Reply Letter

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

Author(s): Guang Yang and Paul Block

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

Reviewer: Michael J Tumbare

1. General Comments

The Article is well written, and is technically and scientifically sound.

Reply: Thank you very much for your positive feedback. The paper has been revised according to your comments.

2. Review Comments/Discussion Points

a. The scenario relating to the reservoir operation rule curve regards spillage, in which case there could be adverse flooding both upstream and downstream of GERD, has not been dealt with to the same detail and effort as the drought scenario.

Reply: Regarding spilling, releases are set to be lower than the maximum reservoir inflow during the high-flow season to reduce or eliminate downstream floods (see equation 6 in the original manuscript).

According to the GERD operation results, the annual reservoir water release in wet years is lower than the reservoir inflow (all the points in Figure 13 in the original manuscript are below the 1:1 dashed line when the annual reservoir inflow is greater than the multi-year average: 49 BCM). Our overall drought policy recommendation is for a mean output of 1784 MW (top-right of Figure 13 in the original manuscript), for which the GERD operation has effectively eliminated the extreme low and high flows, and thus benefits flood control. Furthermore, another objective in the optimization of the reservoir operating rules is minimum downstream release deviation, which can help to avoid extremely high and low releases.

To clarify this point, the manuscript has been amended as below.

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.

b. It would be interesting to see and compare the results of the resultant water sharing policies if they are applied to, and compared with, other reservoir operation rule curves and water sharing policies for existing dams such as Kariba and Akosombo.

Reply: Thank you for your suggestions. We have compared the results of the proposed (flexible, hydrologic-variability-based) water sharing policies with other conventional water sharing policies in the revised manuscript. The conventional water sharing policy here refers to a "guaranteed quantity at a point," or "minimum flow," strategy. In our case, this would refer to the upstream GERD guaranteeing a fixed amount of water every year or time period. 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) (Draper 2006; McCormick 1994). A comparison (Fig. 14) 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. 14) than static policies for similar power output levels.

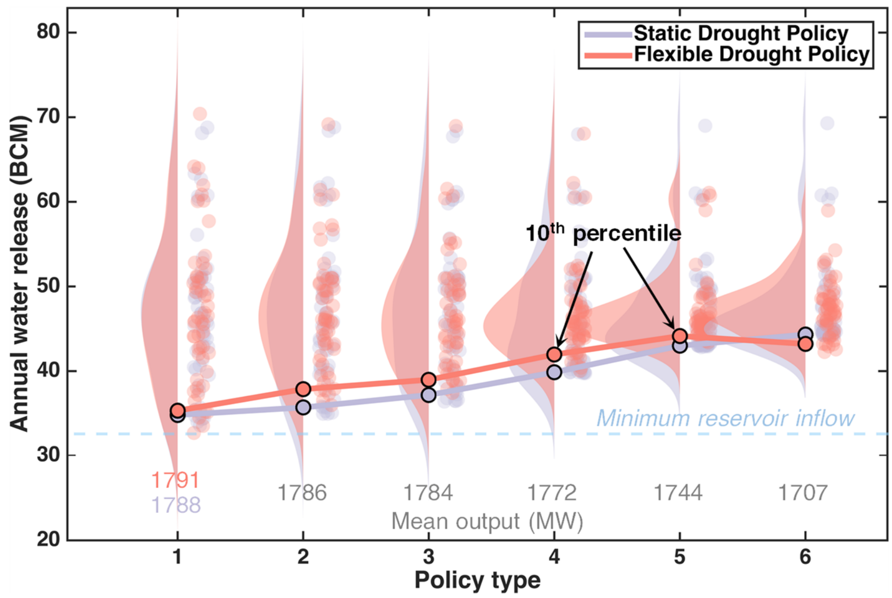

Fig. 14 Comparison of reservoir operations using flexible and static drought policies based on power generation output and water release distribution analysis. Policy type 1 refers to the comparison with a similar statistical distribution of water releases; Policy type 2-6 refer to comparisons with similar power generation outputs.

c. The concepts of “benefit sharing” and “water sharing” are being intermixed in the Article and yet result in different end states. The concept of “benefit sharing” should also be followed to its logical conclusion in the Article, such as optimizing the reservoir operating rules incorporating derived benefits from “benefit sharing” policies and thereafter compare with “water sharing” policies.

Reply: Thank you for your comments. Yes, we agree that “benefit sharing” and “water sharing” are unique concepts and should not be intermixed in the Article. Our intention is to mainly focus on “water sharing” instead of “benefit sharing”. We mention the “benefits” in the Introduction (Section 1), Models and Methods (Section 3), and Results and Discussion (Section 4.1), but again the intent is to be separate from “water sharing.”

In the Introduction, we reference literature regarding “benefit sharing” in transboundary river basins. For example, Arjoon et al. (2016) proposed a benefit-sharing method based on the optimization results from a hydro-economic model and evaluated the value of cooperative water management in the Eastern Nile River basin, in which “benefit sharing” represents developing a sharing strategy for the allocation of monetary benefits from, to, and beyond the river, to ensure basin-wide coordination. In comparison, the “benefit” in other sections refers to the preferences of upstream and downstream in reservoir water release patterns (the upstream prefers releasing less and more water in dry and wet years, respectively for maximum power generation, while the downstream may prefer more evenly distributed releases each year for drought mitigation).

Most benefit sharing policies heavily rely on hydro-economic modeling and cost-benefit analysis (Jeuland et al. 2014), which strives for maximizing the overall aggregated benefit and then allocating the benefit in an equitable way. However, (1) the aggregation of benefits can hide important trade-offs and may increase the risk of droughts for maximum economic benefit; (2) currently, there is no standard that regulates how benefits from various sectors are quantified in Blue Nile basin and it is difficult to develop a mutually agreed-on benefit allocation strategy because of the diversity of stakeholders and their preferences. Also, currently, there is no basin-wide authority in the Blue Nile Basin to enforce benefit allocations (e.g. payments from one country to another), which is another limitation of benefit sharing policies (Arjoon et al. 2016; Dombrowsky 2009). Therefore, we focus on a “water sharing” policy instead of a “benefit sharing” policy in this study. We optimize both power generation and temporal distribution of water releases to account for the trade-off between economic benefits and downstream drought risk, and in this way, drought mitigation becomes an inherent part of the water sharing framework. To avoid confusion of “benefit sharing” and “water sharing” in this study, we have further clarified in the Introduction of the revised manuscript as below.

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.*

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

Dombrowsky, I. (2009). "Revisiting the potential for benefit sharing in the management of trans-boundary rivers." *Water Policy*, 11(2), 125-140.

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.

d. How do the drought-focused water sharing policy results compare with the natural minimum flow policy criteria for passage of water to downstream users (Equation 10)?

Reply: We have included the comparison between the proposed drought-focused water sharing policy and natural minimum flow policy (static policy) in the revised manuscript (see the comparison in Policy type 1 in Figure 14 as below). It can be seen that the proposed flexible drought policy can produce more power than a static drought policy with a similar statistical distribution of water releases. This is because the flexible policy is derived from optimal reservoir operation results, which tends to produce more power generation. In contrast, the strategy of "guaranteeing a certain flow volume" (which is presented as a horizontal line instead of sloped lines in Figure 13) transfers the risk of water shortages (or hydrologic variability) to the upstream GERD, which will limit GERD's ability to produce more power. Thus, to ensure the same/similar amount of power generation, the 'fixed flow quantity' (release criteria) needs to be lower than the minimum release from the flexible policies (see the lowest scatters of Policy types 2-5 in Figure 14). It can thus be inferred that the static policy will produce less power than the flexible policy when the criteria of the 'fixed flow amount' is the same as the minimum release constraint of flexible policies (Policy type 1 in Figure 14). We have included the analysis in the revised manuscript as below.

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.*

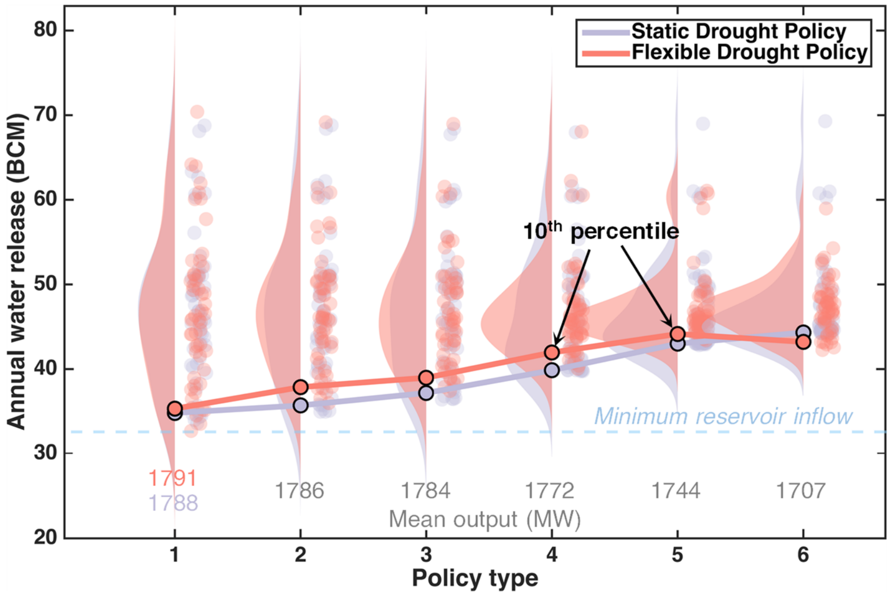

Fig. 14 Comparison of reservoir operations using flexible and static drought policies based on power generation output and water release distribution analysis. Policy type 1 refers to the comparison with a similar statistical distribution of water releases; Policy type 2-6 refer to comparisons with similar power generation outputs.

e. Page 18, Lines 289 to 290. It is proffered that the passage of the natural minimum flow rule/policy should apply in the case that downstream releases should not be less than the natural minimum flows or inflows into the GERD.

Reply: Yes, downstream releases should not be less than the minimum GERD reservoir inflow. This constraint has been included in the revised manuscript and the results have been updated. For example, according to the updated Figure 6 (b) as below, reservoir water releases are equal to or greater than the minimum reservoir inflow (shown with a dashed line).

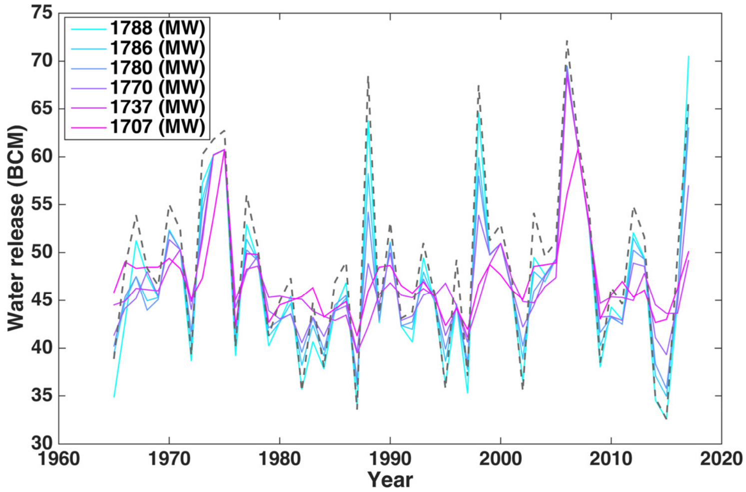

Fig. 6 Boxplots and values of ... (b) water releases .... dashed line in (b) refers to reservoir inflow.
Also, we have updated the corresponding description as below.

However, releasing less water in dry years is not a strategy preferred by downstream countries. Although downstream releases are always greater than the minimum natural GERD inflow (which occurs in 2015), releases may clearly be less than natural flow in some other dry years (e.g., 1965 & 1997, see Fig. 6 (b)), which may aggravate drought conditions. According to the relationship between annual reservoir inflow and water release simulated from rule type 1, water release is less than reservoir inflow in most cases (Fig. 7 (a)).

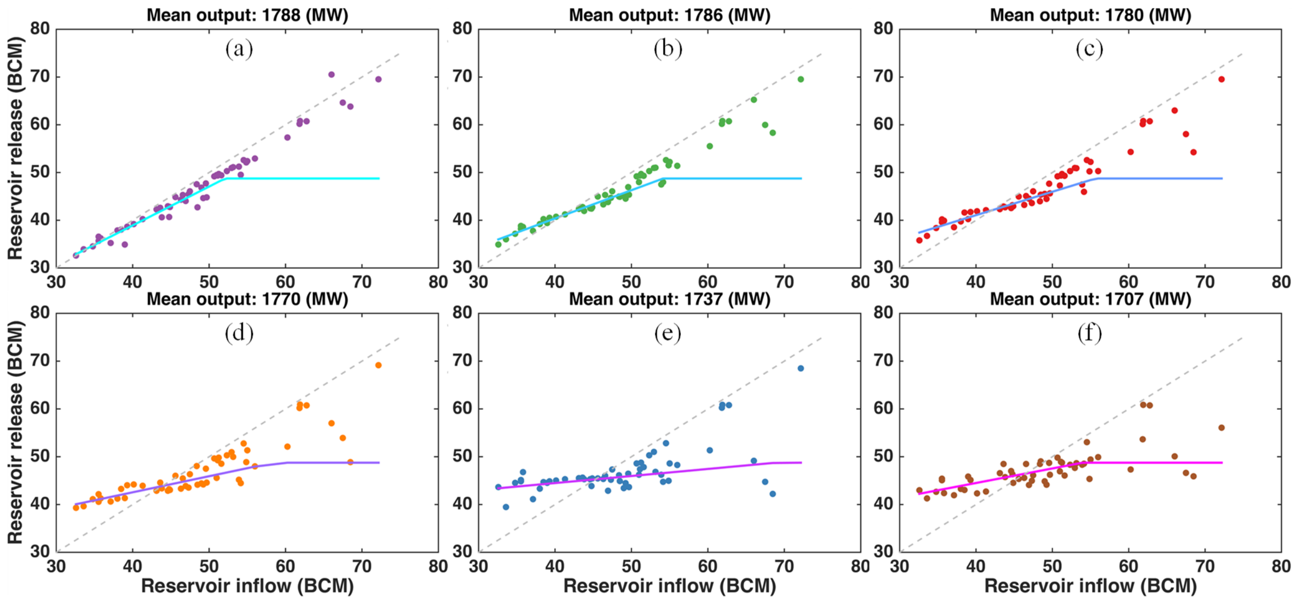

Fig. 7 Relationship between annual reservoir inflow and water release (points) and the corresponding drought mitigation policy (lines) for various power generation levels.

f. Demonstration of reservoir release benefits in drought years should also be shown and compared with those before the GERD impoundments. In any case, the comparison should not only be based on corresponding power generation alone (Page 19, Lines 302 to 303).

Reply: We agree with this suggestion. Reservoir release benefits in drought years have been demonstrated via comparison between the distribution of reservoir releases and inflows (or natural flows) such as in Fig. 9 of the original manuscript. We did not estimate the monetary benefits from reservoir releases by using hydrological-economic simulations as in previous studies (Arjoon et al. 2016). Instead, we use the annual reservoir release amount and the deviation of annual release as a proxy of downstream benefits. More specifically, we compare the statistical distribution of annual reservoir releases and inflows (natural flows). Except for the rule type with a power output of 1788 MW, for all other rule types the 10th percentile of releases is greater than the 10th percentile of annual reservoir inflow (35.8 BCM) (see Figure 9), demonstrating benefits downstream. The comparison of the statistical distribution of annual reservoir inflow (Qin) and release (Qout) from rule type 2 with a mean output of 1786 MW is shown in Fig. 9 and also below, in which vertical lines represent the 10% exceedance value. If this 10% exceedance value of annual reservoir inflow is used as a drought threshold, this rule can be considered effective for drought mitigation (e.g. the 10th percentile of flows increases from 35.8 to 38.5 BCM due to GERD operation). However, this rule will fail to mitigate drought at a threshold of 25% exceedance value (e.g. 25th percentile of releases is less than natural inflow).

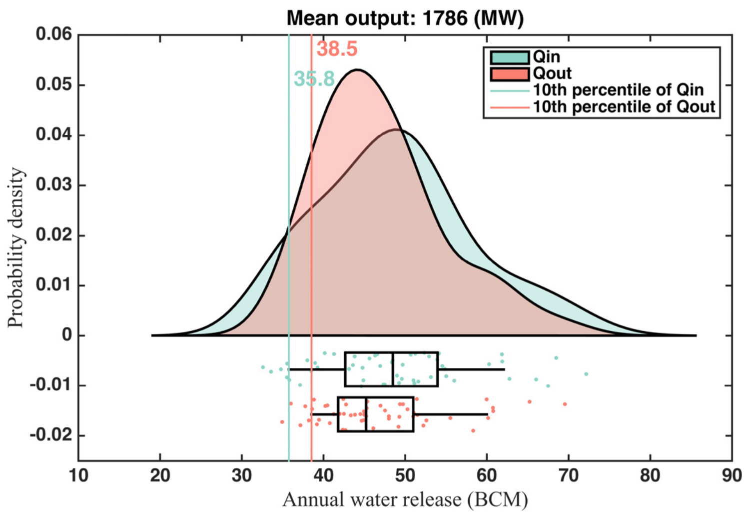

Fig. 9 (upper-left) Kernel distribution of annual reservoir inflow (Qin) and water release (Qout) under different power generation levels (1965-2017). Vertical lines represent the 10% exceedance value.

We have further explained this reservoir release benefit in drought years in the revised manuscript as below.

To select the most suitable drought mitigation policy, both the corresponding power generation and reservoir release benefits in drought years may be evaluated. In this study, annual reservoir release amount and the deviation of annual releases are used as proxies for downstream benefits. For example, if annual releases during drought years is greater than annual reservoir inflow (or *natural flow), downstream droughts are partially mitigated. In general, the statistical distributions of annual reservoir inflow and releases are significantly different when reservoir operations are tailored to drought mitigation. This difference is more pronounced for lower power generation levels (Fig. 9). Considering low flows, the 10th percentile of water releases increases as hydropower generation decreases, from 35.6 BCM for rule type 1 (1788 MW) to 42.7 BCM for rule type 6 (1707 MW). Except for rule type 1, all rule types ensure that the 10th percentile of releases is greater than the 10th percentile of annual reservoir inflow (35.8 BCM).*

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

g. Page 24, Lines 362 to 364. The logic here inclines towards the need for negotiations. If GERD was not there, were they going to be "release" negotiations during droughts or the natural minimum flows would have been expected out of Ethiopia for that drought period?

Reply: It is paramount to develop a water sharing policy for the realization of mutual benefits in the management of trans-boundary rivers. If GERD did not exist, "release" negotiations would clearly not be necessary as Ethiopia has no other major on-stream storage capacity. With GERD, of course, negotiations are vitally important, and the proposed drought policy provides intuitive guidance (including the trade-off between power generation and water releases in drought conditions as well as the framework to develop flexible water sharing policies) and maps out what levels of power generation and statistical distributions of releases in drought and non-drought conditions are possible.

Also, we find that the proposed drought policy outperforms the "minimum flow" strategy in drought mitigation and power generation. The limitation of the "minimum flow" strategy is that the risk of water shortage mainly falls to the upstream country and uncertainty of flows increases the risks of the upstream party's ability to meet their obligations.

h. The final optimal operational rule curve and policy for the GERD is not apparently given.

Reply: This study mainly focuses on a framework for deriving operational reservoir water-sharing policies for drought mitigation in transboundary river basins and not in prescribing the optimal outcome. The final optimal reservoir operational policy depends on the negotiation between upstream and downstream countries, at least on how much power generation is expected. For example, according to Figure 13 in the original manuscript (Figure 10 in the revised manuscript as below), if Ethiopia expects to produce a mean power output greater than 1780 MW and downstream countries accept the corresponding distribution of water releases (Figure 9 in the original manuscript), then "Policy 3" (Figure 10c, as below) may be the preferred policy.

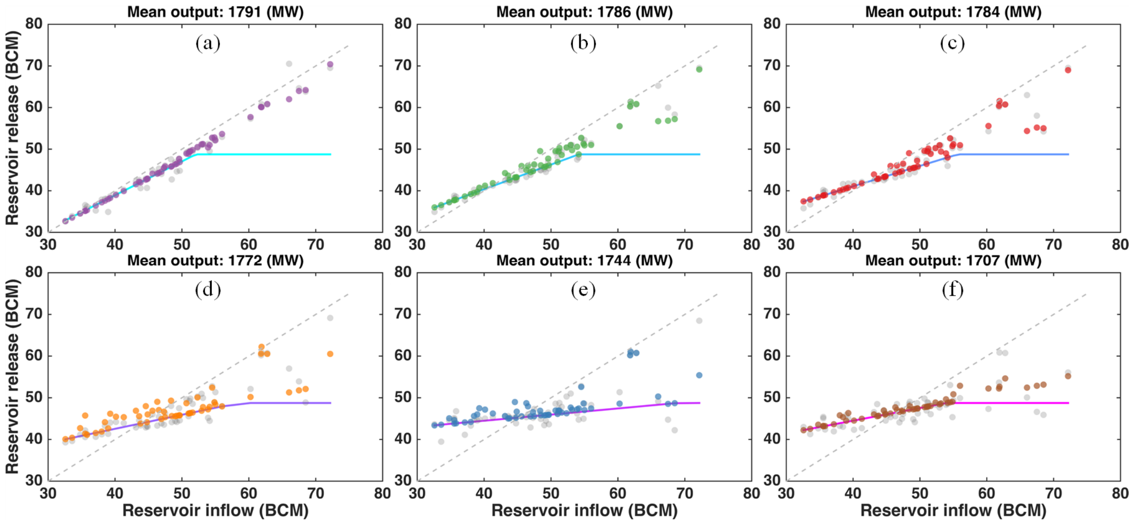

Fig. 10 Relationship between annual reservoir inflow and releases using re-optimized reservoir operating rules; drought policies represented by lines; gray points refer to the inflow and release relationship from which drought policies are derived.

3. Technical Corrections

Remove third tense throughout the Article e.g. Page 1, Line 9 "we".

Reply: Thank you for the suggestion. Third tense and the first-person plural "we" have been corrected with the proper tense in the revised manuscript as below.

A water-sharing policy framework that incorporates reservoir operating rules optimization based on conflicting uses and natural hydrologic variability, specifically tailored to drought conditions, is proposed. First, the trade-off between downstream and upstream water availability utilizing multi-objective optimization of reservoir operating rules is established. Next, reservoir operation with the candidate (optimal) rules is simulated, followed by their performance evaluations, and the rules selections for balancing water uses. Subsequently, a relationship between the reservoir operations simulated from the selected rules and drought-specific conditions is built to derive water-sharing policies. Finally, the reservoir operating rules are re-optimized to evaluate the effectiveness of the drought-specific water sharing policies. With a case study of the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile River, it is demonstrated that the derived water sharing policy can balance GERD power generation and downstream releases…

In this study, a systemic framework is proposed to derive operational reservoir water-sharing policies using multi-objective optimization for water use conflict mitigation.

The Grand Ethiopian Renaissance Dam (GERD) in Ethiopia is selected to demonstrate the framework and illustrate how operational water-sharing strategies,…

In this study, GERD reservoir operation rules are developed considering power generation and downstream water release simultaneously to mitigate upstream-downstream water use conflicts,…

With the water-sharing policy framework proposed here for the Grand Ethiopian Renaissance Dam on the Blue Nile River, a relationship between downstream and upstream water availability is established, water-sharing policies are derived from multi-objective optimization results of reservoir operating rules, and the effectiveness of these policies during drought periods is analyzed.

It is demonstrated that a framework incorporating RBF-based rules and a drought-focused water sharing policy can lead to robust reservoir decision-making.