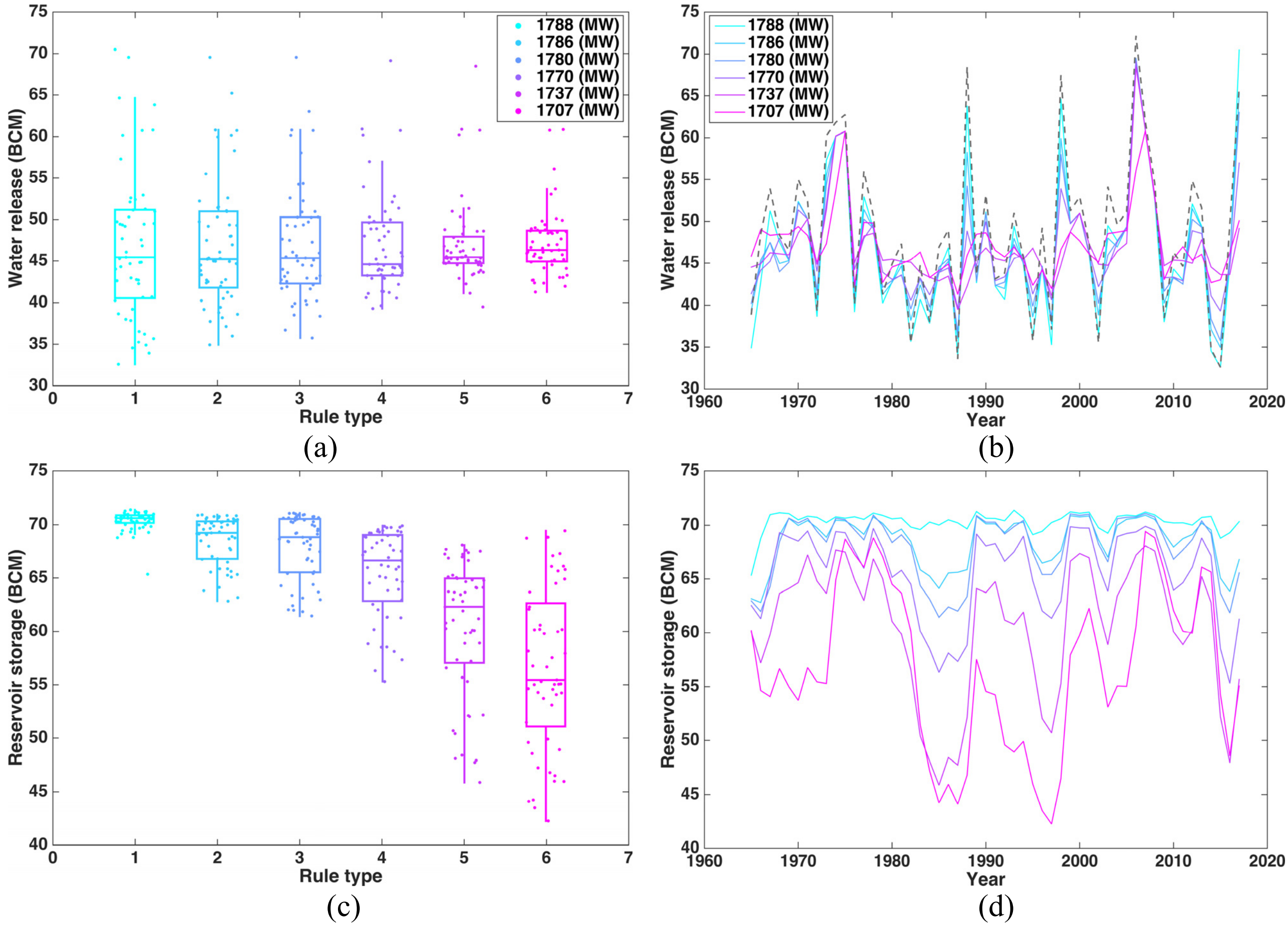
Section 3.1:

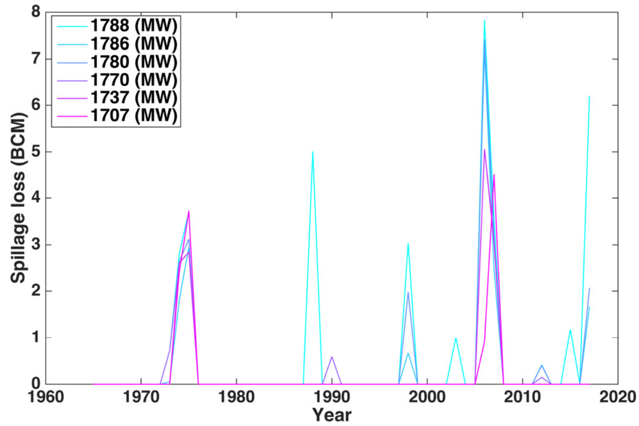
where Q_y^{out} *is the reservoir water release (which includes turbine outflows and spillage losses) in year y and* $\bar{Q}_y^{out}$ *and* $Std\left(Q_y^{out}\right)$ *are the mean value and standard deviation of reservoir annual water release across all operational years Y, respectively.*

3. When minimizing the variance of water releases, do you end up to a point where the energy output starts decreasing due to excessive spillages losses?

Reply: Thank you for your comments. Considering evaporation loss is much smaller than reservoir inflow, the total volume of water release (during 1965-2017) is approximately the same as the total GERD inflow volume. It can be inferred that minimizing the variance of annual water release will lead to less releases in wet years and thus less excessive spillages losses (which mainly occurs in wet years). We have included the spillage losses of various reservoir operating rules in Figure 6 of the original manuscript as below. It shows that monthly rules with less variance of water releases (less power output) produce less spillage than other rules. In contrast, spillage loss from rules with a mean output of 1788 MW (rule type 1, with greatest annual release variance) occurs more frequently (and the magnitude is also greater) than other rules.

It needs to be noted that we are optimizing reservoir operating rules not only for minimum annual release variance, but also for maximum monthly mean output. The latter objective will to some degree avoid excessive spillage losses in dry seasons and years. As shown in Figure 11 of the original manuscript (and copied below), the final reservoir operating rules are optimized for maximum mean output, in which the drought policy is used as a constraint, therefore large excessive spillages are unlikely. Thus, when minimizing the variance of water releases, the energy output starts decreasing mainly due to the lower reservoir water level, rather than excessive spillages losses. Also, releases are set to be lower than the maximum reservoir inflow during the high-flow season to reduce or eliminate downstream floods/spilling (see equation 6 in the original manuscript).





(e)

Fig. 6 Boxplots and values of annual reservoir (a)(b) water releases, (c)(d) storages, and (e) spillages for various reservoir operating rules; dished line in (b) refers to reservoir inflow.

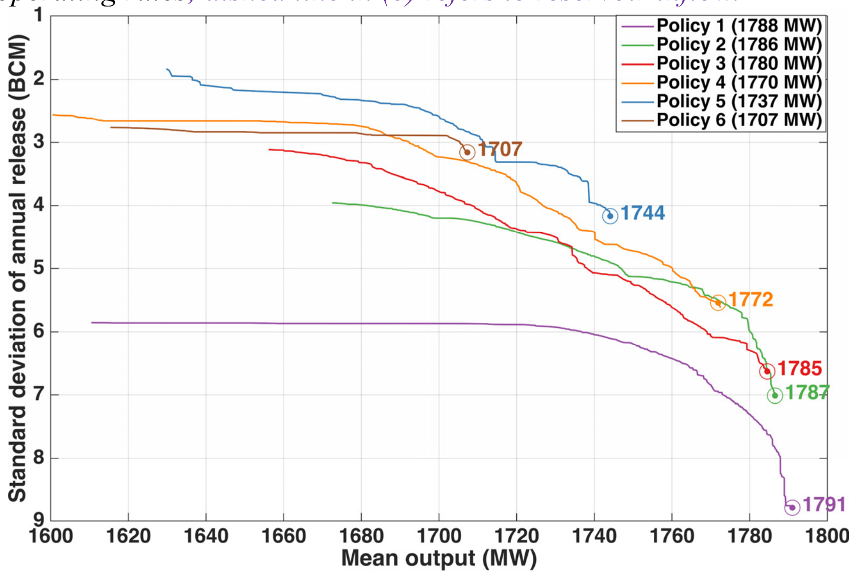


Fig. 11 Multi-objective optimization of reservoir operating rules with drought mitigation policies.

4. My main concern. Why didn't you constrain the operating rule with a minimum "water release" (or minimum deviation from a target release) in the first step of the methodology and construct your Pareto front by varying that minimum like in the traditional constraint method in MOP? The system is small (just one reservoir) and it looks like to me that the Pareto front could be traced out using mathematical programming techniques in a MO framework. In my opinion the introduction must be revised to better explain why that framework was proposed instead of traditional MOP approaches.

Reply: Thank you for your comments. This is an interesting point raised by the reviewer because it's true that the drought mitigation can be considered by constraining the operating rule with a minimum "water release" (or minimum deviation from a target release). This type of "minimum water release" strategy has been applied in whole or in part in the Colorado River Compact, Arkansas River Basin Compact, and Sabine River Compact, 68 Stat. 690 (1953) (Draper 2006; McCormick 1994). We have also optimized the reservoir operating rules with the constraint of minimum GERD "water release" each year and compared this traditional constraint method with our proposed drought policy. We find that the flexible drought policy proposed here can generate more power than the traditional constraint method with a similar statistical distribution of water releases. We have included the results 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. This is because the flexible policy is derived from optimal reservoir operation results, which tends to generate more power. In contrast, the static policy (which is presented as a horizontal line instead of sloped lines in Fig. 10) transfers the risk of water shortages (or hydrologic variability) completely to the upstream GERD, which will limit GERD's ability to produce more power.

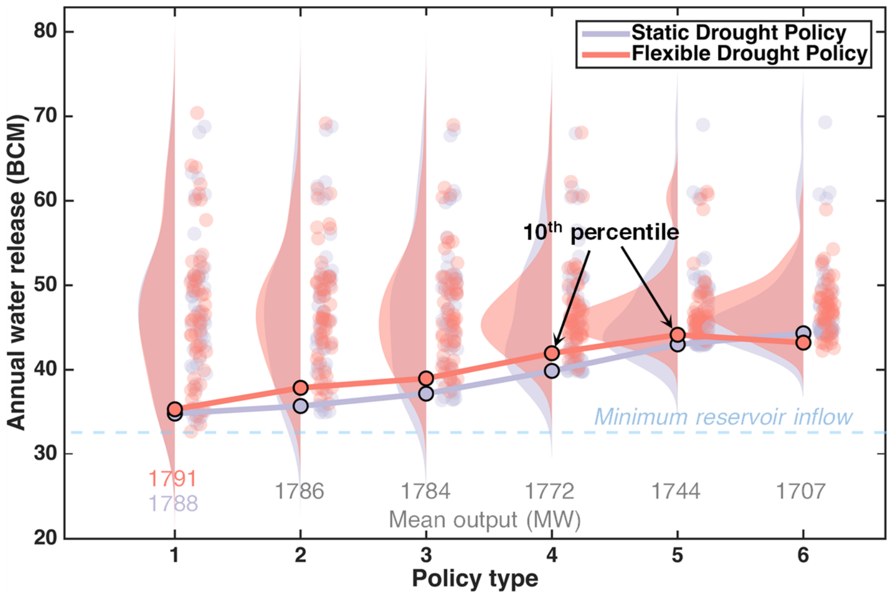


Fig. 11 Comparison of reservoir operations using flexible and static drought policies based on power generation output and water release distribution analysis. Policy type 1 refers to the comparison with a similar statistical distribution of water releases; Policy type 2-6 refer to comparisons with similar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

We agree that the single-reservoir operation problem can be solved by using mathematical programming techniques such as non-linear programming and dynamic programming. However, the main purpose of this study is not to obtain optimal solutions of reservoir operation problems with specific objectives and constraints, instead, we are proposing a framework to derive an intuitive, interpretable, and flexible water sharing policy which can be incorporated into flexible reservoir operating rules. More specifically, we are not minimizing the variance of water releases to select final reservoir operating rules and associated drought policy; instead, we use the release variance as a proxy of downstream benefits to understand the trade-off between GERD power generation and downstream releases to support negotiations between upstream and downstream stakeholders. After negotiation, the selected (mutually agreed) point in the Pareto front in Figure 5(a) of the original manuscript can be used to infer a linear drought constraint to further derive reservoir operating rules.

To better illustrate the procedure of water sharing policy derivation, we have updated the Figure 3 in the revised manuscript as below.

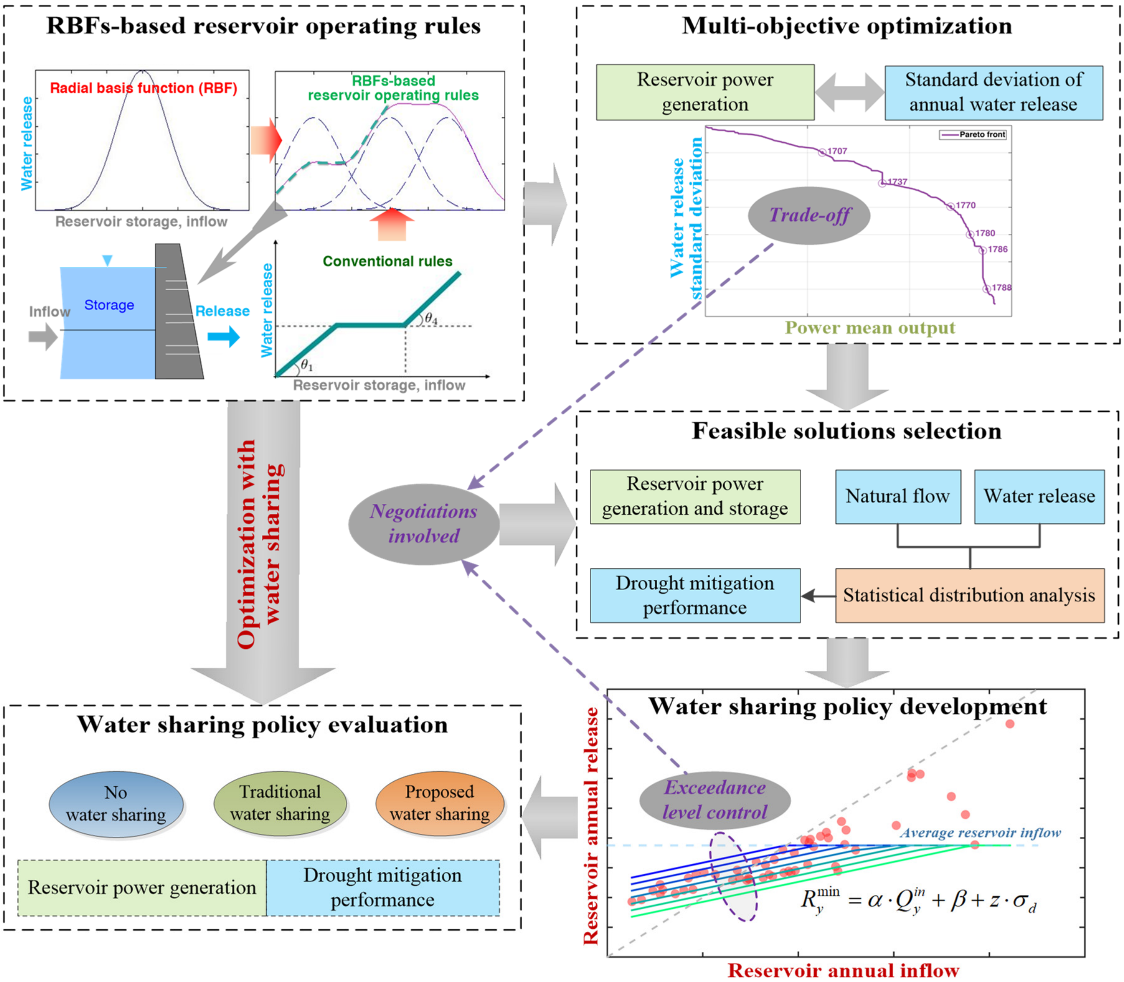


Fig. 3 Procedure of drought mitigation policy derivation and evaluation for reservoir operation.

The procedure of water sharing policy design looks overly "complex" mainly because both the derivation and evaluation of the policy are included (two optimization steps are involved). As shown in the updated Figure 3, optimization in the first step is used to find the trade-off between downstream and upstream benefits and build the linear drought policy, and optimization in the last step is used to validate the drought policy performance for various exceedance levels (equation 10). Also, we consider the potential to inform upstream-downstream negotiations in water sharing policy design through a transparent, flexible, and intuitive process. We have further clarified the necessity of these steps 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%.*

To better integrate the RBFs-based reservoir operating rules and drought policy, we infer the linear drought constraint by optimizing RBFs-based rules (in which reservoir decision-making is only informed by seasonal information, current reservoir storage and inflow) instead of using a 'perfect' reservoir decision-making series optimized from dynamic programming. In that way, the maximum power generation of a drought policy (see selected points '1791', '1787', and '1785', etc. in Figure 11 of the original manuscript) will be similar to the power generation of the original reservoir operating rules (see Figure 5(a) in the original manuscript). Also, using the simulation-optimization method, instead of mathematical programming techniques to obtain the Pareto front in this case, offers the additional advantage of demonstrating a method that can be applied to reservoir systems with more state variables.

To better clarify the novelty of this work and explain why this water sharing framework was proposed, we have revised the 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.*

In this study, a systemic framework is proposed to derive operational reservoir water-sharing policies using multi-objective optimization for water use conflict mitigation. Specifically, (1) optimize reservoir operating rules and establish trade-off between upstream benefits and downstream drought risks, (2) simulate reservoir operation with the candidate (optimal) rules, evaluate performance, and select the most suitable rules for balancing benefits, (3) derive water-sharing policies conditioned on reservoir operations and water availability, and (4) re-optimize reservoir operating rules incorporating derived water-sharing policies to evaluate effectiveness and performance. The drought-focused water-sharing policies are interpretable as they are derived from and evaluated on reservoir operation simulations from existing optimal rules. Further, the policies are considered flexible by offering opportunities for informing upstream-downstream negotiations.

5. Line 90. Please check the paper from Teasley and McKinney, JWRPM, 2011 on water and benefits sharing in the Aral Sea Basin.

Reply: Thank you for your reminder. The paper from Teasley and McKinney, JWRPM, 2011 develops a draft agreement on the allocation of water and energy resources based on cooperative operation and benefit-sharing. We have included the paper in the introduction of the revised manuscript as below.

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.

In this work, we are developing water sharing policies considering the trade-off between economic benefits and drought risk, which is different from a water allocation strategy or agreement based on benefit-sharing as in this JWRPM paper. It needs to be noted that policies and strategies based on cooperative operation and benefit-sharing 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, we develop water sharing policies considering the trade-off between economic benefits and drought risk, rather than benefit sharing policies based on cooperative operation strategies analysis in this study.

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).

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.
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.

6. I have a small gripe with the title. The methodology is actually applicable to any reservoir and it is not limited to transboundary river basins. Please remove "transboundary" from the title and revise the text accordingly.

Reply: Thank you for your suggestions. We agree to change the title to "Water sharing policies conditioned on hydrologic variability to inform reservoir operations" and revise the text accordingly.

7. Line 56. A wide variety of physiographic conditions is not limited to transboundary river basins!

Reply: Yes, we agree that a wide variety physiographic conditions is not limited to transboundary river basins. Considering this study does not include the impact of various physiographic conditions in reservoir operation, we have removed this in the revised manuscript as below.

Reservoir operations in transboundary river basins are necessarily more complex given a wide variety of social, political, economic, and cultural, ~~and physiographic~~ conditions (Zeitoun and Mirumachi, 2008).

8. Figure 12. Could you also include spillages losses and evaporation losses? Keeping the water level as high and as constant as possible will likely increases these two losses, up to a point where they can negatively impact the power output and the total outflows.

Reply: Thank you for your suggestions. We have included spillages losses and evaporation losses in the revised manuscript as below. According to Figure S3, keeping high reservoir water level (greater mean output) will certainly increase both the frequency and the amount of spillage and evaporation losses. Thus, we mitigate this negative affect by optimizing the reservoir operating rules (monthly RBFs-based on direct policy search rules) for maximum power generation (see the selected points in Figure 11 of the original manuscript). Our overall drought policy recommendation is for "Policy 3" in Figure S3, for which spillages losses and evaporation losses are effectively eliminated.

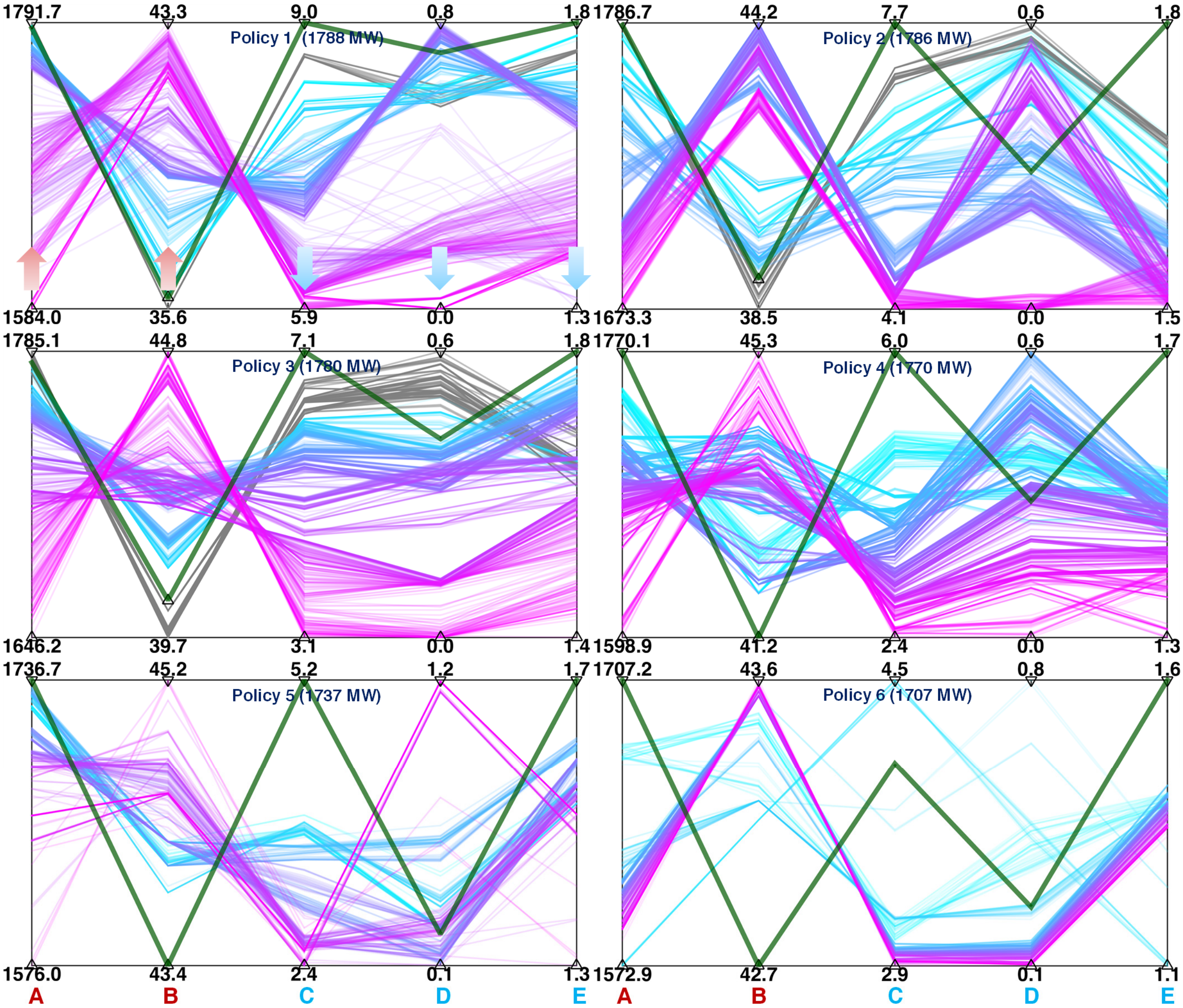


Fig. S3 Parallel plots of multiple objectives (A: mean output (MW), B: 10th percentile of annual water release (BCM), C: standard deviation of annual water release (BCM), D: spillage loss (BCM), E: evaporation loss (BCM)). The bold green line refers to the reservoir operation without the drought policy.